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Hydrodynamic behavior of fluids in the "porous reservoir–well" system

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Abstract. *This work focuses on the thermohydrodynamic processes occurring during fluid flow within a well which are intrinsically linked to similar processes in the surrounding reservoir caused by filtration and the temperature field of the surrounding rocks. This phenomenon must be carefully considered when determining optimal well operation modes.*

Keywords. well · formation · temperature · pressure · gas-saturated · heat conduction · porosity coefficient.

Mathematics Subject Classification (2010): 76S05

1 Introduction

Recently, interest in quantitative interpretation of temperature measurements in a well has increased. The work [1] is devoted to studying the patterns of spatio-temporal distribution of the temperature field in a formation based on numerical modeling of single-phase fluid filtration in a porous medium, taking into account convective and conductive heat transfer, barothermal effect, and heat exchange with impermeable rocks surrounding the formation. A numerical model has been developed and studied, discretization has been carried out by the control volume method, and the alternating direction method has been used. The correctness of the numerical solution was verified by comparison with known analytical solutions, as well as by comparison with the results of modeling in a specialized software package. Using numerical modeling of non-isothermal movement of gasified oil in a well with a multi-layer system, taking into account the Joule-Thomson effect, the adiabatic effect and the heat of degassing, the temperature distribution in the well and the layer is investigated in [2]. It is shown that the temperature distribution can be used to estimate the position of the boundary of the oil degassing region in the wellbore. The paper [3] studies the distribution of temperature and pressure in a formation with a positive and negative skin factor. This problem is of practical interest, since the assessment of the state of the bottom-hole formation zone is an integral factor in conducting geological and technical measures

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on wells. A comparative analysis of the dynamics of temperature and pressure in a homogeneous formation, with contamination of the bottomhole formation zone and a zone of increased permeability is carried out. A multiporosity extension of classical double- and triple-porosity flow models for slightly compressible fluids in fractured rock is presented in [4]. This multiporosity model adapts the multirate solute transport framework developed by Haggerty and Gorelick (1995) to describe viscous fluid flow in fractured reservoirs. It generalizes both pseudo–steady-state and transient interporosity flow models by incorporating a fracture continuum and an overlapping set of multiple matrix continua. The fracture–matrix exchange coefficients are characterized by a discrete probability mass function, allowing for greater flexibility in representing heterogeneity. Semianalytical, cylindrically symmetric solutions to the multiporosity model are developed using the Laplace transform to demonstrate the system's flow behavior. Thermobaric conditions leading to retrograde phenomena in reservoir mixtures of gas condensate and oil fields often correspond to pressures and temperatures observed in the practice of their development. This causes the precipitation of liquid components in gas-saturated formations, changes in the composition of the extracted product, as well as well productivity [5]. In [6] the problem of non-stationary temperature field in two-dimensional fluid filtration in a layered formation is investigated taking into account the barothermal effect, radial and vertical heterogeneity in permeability. The results of comparison of analytical and numerical solutions for the temperature of fluid flowing from the formation for two different models of formation heterogeneity are presented. It follows from the obtained results that to calculate non-stationary temperature in a layered formation with radial heterogeneity in the near-wellbore zone it is necessary to use a two-dimensional filtration model for correct consideration of fluid flows between layers. The formation of a viscous slug (or thickener) in the reservoir as a result of a chemical reaction between two sequentially injected reagents can be described using a two-phase, five-component flow model [7]. This study presents a comprehensive mathematical model comprising two main blocks: a hydrodynamic block, represented by governing flow equations, and a physicochemical block, which includes equations describing chemical reactions between the injected agents, as well as mass transfer of reactants and thickener. The proposed model enables the optimization of both the composition and the injection volume of the blocking agent for each specific well, facilitating more effective water shut-off and improved reservoir management.

