Determining reservoir parameters with nonisothermal real gas flow

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Abstract. Creation and developing methods of determining gas reservoir properties are one of the most important gas hydrodynamics tasks as production project efficiency and reservoir exploitation depend upon layer properties knowledge. Nonstationary gas hydrodynamics investigations are one of the base well and layer researching methods. Results of these investigations are interpreted based on solving of linear isothermal gas flow equation. The current investigation describes the nonstationary gas hydrodynamic survey results interpretation algorithm, which is based on nonlinear equations system solving. The system consists of nonlinear nonisothermal real gas flow and energy equations accounting well influence, Joule-Thompson and adiabatic expansion effects. Integro-interpolation and iteration finite methods were used for creating their own numerical algorithm. Numerical programs allow solving as direct as inverse gas flow tasks in the cylindrical layer. For verification of inverse task solution, the survey interpretation results from the real gas field were paralleled with currently methods results and showed sufficient accuracy. The described method allows to interpret survey gas hydrodynamic results accounting real gas and porous matrix properties, and well influence to enhance integrity and precision reservoir properties estimation.

1. Introduction

Eastern Siberia and the Arctic shelf deposits are perspective resource base for the Russian fuel and energy complex development. Eastern Siberia gas and gascondensate fields are complex objects with abnormal thermobaric characteristics that generate favorable conditions for the technogenic gas hydrate formation and the presence of natural gas hydrate. There is a need to form a scientifically based field development system when wells are exploited in such conditions. GIS research methods quality improving and obtained parameters interpretation reliability have special significance.

Hydrodynamic simulation allows to estimate the possibility of applying some impacting on layer technologies adequately. There are several ways for numerical task solution: the first is the created mathematical model and numerical code adaptation to the development history, which make it possible to estimate all reservoir parameters in dynamics. As a rule, it means the stationary well production for sufficiently large time period. According to the current production data and reservoir filtration characteristics, all filtration-capacity parameters are iteratively corrected until they correctly match the production parameters. Mathematically this approach is called solving a direct problem with adaptation to production history. Second way is based on more information about the current reservoir state, which is obtained by using wells hydrodynamic studies (GIS). It is solved the inverse task- buildup/drop curves are paralleled with numerical task solution describing the physical process. Comparing with direct
method (at stationary mode) there is analyzed short-term non-stationary well operation with sufficient changing pressure and less changing reservoir temperature. The latter circumstance is connected with the mineral skeleton accumulative ability to absorb and slowly release energy. In numerical modeling, both direct and inverse methods are usually combined to achieve high-quality results.

2. Fluid dynamic task

Conditions for gas hydrate formation in the well, near bottom hole zone, in a plume, in the chokes are emerged during hydrodynamic well investigations leading to complications during logging and large errors in the obtained GIS results [1]. These conditions depend primarily on the gas composition, its moisture content, the pressures along the gas path, the gas thermophysical properties and the reservoir surrounding the wellbore. Paper [2] calculations with difference differential pressure in the layer showed, the gas hydrate decomposition rate increases significantly with an increase in depression. Consequently the hydrate formation possibility during well testing in various modes is significantly higher than at stationary production condition, because it is necessary to change the depression and flow rate in a large range during the GIS investigations. Also, the results of [2] showed a change in the direction of propagation of the gas hydrate melting front (inversion of the process), since the conditions of hydrate formation are again realized in the reservoir, which makes it necessary to take this phenomenon into account when calculating production for long periods.

Generalized flow model accounting phase compressibility (liquid and solid), fluid state equation and thermal effects influence for isotropic reservoir is created by current paper authors for interpretation field data and hydrate formation possibility estimation during gas production. In order to clarify the input parameters influence obtained from GIS results on the flow characteristics, the authors solved the direct and inverse non-isothermal gas flow problems accounting the well influence [1,3] and Joule-Thompson effect. Account Joule-Thompson effect in GIS results interpretation may impact on finish oil and gascondensate well parameters [4].

