ORIGINAL RESEARCH ARTICLE

DOI: https://doi.org/10.18599/grs.2018.1.39-43

The results interpretation of thermogasdynamic studies of vertical gas wells incomplete in terms of the reservoir penetration degree

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Abstract. A method is proposed for interpreting thermogasdynamic studies of vertical gas wells that are incomplete in terms of the reservoir penetration degree on the basis of inverse problem theory. The inverse problem has the aim to determine the reservoir parameters for nonisothermal filtration of a real gas to a vertical well in an anisotropic reservoir. In this case, the values of the pressure and temperature at the well bottom, recorded by deep instruments, are assumed to be known. The solution of the inverse task is to minimize the functional. The iterative sequence for minimizing the functional is based on the Levenberg-Marquardt method. The convergence and stability of the iterative process for various input information have been studied on specific model examples. The effect of reservoir anisotropy on the pressure and temperature changes at the bottom of the well is studied. It is shown that if the reservoir is not completely penetrated by the results of pressure and temperature measurements at the bottom of the well after its start-up, anisotropy of the reservoir can be estimated. It should be noted that when studying thermodynamic processes in the vicinity of a well, which penetrates thick layers, it is necessary to take into account not only the heat exchange of the reservoir with the surrounding rocks, but also the geothermal temperature gradient.

Keywords: anisotropy, thermogasdynamic studies, incomplete well

Recommended citation: Shamsiev M.N. (2018). The results interpretation of thermogasdynamic studies of vertical gas wells incomplete in terms of the reservoir penetration degree. *Georesursy = Georesources*, 20(1), pp. 39-43. DOI: https://doi.org/10.18599/grs.2018.1.39-43

Introduction

Most of the gas fields have a layered structure, due to the peculiarities of the sedimentation process. In layered reservoirs, the filtration properties in the plane of the layers differ from the filtration properties in the direction perpendicular to the layers, i.e. such reservoirs are anisotropic. In real gas reservoirs, anisotropy can be caused by fracturing, layering, the presence of various inclusions, which lead to unequal properties of the medium in different directions.

The heterogeneity of the formation in the vertical and horizontal directions is characterized by the anisotropy parameter. The parameter of reservoir anisotropy is of decisive importance in predicting the technological regime of wells operation, exposing reservoirs with bottom water, multi-layer deposits, etc. In work (Gritsenko et al., 1995), a grapho-analytical method is suggested for estimating anisotropy based on the results of gas-hydrodynamic studies of vertical wells that are incomplete in terms of the reservoir penetration degree. The incompleteness of the bottom entails the appearance of additional filtering resistances arising in the bottomhole zone and a decrease in production rates as a result of the deviation in the liquid flow geometry from the flat-radial flow (Basniev et al., 1993; Gritsenko et al., 1995; Korotaev et al., 1991; Masket, 1949; Shchurov, 1983). In this regard, consideration of the characteristics of the inflow to incomplete wells is of great practical importance.

In this paper, we propose a method for interpreting thermogasdynamic studies of vertical gas wells that are incomplete in terms of the reservoir penetration degree on the basis of the inverse problem theory. The effect of anisotropy on the pressure and temperature changes at the bottom of the well is investigated. It is shown that the results of pressure and temperature measurements at the bottom of the well after its start-up can be used to evaluate the anisotropy of the reservoir.

Nonisothermal gas filtration in an anisotropic reservoir

Thermogasdynamic methods for studying gas wells are based on the processes of pressure and temperature redistribution in the reservoir when they are put into operation and after a stop. The process of non-isothermal filtration of a real gas to a vertical well in an anisotropic reservoir is described by a system of differential equations:

$$m\frac{\partial}{\partial t}\left(\frac{p}{T\varsigma}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{k_r}{\mu}\frac{p}{T\varsigma}r\frac{\partial p}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{k_z}{\mu}\frac{p}{T\varsigma}\frac{\partial p}{\partial z}\right),$$

$$r\in(r_w,R_k),\ z\in(0,L),\ t>0, \quad (1)$$

$$C_1\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_1\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda_1\frac{\partial T}{\partial z}\right)+$$