2 Mathematical problem statement

A mathematical model of single-phase fluid movement in a formation and a well under conditions of heat transfer with rocks is assumed. A radial three-layer reservoir is considered, with a centrally located well that functions simultaneously as both an injection and production well. The upper layer is gas-saturated, the lower layer is oil-saturated, and an impermeable interlayer separates them. Hot water is injected into the gas-saturated formation through the annulus. Oil is extracted from the underlying formation through lift pipes. It is assumed that gas is uniformly withdrawn along the outer boundary of the reservoir. Real thermophysical properties of fluids are taken into account. The following assumptions are made in order to simplify the model: the vertical heat conduction in the well due to thermal conductivity and the heat generated due to dissipation of mechanical energy are small compared to convective ones; the temperature and pressure of fluids across the well cross-section do not change; vertical heat conduction within the tubing is negligible relative to radial conduction; the rock matrix is homogeneous and isotropic; the thermophysical properties of the layers and surrounding rocks are assumed identical.

A mathematical model of single-phase fluid flow in a formation and a well under conditions of heat transfer with rocks is assumed. In each element of the formation volume, the average temperature of the particles constituting the solid skeleton coincides with the average temperature of the fluids filling the pore space; heat transfer is taken into account due to thermal conductivity in formations and pipe walls (horizontal direction), rocks (vertical and horizontal), impermeable interlayer (vertical); gas displacement by water is piston; all thermohydrodynamic processes are considered quasi-stationary. It is assumed that the thermal field of wells extracting gas does not affect the temperature fields of rocks and productive formations.

3 Formulation of a problem

Fluid flow in the considered system is described by differential equations of continuity, momentum, energy and heat conduction. The governing system of equations is formulated as follows:

$$\frac{d\,(\rho_1 \upsilon_1 F_1)}{dz} = 0 \tag{3.1}$$

$$\frac{d\,(\rho_2 \upsilon_2 F_2)}{dz} = 0 \tag{3.2}$$

$$-\frac{dP_1}{dz} = \rho_1 \upsilon_1 \frac{d\upsilon_1}{dz} + \rho_1 g \sin\beta + \frac{\lambda_1 \upsilon_1^2 \rho_1}{2d_1} \tag{3.3}$$

$$-\frac{dP_2}{dz} = \rho_2 \upsilon_2 \frac{d\upsilon_2}{dz} + \rho_2 g \sin\beta - \frac{\lambda_2 \upsilon_2^2 \rho_2}{2d_e} \tag{3.4}$$

$$\frac{d}{dz}\left[G_1\left(i_1 + gz + \frac{\upsilon_1^2}{2}\right)\right] = \frac{dQ_1}{dz} \tag{3.5}$$

$$\frac{d}{dz}\left[G_2\left(i_2 + gz + \frac{\upsilon_2^2}{2}\right)\right] = \frac{dQ_2}{dz} \tag{3.6}$$

$$\frac{d}{dr}\left(r\frac{K_1\rho_1}{\mu_1}\frac{dP_1}{dr}\right) = 0 \tag{3.7}$$

$$\frac{d}{dr}\left(r\frac{K_2\rho_2}{\mu_2}\frac{dP_2}{dr}\right) = 0 \tag{3.8}$$

$$\frac{d}{dr}\left(r\frac{K_3\rho_3}{\mu_3}\frac{dP_3}{dr}\right) = 0 \tag{3.9}$$

$$\upsilon_{1f}\rho_1 H_1 C_{p1}\left(\varepsilon_1\frac{dP_1}{dr} - \frac{dT_1}{dr}\right) = \frac{dQ_3}{dr} \tag{3.10}$$

$$\upsilon_{2f}\rho_2 H_2 C_{p2}\left(\frac{dT_2}{dr} - \varepsilon_2\frac{dP_2}{dr}\right) = \frac{dQ_4}{dr} \tag{3.11}$$

$$\upsilon_{3f}\rho_3 H_2 C_{p3}\left(\frac{dT_3}{dr} - \varepsilon_3\frac{dP_3}{dr}\right) = \frac{dQ_5}{dr} \tag{3.12}$$

$$\frac{\partial^2 T_{gf}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{gf}}{\partial r} + \frac{\partial^2 T_{gf}}{\partial z^2} = 0 \tag{3.13}$$

$$\frac{d^2 T_{in}}{dz^2} = 0 \tag{3.14}$$

$$\frac{\partial^2 T_{tube}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{tube}}{\partial r} = 0 \tag{3.15}$$

The system of equations (3.1) – (3.15) is closed using the Peng-Robinson equation of state [8].