To simulate field experiments and determine the final results sensitivity changing all input data, the model was simplified for the case with single-phase gas fluid flow. The oil presence in a stationary state corresponds to the oil nonlinear properties manifestation when limiting gradients are not reached [5]. Task is numerically solved at isotropic porous reservoir, cylindrical layer conditions accounting inhomogeneity flow influence near the wellbore. The mathematical formulation includes the keeping for compressible gas mass law (1), the filtration equation (2) and the thermal conductivity equation (3):

$$\frac{\partial\rho_m}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r}(r \rho \frac{\partial w_r}{\partial r}) = 0$$

(1)

$$w_r = -\frac{k}{\mu} \frac{\partial P}{\partial r}$$

(2)

$$\frac{\partial}{\partial t}(m \rho_g C_{vg} T + (1-m) \rho_s C_{vs} T) + \rho_g C_{vg} w_r \frac{\partial T}{\partial r} = \frac{1}{r} \frac{\partial}{\partial r}(r (\lambda_g + \lambda_s) \frac{\partial T}{\partial r}) - \rho_g C_{vg} w_r \frac{\partial P}{\partial r} + m \eta \frac{\partial P}{\partial t}$$

(3)

In the thermal conductivity equation for a saturated porous collector, we took into account the throttle effect and the adiabatic gas expansion in the form on the right with Joule-Thompson coefficient $\epsilon_a = -\frac{1}{\rho_g C_{vg}} \frac{T}{Z} \frac{\partial Z}{\partial T}$, and adiabatic expansion coefficient:

$$\eta = -\frac{1}{\rho_g C_{vg}} \epsilon_a$$. The stationary skeleton thermal characteristics and the pinched phase will be described by uniform parameters, the internal energy of both the gas and solid phases are determined only by thermal components with constant heat capacity coefficients ($C_{vg}$ и $C_{vs}$) without taking into account the elastic
component, \( \lambda_g \) - gas thermal conductivity, \( \lambda_s \) - matrix (skeleton) with oil membrane thermal conductivity.

To close the system (1)-(3), we use the real gas state equation:

\[
\rho_s = \frac{P}{ZRT} \tag{4}
\]

where the Gurevich-Latonov formula is used to calculate the gas super-compressibility \( Z \) [6]:

\[
Z(P,T) = \left( \frac{0.17376}{T_c} + 0.73 \right) \left( \frac{P}{P_c} \right)^{0.1} + 0.1 \left( \frac{P}{P_c} \right)^{0.1} \tag{5}
\]

\((T_c =190.5K, P_c=4.58\text{MPa}-\text{critical pressure and temperature})\). Taking into account the matrix compressibility coefficient \( \beta_s \). It is necessary to take into account the change in porosity \( m \) and permeability \( k \), the relationship of which is assumed in the modified Kozeni-Karman’s formula (taking into account the field-coefficient):

\[
m = m_0 + \beta_s (P - P_0) \quad k = \frac{B}{(1-m)^2} \tag{6}
\]

The system (1)-(6) can be solved numerically with given initial and boundary conditions accounting well influence coefficient \( C = \frac{V_{RT}}{P_{min}} \), \((T_0 = 273K, P_{min} = 10^5 P\text{a})\). At the initial moment, the formation is undisturbed, then production begins with the constant mass flow rate \( q = \text{const} \). The well drains a layer with a thickness \( H \). Well is started under constant \( q \) in a formation characterized by reservoir parameters \( c_k, k_k, r_r, r_r, T_k, m, k, w_0 \). While \( t > 0 \) on the well

\[
(r = r_k): 2\pi r H \rho_s \frac{k}{\mu} \left( \frac{\partial P}{\partial r} \right) = q + C \frac{\partial P}{\partial t} + r \frac{\partial T}{\partial r} = 0, \text{ where } C- \text{ well impacting coefficient}; \text{ external boundary}
\]

\[
(r = R_k): P(R_k) = P_k, T(R_k) = T_k. \tag{11}
\]

### 3. Solution results

The initial data correspond to the Messoyakhsky gas condensate well drainage area there was an intensive gas hydrates formation [7] due to the theromoabaric parameters in the formation were close to the equilibrium hydrate formation, and the bottom-hole zone temperature decreased due to gas throttling and adiabatic expansion effect. The formation is characterized by: \( c_{v_g} = 2093 \text{ Joule/(kg*K)} \), \( c_s = 1000 \text{ Joule/(kg*K)} \), \( \rho_g = 2000 \text{ kg/m}^3 \), \( m = 0.3 \), \( \lambda_g = 2 \text{ W/(m*K)} \), \( \lambda_s = 1.5 \text{ W/(m*K)} \), \( P_0 = P_k = 8 \text{ MPa} \), \( T_0 = T_k = 286.7K (13.7^\circ) \), \( k = 0.05 \mu m^2 \), \( \mu = 0.02 \text{ mPa*sec} \), \( r_0 = 0.1 \text{ m} \), \( R_k = 500 \text{ m} \), \( H = 5 \text{ m} \), \( Q = 103000 \text{ m}^3/\text{day} \), \( R = 519.4 \text{ Joule/(kg*K)} \), \( \beta_s = 10^{-4} \text{ MPa}^{-1} \), experimental time=15 days.

