MULTISENSOR RESEARCH TECHNOLOGIES OF OIL HORIZONTAL WELLS ON FIELDS OF THE REPUBLIC OF TATARSTAN

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Abstract. In the Republic of Tatarstan the development widely involves hard-to-recover reserves of hydrocarbons, confined to low-permeable, heterogeneous and dissected reservoirs. Improvement of recovery efficiency of such reserves largely depends on the operational control system based on information about the filtration and thermal properties of the oil reservoir. Issues, related to the interpretation of geological field information, lead to incorrect mathematical problems in terms of Hadamard. The numerical solution of such problems requires the development of special methods. A mathematical model of thermohydrodynamic processes occurring in the 'horizontal well' system is constructed in the paper.

Based on this model and regularization methods of A.N. Tikhonov, a computational algorithm is proposed for interpreting the results of thermohydrodynamic studies of horizontal wells and layers. Curves of the temperature changes are taken as the initial information, taken simultaneously by several deep instruments installed at different parts of the horizontal part of the wellbore. This approach makes it possible to evaluate the filtration parameters of an inhomogeneous reservoir and to construct an inflow profile along the trunk of a horizontal well.

Key words: horizontal well, pressure, temperature, permeability, multi-sensor technologies, inverse task
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Conducting and processing the results of thermohydrodynamic studies in the development of fields with hard-to-recover hydrocarbon reserves, as a rule, involve significant difficulties. These include: the mechanization of the producing wells stock, that makes it difficult to deliver deep measuring instruments to the bottom of wells; low rates, leading to low information content of debitometric studies; thermodynamic processes accompanied by small temperature changes; a long duration of hydrodynamic studies hindering the use of classical methods of interpreting pressure recovery curves.

Measurements of temperature and pressure in the trunk of a horizontal well based on multi-sensor technology (Farkhullin et al., 2003; Khairullin et al., 2006) provide quite complete information on the thermohydrodynamic processes occurring in the reservoir and the trunk. The change in temperature in the trunk of a horizontal well is an integral indicator of heat and mass transfer processes occurring both in the well itself and in the reservoir.

We will assume that the trunk of the horizontal well is parallel to the roof and the base of the reservoir; fluid movement in the trunk is one-dimensional. The process of pressure distribution in the trunk is quasi-stationary; the inflow of fluid to the trunk at the start of the well is radial. Under these assumptions, the laws of conservation of mass, momentum, and energy, it follows that (Vasilyev, Voevodin, 1968; Charnyi, 1975):

$$\frac{\partial v}{\partial x} = -\frac{2w}{r_c}, \quad w = -\frac{k}{\mu}\frac{\partial p_2}{\partial r}\bigg|_{r=r_c}, \quad 0<x\le L, \tag{1}$$

$$-\frac{\partial p_1}{\partial x} = \rho\frac{\partial (v^2)}{\partial x} + \frac{\psi}{4r_c}\rho v|v|, \quad 0<x\le L, \tag{2}$$

$$\frac{\partial T_1}{\partial t} + v\left(\frac{\partial T_1}{\partial x} + \varepsilon\frac{\partial p_1}{\partial x}\right) = \frac{2(\alpha_m - w\rho C_p)}{\rho C_p r_c}\left(T_2\big|_{r=r_c} - T_1\right),$$

$$0<x\le L, \; 0<t\le t_{\exp}, \tag{3}$$

$$\beta^*\frac{\partial p_2}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{k}{\mu}r\frac{\partial p_2}{\partial r}\right),$$

$$0<x\le L, \; r_c<r<R_k, \; 0<t\le t_{\exp}, \tag{4}$$

$$C_{п}\frac{\partial T_2}{\partial t} = \rho C_p\frac{k}{\mu}\frac{\partial p_2}{\partial r}\left(\frac{\partial T_2}{\partial r} + \varepsilon\frac{\partial p_2}{\partial r}\right),$$

