Journal of Engineering Physics and Thermophysics, Vol. 82, No. 4, 2009

DETERMINATION OF THE INTERVALS OF TECHNOGENIC ACCUMULATIONS OF HYDROCARBONS IN A LAMELLAR ROCK MASS

G. G. Kushtanova

UDC 536.546

In rock masses consisting of layers with different thermophysical properties, the formation of a technogenic accumulation of hydrocarbons that leaked from the borehole and the recovery of the disturbed thermal field after the shutdown of the well are being modeled. The characteristic features of the section temperature dynamics related to different thermophysical properties and to the presence of the absorption interval are considered and a technique of finding the places with absorption of fluids is suggested.

Keywords: *technogenic deposit, filtration, temperature recovery, numerical simulation.*

Introduction. In recent decades, the requirements of society on the technologies of development of hydrocarbon deposits also involve minimization of the negative effect exerted by the results of technogenic activity on the environment and, in particular, prevention of the pollution of the ground with hydrocarbons, especially of the backs, i.e., of the overproductive strata. Of frequent occurrence in practice is that through the damages in the string a certain quantity of hydrocarbons moving in the well penetrate into the collectors lying above the horizons, resulting in the formation of their technogenic accumulations. The temperature of the penetrating fluid differs from the intrinsic temperature of the rocks. Usually it is higher, and the position of the hydrocarbon accumulation intervals can be found by this diagnostic feature. However, the fluid moving in the well also introduces disturbance in the temperature in the space around the well, with the time of recovery of the rock temperature at the boundary with the well exceeding the time of action of the disturbing factor. Prolonged shutdowns of wells for direct measurements of temperature are uneconomical; moreover, during the time of the shutdown the thermal anomaly caused by the secondary accumulation of the fluid may dissolve. The temperature of the rock near the well can be determined computationally using the method of [1] and the thermograms measured during a short shutdown of a well. However, when the leak rates are small, these cases are difficult to interpret. Additional difficulties arise because of the fact that often rock masses consist of layers with different thermophysical properties, with the layers themselves being as thick as the collector (usually 1–10 m). In the case of lamellar rock masses the thermograms recorded after the shutdown of the well will be heavily "dissected," with the appearance of a multitude of anomalies, making the interpretation of the thermograms difficult. In this case, it becomes rather difficult to distinguish between the forms of anomalies of secondary accumulations of hydrocarbons and the anomalies caused by different rates of temperature recovery only from the computational thermogram by the method of [1]; the use of additional criteria is needed. The problem indicated is of great interest, in particular, for underground reservoirs of gas.

Statement of the Problem. The mathematical statement of the problem on nonisothermal penetration of a gas into a collector with allowance for its heat exchange with the surrounding rocks and Forchheimer's law of filtration is as follows:

$$m\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho V)=0\,,\quad -\frac{\partial P}{\partial r}=\frac{\mu}{k}V+\beta\rho\,\left|V\right|\,V\,,\quad r_{\rm w}<r<R_{\rm c}\,,\quad l<x<l+H\,,$$
$$c_{\rm bed}\frac{\partial T}{\partial t}=c\,(-\rho V)\left(\frac{\partial T}{\partial r}+\varepsilon\frac{\partial P}{\partial r}\right)+\frac{\partial}{\partial x}\left(\lambda_{\rm bed}\frac{\partial T}{\partial x}\right),\quad \frac{P}{\rho}=zRT\,. \tag{1}$$

Kazan' State University, 18 Kremlevskaya Str., Kazan', 420008, Russia; email: Galya.Kushtanova@ksu.ru.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 82, No. 4, pp. 663–667, July–August, 2009. Original article submitted March 27, 2007; revision submitted September 22, 2008.

