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**DETERMINATION OF POROSITY, PERMEABILITY
AND INITIAL CRITICAL WATER SATURATION
OF A DEEP-SEATED CREEP-DEFORMABLE GAS RESERVOIR**

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During the development of oil and gas fields, the rocks that comprise them undergo complex deformations, which in turn leads to changes in the porosity and permeability of the formations according to patterns that deviate from linear elastic models. Since the efficient development of deep-seated gas deposits critically depends on the petrophysical properties of the host rocks, adequate development design requires comprehensive consideration of these properties. However, the extreme complexity of the reservoir system and the processes occurring therein makes it difficult to formulate and study such issues in terms of obtaining favorable practical results. The identification of these properties, in accordance with reservoir conditions, is possible, first of all, by solving the corresponding inverse problems of underground hydrogasdynamics. In light of this fact, this article proposes a computational method for determining the porosity, permeability, and initial critical water saturation of deep-seated gas reservoirs whose rocks undergo creeping deformation. The method is based on a comparison of field development history data obtained from field observations with the results obtained from solving a corresponding direct problem to determine the time-dependent change in reservoir pressure, including bottom hole pressure. The proposed approach allows one to estimate the permeability, porosity, and residual water saturation coefficients of a deep-seated gas field developed in a depletion mode, which is critical for optimizing the exploitation strategy and predicting the final gas recovery factor.

Keywords: gas reservoir, deformation, rock, creep, identification.

Introduction

During the development of oil and gas fields, the rocks composing them are subject to various types of deformation, which, in turn, leads to changes in their porosity and permeability according to more complex patterns, different from the elastic law. Since the development of deep-seated gas fields directly depends on the petrophysical properties of the rocks composing them, correct development planning requires comprehensive

consideration of these properties. During the development of deep-seated gas fields, the rocks composing them are typically subject to inelastic deformations under conditions of high stress-strain states, and these deformations are characterized by an irreversible nature [1–22].

To ensure the reliable development of deep-seated gas fields under these conditions, one of the most important practical issues is, first and foremost, determining the petrophysical parameters that characterize them—porosity, formation permeability, and the degree of fluid saturation. Since these characteristics are determined based on laboratory tests of rock samples, the values obtained from these tests typically differ significantly from the actual values corresponding to reservoir conditions. Therefore, incorporating such inaccurate values into design calculations leads to correspondingly large estimation errors. Determining these characteristics based on the processing of wellbore hydrodynamic data can also lead to similar errors.

In such cases, particularly in the context of complex filtration objects, a methodology has recently been applied to achieve high accuracy in determining process parameters when solving various process problems. This methodology involves adapting field development during hydrodynamic modeling to determine the geological and physical properties characterizing the rocks and fluids of the fields [4, 6, 15].

In addition to formation porosity and permeability coefficients, which are considered reservoir filtration and capacity parameters, the petrophysical indicator characterizing initial fluid saturation has a significant impact on the accuracy of forecasting the development parameters of developed oil and gas fields. In recent years, the importance of considering this indicator in field development has been particularly emphasized. Initial critical water saturation characterizes the maximum amount of water contained in the pores of the formation and not participating in movement through the pore channels. This value is determined primarily based on experimental studies conducted in laboratory conditions and, in many cases, inadequately reflects reservoir conditions. Thus, assessing the initial critical water saturation of pores during reservoir development can also allow for an accurate assessment of the potential for its remaining recoverable reserves [23, 24]. In connection with the above, the problems of determining the permeability, porosity, and initial critical water permeability coefficients characterizing deep-seated hydrocarbon deposits with thermobaric conditions under complex rock deformation conditions arise, based on historical data on their development.

The article proposes a solution to the problem of adequate identification for an adequate assessment of the coefficients of permeability, porosity and initial critical water permeability of a gas reservoir developed in depletion mode, taking into account creeping deformations of rocks.

1. Statement of the problem

It is assumed that a circular closed homogeneous gas reservoir is exploited with a flow rate $q_g(t)$ from a central well with a radius r_w . Let us consider the problem of determining the filtration-capacity parameters – the permeability coefficients (k), porosity (m) of reservoir rocks and the initial critical water saturation (s_0), in the case of axisymmetric radial plane-parallel gas filtration in the reservoir in the depletion mode. The filtration process in accordance with this case is expressed in the spatio-temporal domain $\bar{G} = \{(r, t) : r \in (r_w, R_k), t \in (0, T)\}$ by the following partial differential equation [25]:

$$\frac{1}{r} \frac{\partial}{\partial r} \left\{ r \left(\frac{kp}{\mu_g(p)z(p)} \right) \frac{\partial p}{\partial r} \right\} = \frac{\partial}{\partial t} \left\{ \frac{m(1-s_0)p}{z(p)} \right\}. \quad (1)$$

Here p is the current reservoir pressure; μ_g and z are, respectively, the gas viscosity and the gas supercompressibility coefficient; r_w and R_k are, respectively, the wellbore radius and the well influence radius; t is the reservoir development time.