$$C_p\frac{p}{RT\varsigma}\left(\frac{k_r}{\mu}\frac{\partial p}{\partial r}\left[\frac{\partial T}{\partial r}-\varepsilon\frac{\partial p}{\partial r}\right]+\frac{k_z}{\mu}\frac{\partial p}{\partial z}\left[\frac{\partial T}{\partial z}-\varepsilon\frac{\partial p}{\partial z}\right]+m\eta\frac{\partial p}{\partial t}\right),$$

$$r\in(r_w,R_k),\ z\in(0,L),\ t>0, \quad (2)$$

with initial

$$p(r,z,0)=p_0,\ r\in(r_w,R_k),\ z\in(0,L), \quad (3)$$

$$T(r,z,0)=T_0+(L-z)G,\ r\in(r_w,R_k),\ z\in(0,L), \quad (4)$$

and boundary conditions:

$$2\pi\int\limits_{L-L_w}^{L}\left[\frac{k}{\mu}\frac{pT_{st}}{p_{st}T\varsigma}r\frac{\partial p}{\partial r}-\frac{C_w}{L_w}\frac{\partial}{\partial t}\left(\frac{p}{T\varsigma}\right)\right]_{r=r_w}dz=Q,$$

$$z\in[L-L_w,L], \quad (5)$$

$$\left[C_1\frac{\partial T}{\partial t}-C_p\frac{p}{RT\varsigma}\left(\frac{k}{\mu}\frac{\partial p}{\partial r}\left[\frac{\partial T}{\partial r}-\varepsilon\frac{\partial p}{\partial r}\right]\right)-\right.$$

$$\left.-C_p\frac{p}{RT\varsigma}\left(m\eta\frac{\partial p}{\partial t}\right)\right]_{r=r_w}=0,\ z\in[L-L_w,L], \quad (6)$$

$$\left.\frac{\partial p}{\partial r}\right|_{r=r_w}=0,\ z\in[0,L-L_w), \quad (7)$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=r_w}=0,\ z\in[0,L-L_w), \quad (8)$$

$$p(r_k,z,t)=p_0,\ z\in[0,L],\ t>0, \quad (9)$$

$$T(r_k,z,t)=T_0+(L-z)G,\ z\in[0,L],\ t>0, \quad (10)$$

$$\left[\frac{\partial p}{\partial z}\right]_{z=0}=\left[\frac{\partial p}{\partial z}\right]_{z=L}=0,\ r\in(r_w,R_k),\ t>0, \quad (11)$$

$$\left[\frac{\partial T}{\partial z}\right]_{\substack{z=0\\z=L}}=\sqrt{\frac{\lambda_2C_2\rho_2}{\pi t}}\left(T-T\big|_{\substack{z=0-\xi(t)\\z=L+\xi(t)}}\right)\ \text{или}$$

$$\left[\frac{\partial T}{\partial z}\right]_{\substack{z=0\\z=L}}=0,\ r\in(r_w,R_k),\ t>0 \quad (12)$$

where L – the thickness of the reservoir, L_w – the depth of the reservoir penetration, μ – the gas viscosity, m – the reservoir porosity, p_0, T_0 – the pressure and temperature at the reservoir boundary, p_{st}, T_{st} – the standard pressure and temperature, r_w, R_k – the radii of the well and external boundary, Q – the well production rate, z – the gas supercompressebility, k_r, k_z – the reservoir permeability along the directions of r and z axes, η – the adiabatic expansion factor, ε – the Joule-Thomson coefficient, $C_1=mC_p\,p/RT\varsigma+(1-m)C_2\rho_2$ – the volumetric heat capacity of the reservoir, C_p, C_2 – the specific heat capacity of the gas and medium, p_2 – the medium density, R – the gas constant, λ_1, λ_2 – the thermal conductivity of the gas and medium, C_w – wellbore storage coefficient, G – geothermal gradient. The first expression of condition (12) simulates the process of heat exchange on the roof and the bottom of the gas reservoir by rocks, i.e. non-thermal insulated reservoir. Conditions (5) – (8) simulate the process of heat and mass transfer to a vertical well that is incomplete in the degree of reservoir penetration.

Zone of thermal compensation above the roof and below the bottom of the formation is calculated by the formula:

$$\xi(t)=\sqrt{\pi\frac{\lambda_2}{C_2\rho_2}t}\,.$$

The wellbore storage coefficient is calculated by the formula (Korotaev et al., 1991; Khairullin et al., 2013, Shamsiev, Talipova, 2015). The gas supercompressibility coefficient ζ is calculated by the formula of Gurevich-Latonov (Bondarev et al., 1988). The adiabatic expansion coefficient η and the Joule-Thomson coefficient ε are calculated by the formulas (Korotaev et al., 1991).