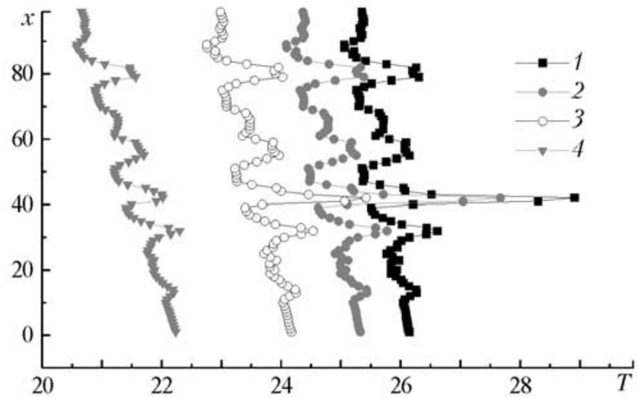


Fig. 1. Thermograms after the shutdown of the well (time elapsed after the shutdown of the well: 1) 10 h; 2) 20; 3) 50; 4) 240. T, ^{o}C; x, m.

The temperature distribution in the rocks surrounding a collector with a penetrating fluid is described by the equation

$$c_{\mathrm{r}}\frac{\partial T}{\partial t}=\lambda_{\mathrm{r}}\Delta T\,,\quad r_{\mathrm{w}}<r<R_{\mathrm{c}}\,,\quad 0<x<l\,,\quad l+H<x<L\,. \tag{2}$$

As the initial conditions the geothermal distribution of temperatures is used. On the assumption of constancy of the heat flux over the depth for a lamellar rock mass, it will have the form of a lumped linear curve with slopes inversely proportional to the thermal conductivities of individual layers. On the cylindrical upper and lower boundaries of the regions the temperature is assumed unperturbed and equal to the geothermal one:

$$r=R_{\mathrm{c}}\,,\quad T\,(R_{\mathrm{c}},x,t)=T_{\mathrm{g}}\,(x)\,;\qquad x=0\,,\quad T\,(r,x,t)=T_{\mathrm{g}}\,(0)\,;\qquad x=L\,,\quad T\,(r,L,t)=T_{\mathrm{g}}\,(L)\,; \tag{3}$$

the condition of absence of inflow is assumed for the pressure:

$$r=R_{\mathrm{c}}\,,\quad l<x<l+H\,,\quad \rho V=0\,. \tag{4}$$

On the wall of the well in the process of its operation the temperature $T(r_{\mathrm{w}},\ x,\ t)\ =\ T_{\mathrm{w}}$ is assigned. At the entrance to the absorbing collector a constant well yield q is assigned:

$$\rho V=q/(2\pi r_{\mathrm{w}}H)\,,\quad r=r_{\mathrm{w}}\,,\quad l<x<l+H\,. \tag{5}$$

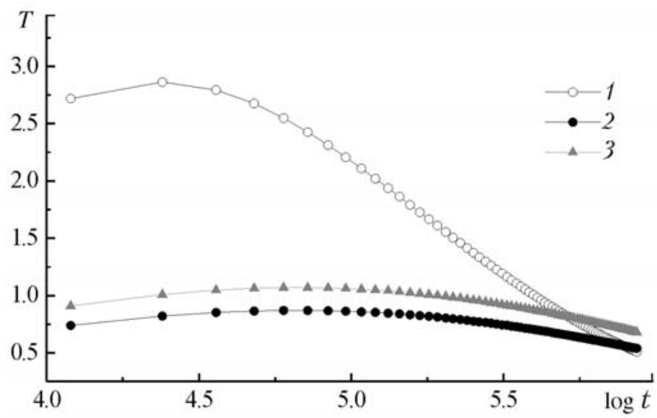
After the shutdown of the well, the cessation of fluid penetration into the collector and symmetricity of the process of recovery over the axial coordinate r are assumed:

$$\frac{\partial T}{\partial r}=0\,,\quad r=r_{\mathrm{w}}\,,\quad 0<x<L\,;\quad \rho V=0\,,\quad r=r_{\mathrm{w}}\,,\quad l<x<l+H\,. \tag{6}$$

In the present work the problem was solved numerically with the application of the method of splitting over processes and spatial variables. An absolutely stable conservative symmetric difference scheme [2] was used.

Discussion of Results. The results of modeling point to the good informativeness of such a parameter as the complex containing the thermal diffusivity of rocks as well as the dynamics of the magnitude of temperature anomalies after the shutdown of the well.