For the numerical initial-boundary problem solution the own numerical code was written converting the system of differential equations to the finite-difference form for the grid model with logarithmic grid. The code was verified on several theoretical solutions and showed a good match with the theoretical dependencies. The problem solution included two stages. At the first stage, a direct problem was solved with the hydrate formation possibility assessment during gas production (a direct problem). This stage allows us to adapt the model to the development conditions by solving a non-stationary nonlinear filtration problem for the specific well. At this stage, the stability of the solution was studied for various grid nodes ratios according to the coordinate \( N=20 \pm 300 \) and the experiment time \( t = 1 \pm 30 \) days, and sensitivity to changes the well influence parameters and permeability \( k = 0.03 \pm 0.07 \mu m^2 \). The program code showed the solution stability at all parameter intervals within the real GIS data measurement error variance.

Figure 1 shows the calculated PT dependences at the perforation intervals level point during the well operation \( t = 15 \) days for various super-compressibility coefficients \( Z \) (direct problem solution) and the equilibrium hydrate formation curve for the gas composition from the P1 formation [8]. The direct problem solution showed sensitivity to a change in the parameter \( Z \). With the above input parameters and the
compressibility coefficient $Z$ calculation in the Latonov-Gurevich form, the hydrate formation conditions at the well bottom occur after time interval about 15 days, which allows us to estimate the possible well research time without using inhibitors and bottom-hole heaters.

![Figure 1. Hydrate formation conditions assessment in P1 layer.](image1)

Figure 2 shows the inverse problem solution in comparison with GIS data [1], following initial data: $Q = 103000 \text{ m}^3/\text{day}$; experimental time – 646200 seconds; $N = 35$; $T_0 = T_k = 281 \text{ K}$; $P_0 = P_k = 14.32 \text{ MPa}$; well depth – 1450 m. Calculated pressure buildup curve at the wellbore are in good agreement with the depth sensors readings in a well. Numerical graphs are constructed with the selected problem parameters values: $m = 0.2$, $h = 0.615 \text{ m}$, $kh/\mu = 2.06 \mu\text{m}^2\text{m}/(\text{mPa*sec})$. Assessment according to the classical method: $kh/\mu = 1.97 \mu\text{m}^2\text{m}/(\text{mPa*sec})$ [1].

![Figure 2. Changing bottom pressure with time.](image2)
4. Conclusions
The direct problem solution allowed to estimate the hydrate formation possibility during gas production and identify the solution sensitivity to changes input parameters (porosity, penetrability, the well influence and compressibility coefficient $\beta$). The most sensitive parameter to changing parameters within the measurement real GIS error is permeability $k$, when this parameter was varied by 2%, the indicators deviation to the controlled measurement 15 days period was 0.5%. The inverse problem solution showed good convergence with the classical method for determining reservoir and fluid parameters.

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References
[1] Gritsenko A I, Aliyev Z S, Ermilov O M, Remizov V V and Zotov G A 1995 Guide to Well Research. (Moscow: Nauka) p 523.
[2] Kravchenko M N and Chidyakina O O 2021 Hydrodynamic aspects of the search for approaches to the development of gas hydrate deposits, Elasticity and Anelasticity. (Moscow: Moscow State University) p 490.
[3] Gadilshina V R, Kazunin D V, Khairullin M N and Shamsiev M N 2013 Research of vertical gas wells in non-stationary modes, Vestnik MSTU. Proc. Murmansk State Tech. Univ. 16(1), 66-9.
[4] Sultanova M V, Gafurov A I and Sharafutdinov R F 2017 Thermohydrodynamic effects in multiphase environment, Bulatov Readings. 1, 164-167.
[5] Badertdinova E R, Khairullin R M, Gadilshina V R and Khairullin M Kh 2020 Thermohydrodynamic studies of vertical wells in non-linear filtration, Lobachevskii J. Math. 41(7), 1162-6.
[6] Bondarev E A, Vasiliev V I, Voevodin A F, Pavlov N N and Shadrina A P 1988 Thermohydrodynamics of Gas Production and Transport Systems. (Moscow: Nauka) p 270.
[7] Radionova T V 2014 Program and abstracts of the conference "Gas hydrates in the Earth’s ecosystem-2014". (Novosibirsk: INH SB RAS) p 104.
[8] Borodin S L 2015 Numerical algorithm for solving the problem of one-dimensional radial non-isothermic gas filtration, Bull. Tyumen State Univ. Phys. and Math. Model. Oil, Gas, Energy. 1(4), 58-68.