Equations (1) – (12) belong to the class of quasilinear parabolic equations. The greatest difficulty is the numerical solution of equation (2), which simultaneously describes conductive and convective heat transfer, including the Joule-Thomson effect, as well as a decrease in the gas temperature due to its adiabatic expansion. For the numerical solution of the system (1) – (12), the finite difference method is applied. The solution area is covered by a non-uniform grid, which thickens at the approach to the well.

Results of the calculations

In the case of model examples, influence the reservoir anisotropy on pressure and temperature curves at the bottom of the well is studied. A model reservoir with the following data is considered: H = 20 m, R_k = 250 m, r_w = 0.1 m, p_0 = 20 MPa, T_0 = 300 K, T_{st} = 293 K, μ = 0.012 mPa s, m = 0.2, k_r = 0.01 мкм^2, C_p =2093 J/ kg K, C_2 = 920 J/ kg K, r$_2$ = 2700 kg / m^3, R = 520 J/kg K, λ_1 = 1.52 W/m K, λ_2 = 1.9 W/m K, G = 0.01 K/m, Q = 500 thousand m^3/day, operation time of the well t_{exp} = 5 days.

From the results obtained, it follows that the process of heat exchange of the reservoir with surrounding rocks affects the temperature field and has little effect on the pressure field in the reservoir. It should be noted that when studying thermodynamic processes in the vicinity of a well, which penetrates thick layers, it is necessary to take into account not only the heat exchange of the reservoir with the surrounding rocks, but also the geothermal temperature gradient. Comparison of the numerical solution of the system (1) – (12) with the numerical solution of the one-dimensional task (Shamsiev, Talipova, 2015) at $G = 0$, $k_r = k_z$ is shown in Figure 1. Deviations of the final sections of the derivatives of the bottomhole temperature curves are observed. This is due to the process of heat exchange with surrounding rocks. In the case of a thermally insulated reservoir, numerical solutions of one-dimensional and two-dimensional tasks almost coincide.

Figure 2 shows curves of bottomhole pressure, temperature and their derivatives depending on the

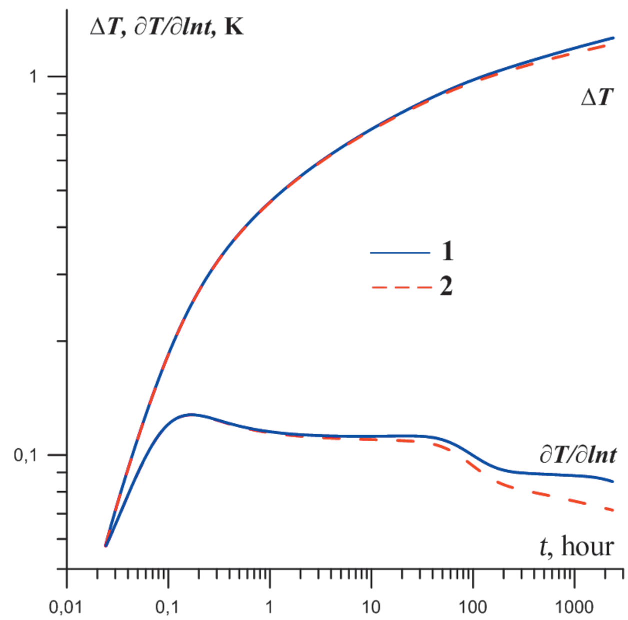

Figure 1. The bottomhole temperature curve and its derivative. The reservoir is completely penetrated and not thermally insulated, G = 0. $k_r = k_z$. 1 – numerical solution of system (1) – (12), 2 – numerical solution of one-dimensional task.

reservoir anisotropy after the well has been put into operation without full penetration. The calculations were carried out at $k_r = k_z = 0.01$ μm^2; $k_r = 0.01$ μm^2, $k_z = 0.02$ μm^2; $k_r = 0.01$ μm^2, $k_z = 0.005$ μm^2. When launching a vertical well with a constant production rate and incomplete penetration of the reservoir, the initial radial, spherical and late radial flows are observed. The initial radial flow is masked by the presence of the influence of the borehole volume (Figure 2). The negative slope of the derivative curve characterizes the presence of a spherical flow. The less the reservoir is penetrated, the longer the duration of the spherical flow. The straight section on the pressure derivative curve is the diagnostic sign of the late radial flow (Figure 2). The deviations of the final sections of the pressure and temperature curves characterize the influence of the reservoir boundary.