The origin of coordinates corresponds to the well bottom. Subscripts “1”, “2”, “3” re used throughout the model to denote oil, water, and gas, respectively; T, P, G, ρ, υ, i, μ - temperature, pressure, mass flow, density, velocity, enthalpy, viscosity of fluids; g - gravitational acceleration; β - well inclination angle from the horizontal; d_1, d_2, d_3, F_1 - internal and external diameter of the lift pipe, internal diameter of the casing, cross-sectional area of the lift pipe; $d_e = d_3 - d_2$ - equivalent diameter; $F_2 = \frac{\pi}{4}\left(d_3^2 - d_2^2\right)$ - cross-sectional area of the annulus; $dQ_1 = 2\pi a_1 (T_2 - T_1)\, dz$ - heat transfer through the wall of the production tubing;a_1 - interfacial convective heat transfer coefficient from the annular fluid to the fluid within the production tubing; $dQ_2 = dQ_1 + dQ'_1$ - heat transfer from the annular fluid to both the fluid inside the production tubing and the surrounding rock formation; $dQ'_1 = b_{gf} \frac{dT_{gf}}{dr} dz$ - heat flow from the annular fluid to the surrounding rock formation; b_{gf} - thermal conductivity of the rock formation (thermal conductivity coefficient of geological formations); d_5 - outer diameter of the cement sheath; K_1, K_2 - permeability coefficients of rocks of oil-saturated and gas-saturated formations; C_p - isobaric heat capacity of fluids; H_1, H_2, h - thicknesses of productive formations and impermeable interlayer; ε - Joule-Thomson coefficient; λ - hydraulic resistance coefficient.

The boundary conditions for equations (3.1) - (3.15) are formulated as follows:

$$T_1 = T_{1\,bw}, P_1 = P_{1\,bw}, \upsilon_1 = \upsilon_{1\,bw} \text{ when } z = 0; \tag{3.16}$$

$$T_2 = T_{2\,wh}, P_2 = P_{2\,wh}, \upsilon_2 = \upsilon_{2\,wh} \text{ when } z = 0 \tag{3.17}$$

$$\frac{\partial T_{tube}}{\partial r} = \frac{2\beta_{i1}}{d_1}\left(T_1 - T_{tube}\right) \text{ when } r = \frac{d_1}{2} \tag{3.18}$$

$$\frac{\partial T_{gf}}{\partial r} = \frac{2\beta_{i3}}{d_1}\left(T_{gf} - T_2\right) \text{ when } r = \frac{d_3}{2} \tag{3.19}$$

$$T_{gf} = T_{pr} - \Gamma z \text{ when } r \to \infty; \tag{3.20}$$

$$T_{gf} = T_2, \text{ when } r \le \frac{d_6}{2}, z = H_1 + H_2 + h \tag{3.21}$$

$$T_{gf} = T_3, \text{ when } r \le \frac{d_6}{2}, z = H_1 + H_2 + h \tag{3.22}$$

$$T_1 = T_{pr}, P_1 = P_{pr}, \text{ when } r = R_c; \tag{3.23}$$

$$\frac{dP_1}{dr} = \frac{G_1\mu_1}{2\pi K_1\rho_1 H_1}, \text{ when } r = \frac{d_5}{2} \tag{3.24}$$

$$P_2 = P_{2,3}, \text{ when } r = \frac{d_6}{2} \tag{3.25}$$

$$T_2 = T_3, \text{ when } r = \frac{d_6}{2} \tag{3.26}$$

$$T_2 = T_{2\,bw}, \text{ when } r = \frac{d_5}{2} \tag{3.27}$$

$$\frac{dP_2}{dr} = \frac{G_2\mu_2}{2\pi K_2\rho_2 H_2}, \text{ when } r = \frac{d_5}{2} \tag{3.28}$$

$$\frac{d\,P_3}{d\,r}=\frac{G_3\,\mu_3}{2\,\pi\,K_2\,\rho_2\,H_2},\ \text{when}\ r=\frac{d_5}{2} \tag{3.29}$$

$$T_{in}=T_1,\ \text{when}\ z=H_1 \tag{3.30}$$

$$T_{in}=T_2,\ \text{when}\ z=H_1+h,\frac{d_6}{2}<r\le R_c \tag{3.31}$$

$$T_{in}=T_3,\ \text{when}\ z=H_1+h,\frac{d_5}{2}\le r\le \frac{d_6}{2} \tag{3.32}$$

$$B_{i\,1}=\frac{\alpha_1\,d_1}{2\,b_{tube}},\ B_{i\,3}=\frac{\alpha_2\,d_3}{2\,b_{gf}};$$

$$a_1=\left(\frac{2}{\alpha_1\,d_1}+\frac{1}{b_{tube}}\ \ln\,\frac{d_2}{d_1}+\frac{2}{\alpha_2\,d_2}\right)^{-1};$$