$$0<x\le L, \; r_c\le r<R_k, \; 0<t\le t_{\exp}, \tag{5}$$

with initial

$$p_2(x,r,0)=p_0(x,r), \; T_2(x,r,0)=T_0(x,r), \; 0\le x\le L, \; r_c\le r<R_k, \tag{6}$$

and boundary conditions

$$\int_S \frac{k}{\mu}\frac{\partial p_2}{\partial r}\mathrm{d}S = q, \quad 0<t\le t_{\exp}, \tag{7}$$

$$p(x, R_k, t)=p_k, \; T_2(x, R_k, t)=T_k. \tag{8}$$

Here, $p_1=p_1(x)$, $T_1=T_1(x, t)$ is the pressure and

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temperature in the trunk of a horizontal well, $p_2=p_2(x, r, t)$, $T_2=T_2(x, r, t)$ is the pressure and temperature in the reservoir, p_k – reservoir pressure, T_k – reservoir temperature, q – horizontal well production rate, S – trunk surface of a horizontal well, r_c – trunk radius, R_k – external boundary radius, β^* – reservoir elasticity, $v(x)$ – fluid velocity in the trunk of a horizontal well, ρ – fluid density, ε – Joule-Thomson coefficient, ψ – coefficient of hydraulic resistance, α_m – coefficient of heat transfer of horizontal well trunk, C_p – the specific heat of fluid, w – filtration rate, L – the length of the horizontal well trunk, t_{exp} – operating time of the well.

The method of solving the boundary task (1)-(8) is based on the conjugation of the external (reservoir) and internal (trunk of a horizontal well) tasks. The system (1)-(8) is solved numerically by the method of finite differences. The filtration area is covered by a non-uniform grid, which thickens to the well. The resulting non-linear system of difference equations is solved iteratively.

The model task with data corresponding to the real deposits of the Republic of Tatarstan explores the thermohydrodynamic processes occurring in the "reservoir – horizontal well" system.

A simulated oil reservoir is considered, which is developed by a horizontal well. The horizontal well is put into operation with a constant recovery of liquid from the reservoir. Initial data:

$C_n = 1.48\ 10^6$ $J/(m^3K)$,
$C_p = 1929$ $J/(kg\ K)$,
$T_k = 300$ K,
$p_k = 15$ MPa,
$\beta^* = 10^{-4}$ MPa^{-1},
$\mu = 25$ $mPa\ s$,
$\rho = 800$ kg/m^3,
$\varepsilon = 0.4$ K/MPa,
$L = 100$ m,
$r_c = 0.1$ m,
$R_k = 5$ m,
$q = 30$ m^3/day.

It is assumed that the permeability of the reservoir is a piecewise constant function. In each zone of the reservoir homogeneity, a deep instrument is located (Fig. 1). The following variants of zones of the reservoir heterogeneity are considered:

$k_1>k_2$, $k_1 = 0.05$ μm^2, $k_2 = 0.01$ μm^2,
$k_1<k_2$, $k_1 = 0.01$ μm^2, $k_2 = 0.05$ μm^2.

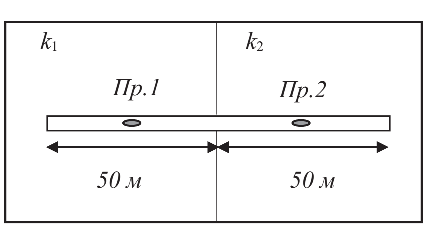

Fig. 1. Arrangements of instruments in a heterogeneous reservoir

In the trunk of a horizontal well, liquid comes from zones of heterogeneity of the oil reservoir with different temperatures due to the Joule-Thomson effect (Fig. 1). The change in temperature in the trunk of a horizontal well is due to the calorimetric effect.

The results of numerical calculations showed that for a homogeneous oil reservoir, the temperature along the trunk is constant and increases with time. The fluid velocity along the horizontal well trunk changes linearly. Figures 2-3 show the calculation results of the change in temperature and flow velocity for variants 1,2 at time = 120 h. The temperature (Fig. 2), the flow velocity (Figure 3) in the trunk of a horizontal well changes non-linearly. The intensity of the fluid inflow to the trunk of a horizontal well (Figu. 4-5) has a discontinuity at the point corresponding to the boundary of the reservoir homogeneity zones in terms of permeability. The distribution of temperature, flow velocity along the horizontal well trunk and the intensity of the fluid inflow to the horizontal well trunk depend on the permeability values and the size of the uniformity zones.