Changes in the porosity and permeability of a creeping-deformable porous medium occur according to the following laws [1–3]:

$$m = m_0 \left(1 + \beta_r(p - p_0) + m_1 \int_0^t \exp(-\gamma_m(t - \tau))(p - p_0) d\tau \right), \quad (2)$$

$$k = k_0 \left(1 + \alpha_k(p - p_0) + k_1 \int_0^t \exp(-\gamma_k(t - \tau))(p - p_0) d\tau \right). \quad (3)$$

Here p_0 , k_0 and m_0 are the initial values of reservoir pressure, permeability and porosity, respectively; m_1 , k_0 , γ_m , γ_k are the reservoir creep parameters; β_r is the compressibility coefficient of the reservoir rock; α_k is a constant coefficient that expresses the rate of permeability decrease depending on the change in pressure.

These relationships represent the porosity and permeability of a formation corresponding to linear hereditary creep deformation of rocks with a Volterra-type core. The solution of similar problems in the case of creep deformation with a different type of creep kernel (strain memory function) has not yet been studied due to mathematical difficulties [2, 3]. The problem is solved within the framework of the following initial and boundary conditions:

$$p(r, t)|_{t=0} = p_0, \quad m(r, t)|_{t=0} = m_0, \quad r \in (r_w, R_k), \quad (4)$$

$$2\pi r h \left(\frac{kp\beta}{\mu_g(p)z(p)p_{at}} \right) \frac{\partial p}{\partial r} \bigg|_{r=r_w} = q_g(t), \quad t \in (0, T), \quad (5)$$

$$\frac{\partial p}{\partial r} \bigg|_{r=R_k} = 0, \quad t \in (0, T). \quad (6)$$

Here h is the thickness of the formation; β is the temperature correction coefficient for gas; p_{at} is the atmospheric pressure.

2. Solving the problem

Under depletion conditions, the change in reservoir pressure over time and radial coordinates is determined from the solution of the direct problem (1)–(6), which characterizes gas flow to the well in a reservoir undergoing creeping deformation. To do this, introducing the notations

$$A = 2\pi h \left(\frac{kp\beta}{\mu_g(p)z(p)p_{at}} \right) \text{ and } B = \frac{2\pi h \beta (1 - s_0) m p}{z(p)p_{at}},$$

we write the direct problem as follows:

$$\frac{1}{r} \frac{\partial}{\partial r} \left\{ rA \frac{\partial p}{\partial r} \right\} = \frac{\partial B}{\partial t}, \quad (r, t) \in \overline{G}, \quad (7)$$

$$p(r, t)|_{t=0} = p_0, \quad m(r, t)|_{t=0} = m_0, \quad r \in (r_w, R_k), \quad (8)$$

$$rA \frac{\partial p}{\partial r} \Big|_{r=r_w} = q_g(t), \quad t \in (0, T), \quad (9)$$

$$\frac{\partial p}{\partial r} \Big|_{r=R_k} = 0, \quad t \in (0, T), \quad (10)$$

where the porosity (m) and permeability (k) coefficients of reservoir rocks vary according to laws (2) and (3).

To directly determine the permeability (k), porosity (m) coefficients of reservoir rocks, and the initial critical water saturation (s_0) based on data comparing the development history of the reservoir, we adopt the following notation:

$$\alpha_1 = \alpha_k, \quad \alpha_2 = k_1, \quad \alpha_3 = \gamma_k, \quad \alpha_4 = \beta_r, \quad \alpha_5 = m_1, \quad \alpha_6 = \gamma_m, \quad \alpha_7 = s_0.$$

In accordance with the scheme of the identification procedure (comparison of the history of reservoir development), a certain quality functional is minimized for the problem under consideration using numerical values $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7$. This functional has the following form:

$$\begin{aligned} J(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7) = & \int_0^T [p(r_w, t) - p_w(t)]^2 dt + \\ & + \iint_{\overline{G}} \Psi(r, t) \left[\frac{1}{r} \frac{\partial}{\partial r} \left\{ rA \frac{\partial p}{\partial r} \right\} - \frac{\partial B}{\partial t} \right] dr dt + \varepsilon \sum_{i=1}^7 a_i^2. \end{aligned} \quad (11)$$

Here $p(r_w, t)$ are the theoretically calculated values of the bottomhole pressure based on the solution of the direct problem; $p_w(t)$ are the measured values of the bottomhole pressure known during the reservoir development process; $\Psi(r, t)$ is an unknown function determined from the solution of the problem conjugate to problem (7)–(10), (2), (3); ε is the regularization coefficient [19, 20].