$T_{1\,bw}, P_{1\,bw}, \upsilon_{1\,bw}$ - temperature, pressure, and flow velocity of the fluid within the lift pipe at the bottom of the well, $T_{2\,wh}, P_{2\,wh}, \upsilon_{2\,wh}$ - temperature, pressure and fluid velocity in the annulus at the wellhead; T_{in}, T_{pr} - temperatures of the impermeable interlayer and the productive formation; T_{nl} - temperature of the thermally neutral layer; Γ - geometric gradient; H - well depth; $T_{tube}, T_{gf}, b_{tube}$ - temperature of the pipe wall, temperature of the surrounding rock formation, thermal conductivity coefficient of the pipe material; α_1, α_2 - convective heat transfer coefficients of the fluids in the production tubing and the annular space.

The system of differential equations (3.1) – (3.15) is simplified as follows. By integrating equations (3.1), (3.2), we obtain:

$$\upsilon_1=\frac{G_1}{\rho_1\,F_1}, \tag{3.33}$$

$$\upsilon_2=\frac{G_2}{\rho_2\,F_2}. \tag{3.34}$$

Derivatives $\frac{d\,i_1}{d\,z}$, $\frac{d\,\rho_1}{d\,z}$, $\upsilon_1\,\frac{d\,\upsilon_1}{d\,z}$, are written as:

$$\upsilon_1\,\frac{d\,\upsilon_1}{d\,z}=-\left(\frac{G_1}{F_1}\right)^2\frac{1}{\rho_1^3}\,\frac{d\,\rho_1}{d\,z}; \tag{3.35}$$

$$\frac{d\,i_1}{d\,z}=\frac{\partial\,i_1}{\partial\,P_1}\,\frac{d\,P_1}{d\,z}+\frac{\partial\,i_1}{\partial\,T_1}\,\frac{d\,T_1}{d\,z}; \tag{3.36}$$

$$\frac{d\,\rho_1}{d\,z}=\frac{\partial\,\rho_1}{\partial\,P_1}\,\frac{d\,P_1}{d\,z}+\frac{\partial\,\rho_1}{\partial\,T_1}\,\frac{d\,T_1}{d\,z}. \tag{3.37}$$

$\frac{d\,i_2}{d\,z}$, $\frac{d\,\rho_2}{d\,z}$, $\upsilon_2\,\frac{d\,\upsilon_2}{d\,z}$ are formulated analogously

As a result, differential equations (3.1) and (3.2) are eliminated, and equations (3.3) - (3.6) assume the following form:

$$\frac{d\,P_j}{d\,z}\left[\left(\frac{G_j}{F_j}\right)^2\frac{1}{\rho_j^2}\frac{\partial\,\rho_j}{\partial\,P_j}-1\right]+$$
$$+\left(\frac{G_j}{F_j}\right)^2\frac{1}{\rho_j^2}\frac{\partial\,\rho_j}{\partial\,T_j}\frac{d\,T_j}{d\,z}=\rho_j\,g\,\sin\,\beta\pm\frac{\lambda_j}{2\,d_j\,\rho_j}\left(\frac{G_j}{F_j}\right)^2 \tag{3.38}$$

$$\frac{dP_j}{dz}\left[\frac{\partial i_j}{\partial P_j}-\left(\frac{G_j}{F_j}\right)^2\frac{1}{\rho_j^3}\frac{\partial \rho_j}{\partial P_j}\right]+\left[\frac{\partial i_j}{\partial T_j}-\left(\frac{G_j}{F_j}\right)^2\frac{1}{\rho_j^2}\frac{\partial \rho_j}{\partial T_j}\right]\frac{dT_j}{dz}=\frac{dQ_j}{dz} \tag{3.39}$$