We will consider an example showing the formation of a technogenic accumulation of a gas in the overproductive horizon represented by layers of rocks with different thermophysical properties. We assume that a small quantity of the gas (126 kg/24h) is absorbed in an interval of 40–42 m. The duration of the well operation is 1 month. The temperature of the gas flowing through the well and entering the collector is T_{w} = 30^{o}C, and the permeability of the absorbing collector k = 10^{-1} μm^{2}. Figure 1 presents the thermograms in the well in the period of temperature recovery after shutdown of the well for different time moments. Since the initial temperature of the rocks in the interval



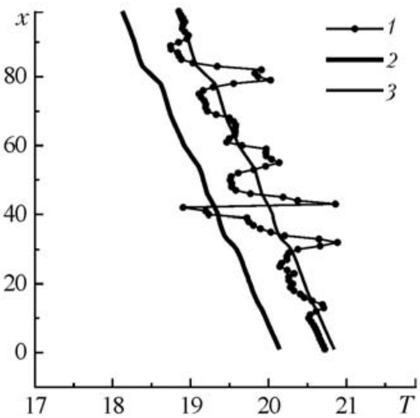


Fig. 2. Dynamics of the amplitude of anomalies: 1) at the depth of the absorbing collector; 2, 3) at the depth corresponding to dense rocks, 32 and 79 m. T, ^{o}C.

Fig. 3. Calculated procedure (1), initial geotherm (2), shifted in parallel (3). T, ^{o}C; x, m.

considered is more than 10^{o}C lower than the gas temperature in the well during its operation, the recovery of the initial temperature occurs after the shutdown of the well, the rocks are gradually cooled, and all the anomalies become less pronounced with time. It is difficult to determine the absorption interval visually. However, one can easily see that the dynamics of the magnitude of anomalies at the depth of the absorbing collector and dense rocks is different and has its own characteristic features (Fig. 2). For dense rocks the magnitude of the anomalies changes little and has an extended maximum. The maximum of the magnitude of the anomaly connected with the difference in the thermophysical properties of rocks is observed at the 13th–78th hour for thermal diffusivities $5–15\cdot10^{7}$ m^2/sec, whereas the moment of appearance of the maximum in the temperature anomaly in the absorption interval is determined by the well yield, and for small yields it occurs much earlier than the maximum of the magnitude of anomalies connected with the difference in the thermophysical properties of rocks. Instead of the magnitude of the anomaly, one can also consider the curves of temperature recovery from individual sections through the depths.

The sought temperature of rocks T_g is calculated from the formula [1, 3]

$$\frac{\Delta T}{\Delta T_{op}} = 1 - 0.5A\,(t_{op} + t_{rec})\left(\ln\frac{8at_{rec}}{r_w^2} - 1\right), \tag{7}$$

where

$$\Delta T = T\,(r_w, x, t_{rec}) - T_g\,;\quad \Delta T_{op} = T_w - T_g\,;\quad A\,(t_{op} + t_{rec}) = \frac{1}{\ln\,(1 + \sqrt{\pi a\,(t_{op} + t_{rec})}/r_w)}\,.$$

If by the time of the well shutdown the process has a quasi-stationary character, then $A(t_{opt} + t_{rec})$ = const. After simple transformations it follows from Eq. (7) that at each section over the depth the temperature in the well during the process of recovery is a linear function of $\ln(t_{rec})$. To determine the coefficients of linear dependence it is desirable to use three thermograms. The coefficients obtained make it possible to determine the sought temperature of rocks $T_g(x)$.

The temperature of rocks (Fig. 3) in the example considered was calculated by the method of [1] with the use of model thermograms obtained 10, 20, and 50 h after the shutdown of the well. The preliminary values of the temperature of model thermograms were rounded off to hundredths of a degree to simulate the accuracy of real measurements. For the sake of convenience of comparison the initial geotherm is shifted parallel to itself. It is seen that all the amplitudes of temperature anomalies occurring because of the difference in the thermophysical properties have magnitude less than a degree. In this case, the anomalies in the intervals of dense rocks on thermograms in the process

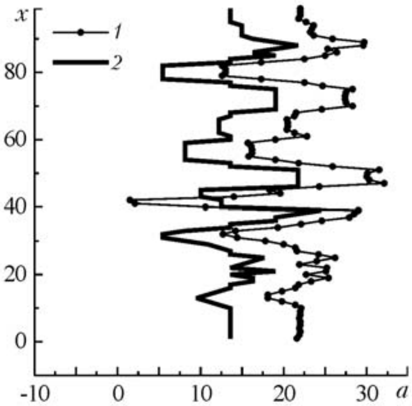


Fig. 4. Thermal diffusivity: 1) calculated; 2) initial. a, 10^{-7} m^2/sec; x, m.

of recovery and on the calculated one are of the same sign, whereas in the absorption interval at small well yields an anomaly can change sign on the calculated thermogram. The variations of the sign of temperature anomaly for various sections over the depth in the interval of fluid absorption are characteristic for situations that are close to the accuracy limit of the technique of [1].