A distinctive feature of the inverse tasks of oil and gas hydromechanics, associated with the study of mathematical models of real filtration processes in oil reservoirs, is that the nature of additional information is determined by the capabilities of the field experiment. On the basis of the proposed mathematical model

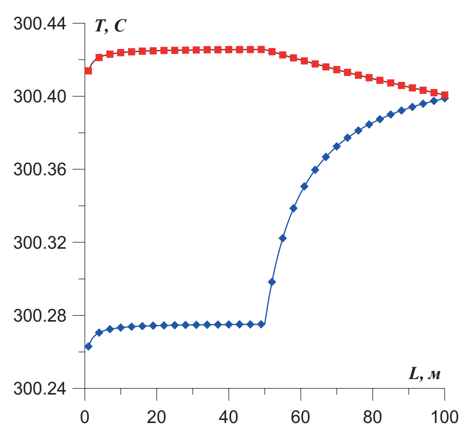

Fig. 2. Temperature distribution along the trunk of a horizontal well. ■ – *Var.1* $k_1>k_2$, ♦ – *Var. 2* $k_1<k_2$.

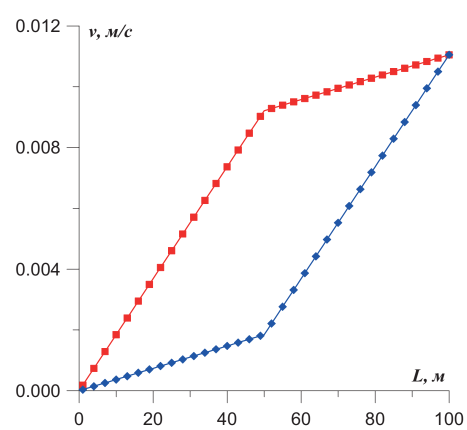

Fig. 3. Distribution of velocity along the trunk of a horizontal well. ■ – *Var.1* $k_1>k_2$, ♦ – *Var. 2* $k_1<k_2$

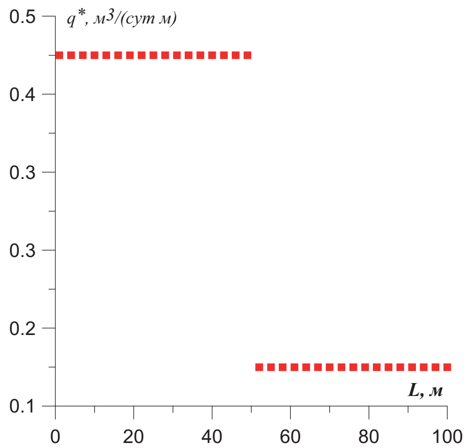

Fig. 4. Temperature distribution along the trunk of a horizontal well. ■ *– Var.1* $k_1>k_2$

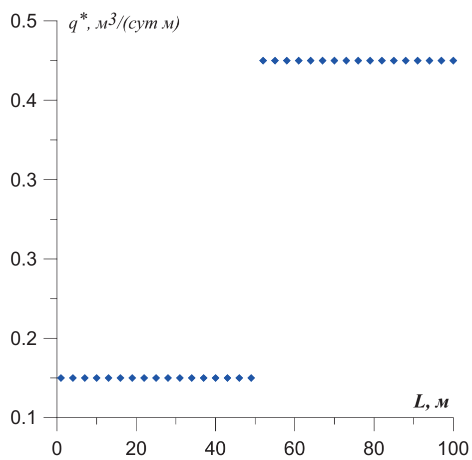

Fig. 5. Temperature distribution along the trunk of a horizontal well. ♦ *– Var. 2* $k_1<k_2$

and regularization methods of A.N. Tikhonov, a computational algorithm is proposed for interpreting the results of thermohydrodynamic studies of horizontal wells. The results of measurements of the temperature change during the start-up period of the well at different sections of the horizontal well trunk are used as initial information. The locations of the deep measuring equipment are determined on the basis of geophysical studies of the well. In works (Farkhullin et al., 2003; Khairullin et al., 2006), a technology for performing thermohydrodynamic studies of a horizontal well with the help of several deep autonomous instruments is described.