The results of calculations showed that the less the reservoir is penetrated, the more sensitive the pressure and temperature curves to variations in the permeability coefficients k_r, k_z.

Evaluation of the reservoir anisotropy

The results interpretation of thermogasdynamic studies of gas wells is based on the solution of the inverse problem. As the initial information, the data on the change in bottomhole pressure and temperature, recorded by deep instruments after the start-up of the well, are used. The aim of the inverse task is to determine the permeability coefficients k_r, k_z and the porosity of the reservoir m, when the process of non-isothermal filtration of a real gas to a vertical well incomplete in the degree of reservoir penetration is described by the system of equations (1) – (12).

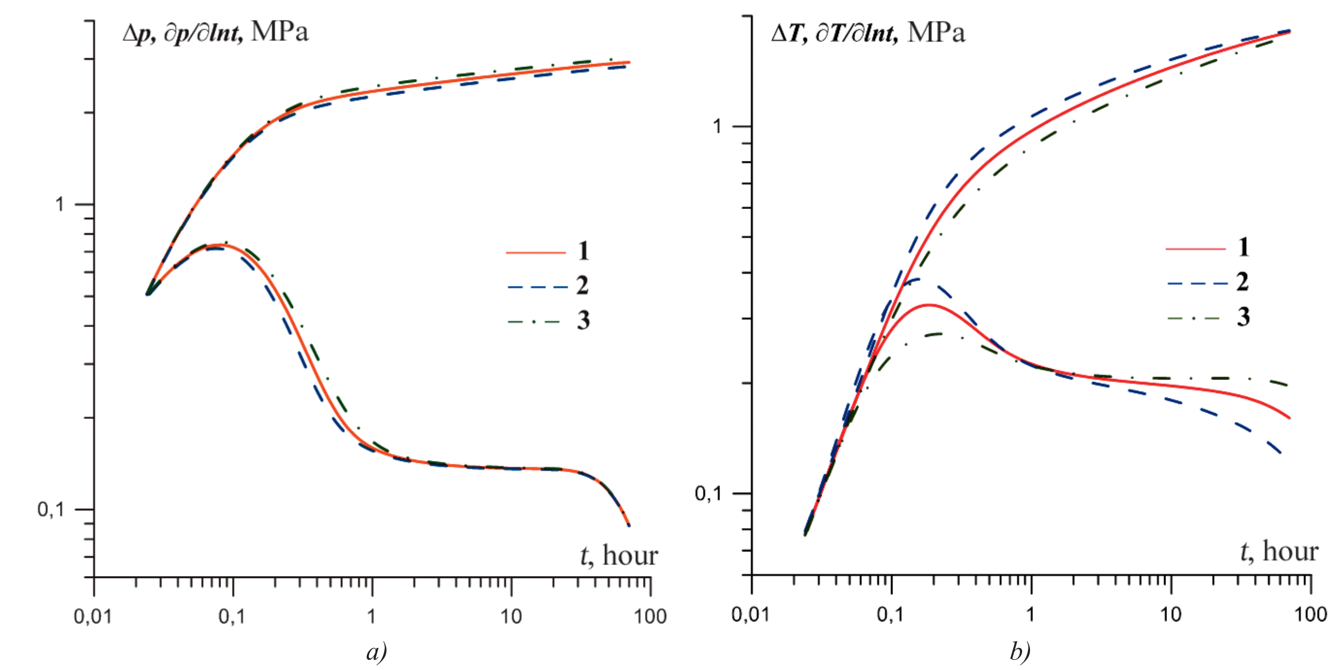

Figure 2. Curves of pressure (a), temperature (b) and their derivatives. The reservoir is penetrated by 50%. 1 – $k_r=k_z$, 2 – $k_r<k_z$, 3 – $k_r>k_z$

The following initial information is considered known:

$$p(r_w,L,t)=\phi(t),\ T(r_w,L,t)=\psi(t), \quad (13)$$

where $\phi(t)$, $\psi(t)$ – observed values of pressure and temperature at the bottom of the well.