where $j = 1,\, 2$.
In equations (3.10) – (3.12), the following substitution is applied:

$$\upsilon_{1f}=-\frac{K_1}{\mu_1}\frac{dP_1}{dr}, \tag{3.40}$$

$$\upsilon_{2f}=-\frac{K_2}{\mu_2}\frac{dP_2}{dr}, \tag{3.41}$$

$$\upsilon_{3f}=-\frac{K_2}{\mu_3}\frac{dP_3}{dr}. \tag{3.42}$$

Equation (3.14) is solved analytically, and the results of the solution are used to determine heat flows:

$$\frac{dQ_2}{dr}=b_{gf}\left[\frac{T_2-T_1}{h}+\frac{\partial T_{gf}}{\partial z}\right],\ \text{when } \frac{d_5}{2}\le r\le\frac{d_6}{2} \tag{3.43}$$

$$\frac{dQ_3}{dr}=b_{gf}\left[\frac{T_3-T_1}{h}+\frac{\partial T_{gf}}{\partial z}\right],\ \text{when } \frac{d_6}{2}\le r\le R_c \tag{3.44}$$

$$\frac{dQ_4}{dr}=-b_{gf}\left[\frac{T_2-T_1}{h}+\frac{\partial T_{gf}}{\partial z}\right] \tag{3.45}$$

$$\frac{dQ_5}{dr}=-b_{gf}\left[\frac{T_3-T_1}{h}+\frac{\partial T_{gf}}{\partial z}\right] \tag{3.46}$$

It is assumed that $K_1 = const$, $K_2 = const$, $\rho_2 = const$. Taking into account the above transformations, equations (3.7) – (3.12) can be expressed as follows:

$$\frac{d}{dr}\left(r\frac{\rho_1}{\mu_1}\frac{dP_1}{dr}\right)=0 \tag{3.47}$$

$$\frac{d}{dr}\left(r\frac{\rho_2}{\mu_2}\frac{dP_2}{dr}\right)=0 \tag{3.48}$$

$$\frac{d}{dr}\left(r\frac{\rho_3}{\mu_3}\frac{dP_3}{dr}\right)=0 \tag{3.49}$$

$$\frac{d\,T_1}{dr}=-\frac{b_{gf}\,\mu_1}{h\,K_1\,\rho_1\,C_{P1}}\frac{\left(\frac{T_i-T_1}{h}+\frac{\partial T_{gf}}{\partial z}\right)}{\frac{dP_1}{dr}}+\varepsilon_1\frac{dP_1}{dr} \tag{3.50}$$

$$\frac{d\,T_2}{dr}=\frac{b_{gf}\,\mu_2}{h\,K_2\,\rho_2\,C_{P2}}\frac{\left(\frac{T_2-T_1}{h}+\frac{\partial T_{gf}}{\partial z}\right)}{\frac{dP_2}{dr}}+\varepsilon_2\frac{dP_2}{dr} \tag{3.51}$$

$$\frac{d\,T_3}{dr}=-\frac{b_{gf}\,\mu_3}{h\,K_2\,\rho_3\,C_{P3}}\frac{\left(\frac{T_3-T_1}{h}+\frac{\partial T_{gf}}{\partial z}\right)}{\frac{dP_3}{dr}}+\varepsilon_3\frac{dP_3}{dr} \tag{3.52}$$

Thermophysical properties of hydrocarbon substances and their derivatives are determined according to [8], and for water – according to [9].

The gas-water interface under conditions of constant well flow rates ($G_2 = const$, $G_3 = const$) is calculated as follows:

$$d_6 = \sqrt{\frac{16\, G_2\, t}{m\, \pi\, \rho_2\, H_2} + d_5^2} \tag{3.53}$$

where t - duration of water injection into the reservoir; m - porosity coefficient.