Let us assume that in the locations of deep measuring instruments in the trunk of a horizontal well with coordinates x_i, $i=\overline{1,N}$, the curves of temperature changes are taken:

$$T_{1,i}(t) \equiv T_1(x_i,t) = \varphi_i(t),\ i=\overline{1,N},\ 0<t\le t_{\exp}. \quad (9)$$

The inverse coefficient task is formulated as follows: determine the permeability coefficient $k=k(x,r)$, when the thermohydrodynamic processes in the oil reservoir and the horizontal well trunk are described by equations (1)-(8). As the initial information, the measured values of temperature by deep autonomous devices are used.

An estimate of the permeability coefficient is sought in the class of piecewise constant functions $k(x,r) = k_n$, $(x,r)\in V_n$, $\bigcup_{n=1}^{N} V_n = V$, where V_n, $n=\overline{1,N}$ – homogeneity areas (Fig. 1).

An approximate solution of the inverse coefficient task (1)-(9) is sought from minimizing the root-mean-square deviation between the observed and calculated quantities:

$$F(\alpha)=\sum_{n=1}^{N}\int_{0}^{t_{\exp}}\left[T_{1,n}(t)-\phi_n(t)\right]^2 dt \quad (10)$$

Where $\varphi_n(t)$ – the observed values of the temperature, $T_{1,n}(t)$ – the calculated temperature values obtained from the numerical solution of equations (1)-(8), $\alpha=(k_1, k_2, \ldots, k_N)$ – the parameter sought, $0 < m_n \le k_n \le M_n$ (m_n, $M_n = const$).

Research of the horizontal well No 18326 (Nazimov, 2007). The well is located in the deposit No. 665 of the Romashkino field of the Republic of Tatarstan. The well has a 313 m open horizontal section in the Dankovo-Lebedyanskian horizon in the interval from 1475 to 1788 m. In 2004, deep thermohydrodynamic studies based on multi-sensor technologies were carried out in the well. Figure 6 shows the locations of the instruments. After the end of the underground repair, the well was put into operation with a flow rate of 7.8 m^3/day.

The proposed computational algorithm is used to

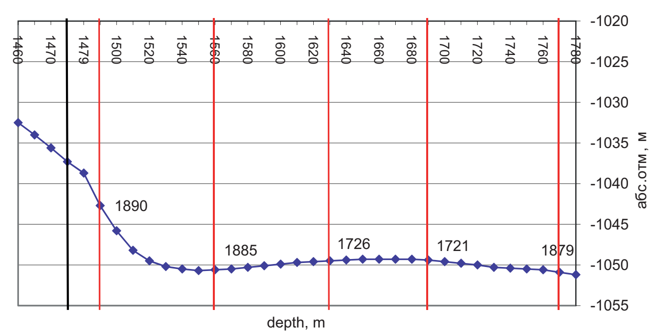

Fig. 6. Trajectory scheme of the trunk of the horizontal well No 18326 and the location of the instruments

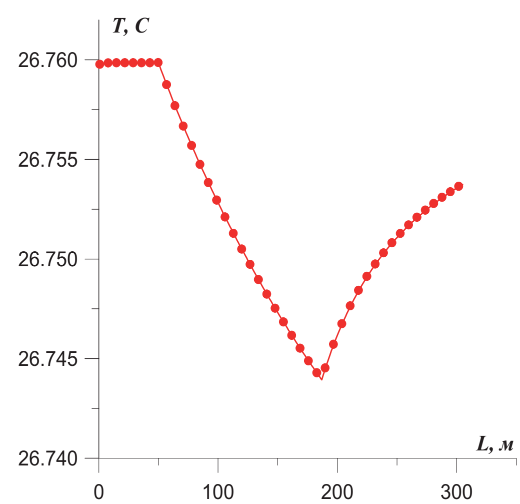

Fig. 7. Temperature distribution along the well trunk

interpret the temperature variation curves taken with the depth instruments No. 1879, 1721, 1726 and 1885. For this purpose, the reservoir was divided into four zones of homogeneity, in which the devices No. 1879, 1721, 1726 and 1885 were located.