The solution of the inverse problem (1) – (12) and (13) is to minimization the functional (Khairullin et al., 2013, Shamsiev, Badertdinova, 2012; Shamsiev, Talipova, 2015):

$$F(\alpha)=\int_0^{t_{exp}}\left\{\xi[\phi(t)-p(r_w,L,t)]^2+[\psi(t)-T(r_w,L,t)]^2\right\}dt, \quad (14)$$

where $\alpha=(k_r, k_z, m)$, $0<a_i\le\alpha_i\le b_i$ $(a_i, b_i=const)$, ξ – weighting parameter.

The iterative sequence for minimizing the functional (14) is based on the Levenberg-Marquardt method. The convergence and stability of the iterative process with different input information have been studied using standard madel examples. The iterative process is considered to be completed when one of the specified precision is reached (10^{-6} – for the functional, 10^{-6} – for the gradient, 10^{-6} – for the argument) or when performing a specified number of iterations ($N_{iter}=40$). For exact values of the initial information, the iterative process of minimizing the functional (14) converges in 6-8 iterations. To study the stability in the model curves, changes in bottomhole pressure and temperature randomly introduced errors, where $\phi_{\delta_1}(t)=\phi(t)+\omega\delta_1$, $\psi_{\delta_2}(t)=\psi(t)+\omega\delta_2$, where δ_1 = 0.05 MПa, δ_2 = 0.05 K, ω – a random variable distributed along a uniform law on the interval [-1, 1]. With the perturbed initial data, the iterative process of minimizing the functional (14) converges for 10-15 iterations. The results of the calculations show that the proposed method is stable with respect to the errors of the initial information.

Figure 3 shows one of the characteristic calculations of the convergence of the iterative process of minimizing the functional (13) with the perturbed initial data

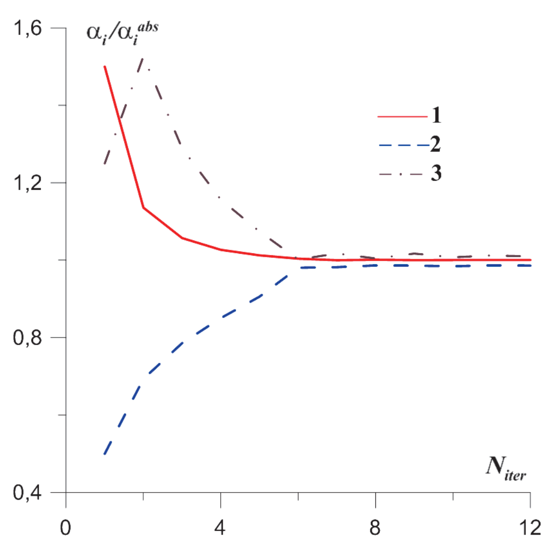

Figure 3. Convergence of the iterative process. 1 – k_r, 2 – k_z, 3 – m

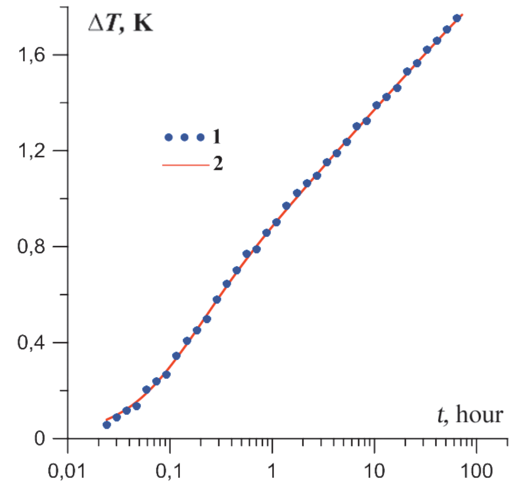

Figure 4. Curves of temperature changes. The reservoir is penetrated by 50%. 1 – perturbed, 2 – calculated curves

(Figure 4, curve-1), where α – true parameters, α_i^{abs} – calculated parameters. The calculated temperature curves are shown in Figure 4 (curve-2). The iterative process converges in 12 iterations.

From the results obtained, it follows that when the reservoir is partially penetrated by the results of thermogasdynamic studies of gas wells, anisotropy of the reservoir can be estimated.

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Manuscript received 18 December 2017;
Accepted 27 February 2018;
Published 30 November 2017