In order to determine the pressure $P_{2,3}$ on the aquifer contour, we assume that it is assumed to vary over time according to the laws of the gas regime [10].

$$P_{2,3} = \left(\frac{P_{pr}\, \alpha\, \Omega_0}{z_{pr}} - P_{atm}\, Q_{ex}\,(t)\, \frac{T_{pr}}{T_{st}} \right) \frac{z\,(P_{bw}\,(t))}{\alpha\, \Omega_0 - Q_{water}\,(t)} \tag{3.54}$$

Where α - gas saturation coefficient; z_{pr}- compressibility factor of gas at reservoir conditions; P_{atm} - atmospheric pressure; T_{st} - standard temperature; $Q_{water}\,(t)$ - the volume of water injected into the reservoir over time t; $Q_{ex}\,(t)$ - volume of gas produced over time t; Ω_0 initial gas-filled volume of the reservoir.

Under conditions of constant hot water injection and gas production rates, $Q_{ex}\,(t)$ and $Q_{water}\,(t)$ are determined as follows:

$$Q_{ex}\,(t) = \frac{G_3\, t}{\rho_3} \tag{3.55}$$

$$Q_{water}\,(t) = \frac{G_2\, t}{\rho_2} \tag{3.56}$$

The initial gas-saturated volume of the formation is calculated using the formula:

$$\Omega_0 = 2\, \pi\, m\; R_c\, H_2 \tag{3.57}$$

4 Conclusions

The solution of the differential equations written above cannot be obtained by analytical methods due to the complexity and heterogeneity of the system. Therefore, a combination of numerical methods — including predictor-corrector techniques, time stepping, and iterative procedures — is used. The following algorithm for solving the problem is proposed:

1. The temperature distribution of the injected water in the well and formation T_2 is specified, as well as the temperature distribution of the gas T_3 within the formation

2. Equation (3.47) with boundary conditions (3.23) and (3.24) is solved using the Runge-Kutta method. The oil temperature is considered equal to the initial formation temperature.

3. Taking into account the obtained distribution P_1, equation (3.50) with boundary condition (3.23) is solved by the the predictor–corrector method. The temperature distribution T_1 is determined.

4. Steps 2 and 3 are repeated until the consecutive values of distributions P_1 andT_1converge within the specified accuracy.

5. Similarly (taking T_1 into account), the pressure distributions P_2, P_3 and temperature distributions T_2, T_3 in the overlying gas-saturated formation are determined.

Equation (3.48) with boundary conditions (3.25) and (3.28) is solved by the sweep method. Equation (3.51) with boundary conditions (3.27) – by the predictor–corrector method. The iteration procedure is terminated upon reaching the specified accuracy. Then equation (3.49) with boundary conditions (3.25) and (3.29) is solved by the sweep method. Equation (3.52) with boundary condition (3.25) – by the predictor–corrector method. The iteration procedure is also terminated upon reaching the specified accuracy.

6. Steps 2–5 are repeated until the previous and subsequent values P_1,P_2, P_3, T_1, T_2, T_3 converge with the specified accuracy.

7. The distribution of temperature and pressure of fluids in the well is determined by solving equations (3.38), (3.39) subjected to boundary conditions (3.16), (3.17) using the predictor–corrector method.

8. The obtained values of water temperature T_2 in the well and formation were used to solve the equation of heat conduction in the surrounding rocks. The calculated temperature field in the environment allows to specify the values of heat flows $\frac{dQ_j}{dz}$ $(j = 1,\ 2)$ and $\frac{dQ_j}{dr}$ $(j = 3,\ 6)$

9. Steps 2–8 are repeated until the iterative procedure converges with the specified accuracy.

The proposed method allows determining the temperature and pressure distributions within productive formations, wells, and the thermal field in the surrounding rock matrix.

As an example, the temperatures and pressures of hot water injected through the annular space into a gas-saturated formation and high-viscosity oil extracted through lift pipes from the underlying formation were calculated. The following parameter values were used in the calculations:

$$G_1 = 0.139\,kg/s; G_2 = 1.157\,kg/s; P_{2wh} = 17\,MPa; T_{2wh} = 383\,K; P_{pr} = 15 MPa;$$
$$T_{pr} = 294\,K; T_{nl} = 273\,K; \varGamma = 0.03\,^{\circ}C/day; \lambda_{tube} = 46.44\,W/mK;$$
$$\lambda_{gf} = 2.19\,W/mK; d_1 = 0.063\,m; d_2 = 0.0755\,m; d_3 = 0.13\,m; d_4 = 0.146\,m;$$
$$d_5 = 0.19\,m; H = 700\,m; R_c = 300\,m; K_1 = 1.12 \cdot 10^{-12}\,m^2;$$
$$K_2 = 1.19 \cdot 10^{-14}\,m^2; t = 60\,days.$$

The values T_1, T_2, P_1, P_2 calculated using the proposed method for the “layer” and “well,” are presented in Fig. 1 and 2.