Figures 7-8 show the calculation results of the distribution of temperature and fluid flow velocity in the trunk of a horizontal well. The distribution of fluid flow along the trunk of a horizontal well is shown in Figure 9. Figures 10, 11, 12 and the table show the interpretation results of the curves of temperature variation with respect to instruments No. 1879, 1721 and 1885. Figures 10, 11, 12 present the calculated and observed curves of temperature changes. The table provides estimates of permeability in the instrument areas.

From the results obtained, it follows that the locations of instruments No. 1721, 1726 have a low permeability – in these sections the inflow to the trunk of a horizontal well is the smallest (Fig. 9). Geophysical studies have shown that in the location of 1680-1721 m (instrument No. 1721), the well trunk passes through a low permeable inclusion, and in the location of 1620-1670 m (instrument No. 1726) – through a weakly

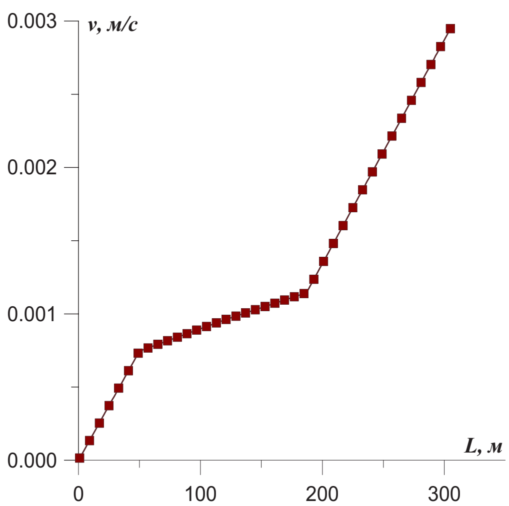

Fig. 8. Velocity distribution along the well trunk

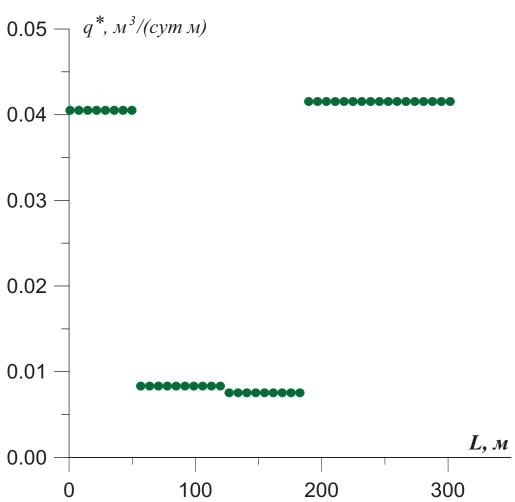

Fig. 9. Inflow distribution along the well trunk

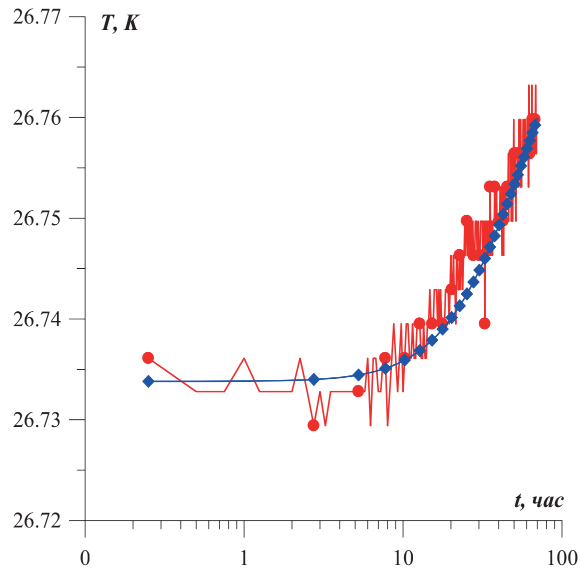

Fig. 10. Instrument No. 1879. Temperature change curve ● *– observed,* ♦ *– calculated*