We can also single out an additional feature corresponding to the absorption interval. Thus, Eq. (7) allows one to determine also the complex a/r_w^2 and, at a known value of r_w, the thermal diffusivity of the bed. The absorption intervals are characterized by low values of the computational coefficient of thermal diffusivity (curve 1 in Fig. 4). For dense rocks the deviation of the thermal diffusivity coefficient is opposite in sign to the anomaly on the thermogram. The situation is more complex for the absorption interval. At large well leakages the low values of the calculated coefficient of thermal diffusivity correspond to temperature anomalies of the same sign as the deviation of the temperature of a penetrating agent from the initial temperature of rocks. But at small well yields the relationship can be reverse. The graph (curve 2) shows also the initial thermal diffusivity coefficient, i.e., that used in simulation. If we shift the curve of the calculated thermal diffusivity coefficient parallel to itself and combine it with the curve of the initial thermal diffusivity coefficient, they will coincide at any depth except for the absorption interval, thus pointing to the high accuracy of the indicated parameter and efficiency of the use of the given criterion.

Conclusions. The anomalies represented on the thermograms recorded in a shutdown may well have different origins. To determine reliably the absorption interval and technogenic accumulation of a fluid at small amounts of leakages in a lamellar rock mass, one has to consider the behavior of a complex of quantities: the dynamics of the amplitude of temperature anomalies or temperature recovery curves over individual depths and calculated values of the temperatures of rocks and of the thermal diffusivity coefficient. To determine the position of problem intervals, special pumping of a fluid with a temperature differing from that of the rocks is envisaged.

NOTATION

a, thermal diffusivity coefficient, m^2/sec; c_{bed}, c_r, heat capacities of a saturated collector of a bed and of dense rocks, $J/(m^3{\cdot}K)$; c, heat capacity of a fluid, J/(kg·K); H, bed thickness, m; k, bed permeability, μm^2; l, base of the bed, m; L, vertical size of the region considered, m; m, porosity; P, pressure, MPa; q, absorption yield, kg/24h; r, radial coordinate, m; r_w, well radius, m; R_c, bed contour; cylindrical boundary of the region considered, m; R, gas constant, J/(kg·K); t, time, sec; t_{op}, time of well operation till its shutdown, sec; t_{rec}, time reckoned from the moment of well shutdown, sec; T, temperature, ^oC; T_w, temperature of the fluid moving in the well, ^oC; T_g, geothermal temperature, ^oC; ΔT_{op}, temperature head during well operation, ^oC; V, percolation rate, m/sec; x, vertical coordinate, m; z, coefficient of gas compressibility; β, coefficient of deviation from the Darcy law; ε, the Joule–Thomson coefficient, $^oC/MPa$; λ_{bed}, λ_r, coefficients of heat conduction of saturated collector of the bed and of dense rocks, W/(m·K); μ, dynamic viscosity of a fluid, Pa·sec; ρ, fluid density, kg/m^3. Subscripts: b, bed; c, bed contour; g, geothermal; op, operation; r, rock; rec, recovery; w, well.

REFERENCES

1. A. A. Davletshin, N. G. Daminov, G. G. Kushtanova, A. I. Markov, and V. F. Shulaev (RF), A means of revealing man-made accumulations of fluids in geological objects opened by a bore, Patent 2013533 of the Russian Federation No. 4942572, Published 30.05.94.
2. N. N. Kalitkin, *Numerical Methods* [in Russian], Nauka, Moscow (1978).
3. S. A. Nikolaev, N. G. Nikolaeva, and A. N. Salamatin, *Thermophysics of Rocks* [in Russian], Izd. Kazansk. Univ., Kazan' (1987).