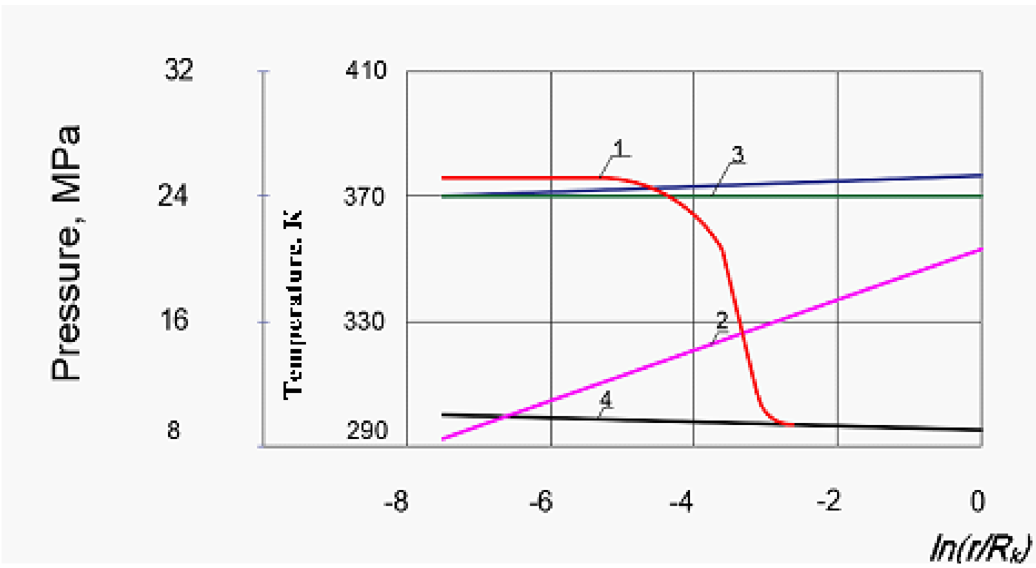

Fig. 1. Distribution of fluid temperature and pressure in formation:
1 – temperature in the gas-saturated formation;
2 – pressure in the oil-saturated formation;
3 – pressure in the gas-saturated formation;
4 – temperature in the oil-saturated formation

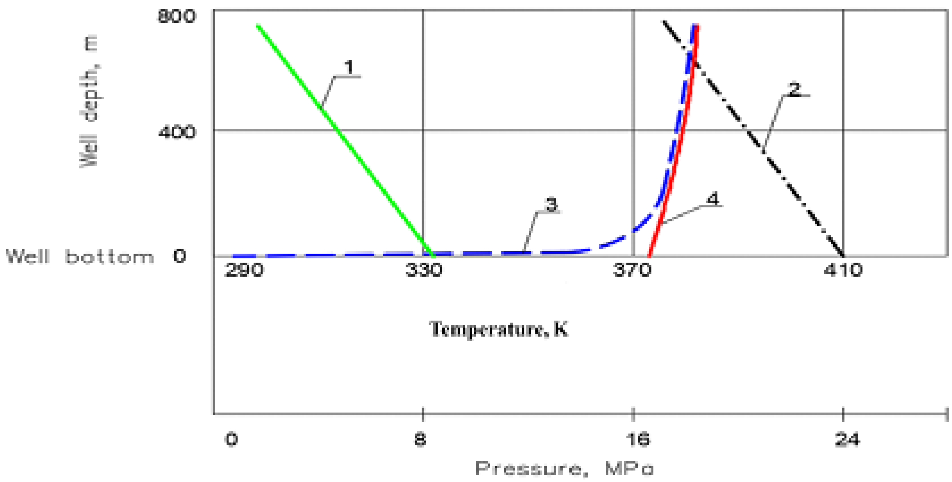

Fig. 2. Distribution of fluid temperature and pressure profiles in the well:
1 – oil pressure; 2 – water pressure; 3 – oil temperature; 4 – water temperature.

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