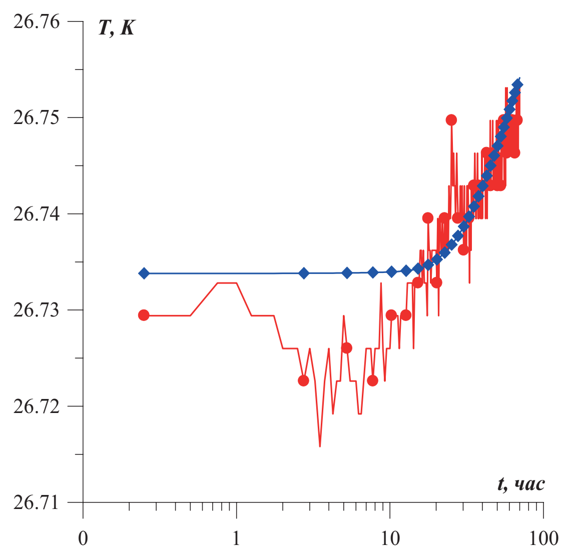

Fig. 11. Instrument No. 1721. Temperature change curve ● *– observed,* ♦ *– calculated*

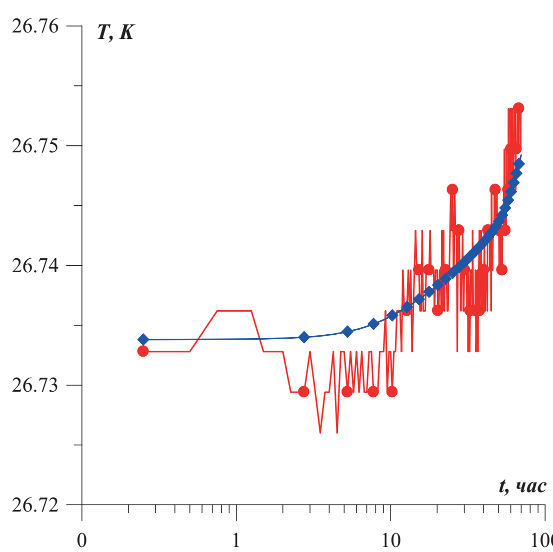

Fig. 12. Instrument No. 1885. Temperature change curve ● *– observed,* ♦ *– calculated*

	Zone device No. 1879	Zone device No. 1721	Zone device No. 1726	Zone device No. 1885
Interpretation of curves of temperature variation				
k/μ (μ $m^2/mPa{\cdot}s$)	$1.04\ 10^{-3}$	$2.13\ 10^{-4}$	$1.93\ 10^{-4}$	$1.07\ 10^{-3}$
Interpretation of curves of pressure variation				
k/μ (μ $m^2/\ mPa{\cdot}s$)	$3,42{\cdot}10^{-3}$	$4,46{\cdot}10^{-3}$	$3,63{\cdot}10^{-3}$	$6,34{\cdot}10^{-3}$

Table. Horizontal well No. 18326. Estimates of the filtration parameters

non-highly-saturated inclusion. The results of the studies carried out by JSC Permneftegeofizika in mid-2006 with the LATERAL-2005 technological complex showed that in the areas where these instruments are located, a low inflow to the horizontal well trunk is observed.

Estimates of conductivity in the locations of instruments Nos. 1885 and 1879, obtained from the curves of temperature and pressure change are in good agreement. In interpreting the results of hydrodynamic studies, the skin effect was not taken into account, and therefore there is a discrepancy between the conductivity estimates in the locations of instruments No. 1721, 1726.

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