The values of the numerical quantities $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$ and α_7 corresponding to the minimum of the functional (11), are taken as the sought parameters of the problem – the quantities $\alpha_k, k_1, \gamma_k, \beta_r, m_1, \gamma_m$ and s_0 .

The adjoint problem for determining the unknown function $\Psi(r, t)$ is obtained in the following form [11]:

$$B_p \frac{\partial \Psi}{\partial t} = rA_p \frac{\partial}{\partial r} \left(\frac{\Psi}{r} \right) \frac{\partial p}{\partial r} - \frac{\partial}{\partial r} \left[\frac{\partial}{\partial r} \left(\frac{\Psi}{r} \right) rA \right], \quad (12)$$

$$\Psi(r, T) = 0, \quad (13)$$

$$\left[\frac{\partial}{\partial r} \left(\frac{\Psi}{r} \right) rA + 2(p - p_w(t)) \right] \Big|_{r=r_w} = 0, \quad \left[\frac{\partial}{\partial r} \left(\frac{\Psi}{r} \right) rA \right] \Big|_{r=R_k} = 0. \quad (14)$$

Here A_p, B_p are the derivatives of A and B with respect to p , respectively.

To solve the resulting minimization problem, the gradient descent method is used.

According to this method, to determine the unknown quantities $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$ and α_7 satisfying the minimum of functional (11), expressions for the gradient of this functional with respect to the same quantities must be obtained. The principal part of the increment of functional (11) with respect to the increments of each quantity $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$ and α_7 was obtained in the following form:

$$\Delta J(\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7) = \sum_{i=1}^3 \left\{ \iint_{\bar{G}} \Psi \frac{1}{r} \frac{\partial}{\partial r} \left(r A_{\alpha_i} \frac{\partial p}{\partial r} \right) dr dt + \int_0^T \Psi A_{\alpha_i} \frac{\partial p}{\partial r} \bigg|_{r=r_w} dt + 2\varepsilon \alpha_i + \varepsilon \Delta \alpha_i \right\} \Delta \alpha_i - \sum_{i=4}^7 \left\{ \iint_{\bar{G}} \Psi \frac{\partial B_{\alpha_i}}{\partial t} dr dt - 2\varepsilon \alpha_i - \varepsilon \Delta \alpha_i \right\} \Delta \alpha_i.$$

From these expressions, to calculate the gradients of the functionals (11) with respect to each sought value $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$ and α_7 we obtain:

$$\frac{\partial J}{\partial \alpha_i} = \iint_{\bar{G}} \Psi \frac{1}{r} \frac{\partial}{\partial r} \left(r A_{\alpha_i} \frac{\partial p}{\partial r} \right) dr dt + \int_0^T \Psi A_{\alpha_i} \frac{\partial p}{\partial r} \bigg|_{r=r_w} dt + 2\varepsilon \alpha_i, \quad i = 1, 2, 3, \quad (15)$$

$$\frac{\partial J}{\partial \alpha_i} = - \iint_{\bar{G}} \Psi \frac{\partial B_{\alpha_i}}{\partial t} dr dt + 2\varepsilon \alpha_i, \quad i = 4, 5, 6, 7. \quad (16)$$

Here

$$A_{\alpha_i} = \frac{2\pi h k_{\alpha_i} p \beta}{\mu_g(p) z(p) p_{at}}, \quad i = 1, 2, 3, \quad B_{\alpha_i} = \frac{2\pi h \beta (1 - \alpha_7) p}{z(p) p_{at}} m_{\alpha_i}, \quad i = 4, 5, 6,$$

$$B_{\alpha_7} = - \frac{2\pi h \beta p m_0}{z(p) p_{at}} \left(1 + \alpha_4 (p - p_0) + \alpha_5 \int_0^t \exp(-\alpha_6(t - \tau))(p - p_0) d\tau \right),$$

$$k_{\alpha_1} = k_0 (p - p_0), \quad k_{\alpha_2} = k_0 \int_0^t \exp(-\alpha_3(t - \tau))(p - p_0) d\tau,$$

$$k_{\alpha_3} = -m_0 \alpha_2 \int_0^t \exp(-\alpha_3(t - \tau))(t - \tau)(p - p_0) d\tau, \quad m_{\alpha_4} = m_0 (p - p_0),$$

$$m_{\alpha_5} = m_0 \int_0^t \exp(-\alpha_6(t - \tau))(p - p_0) d\tau,$$

$$m_{\alpha_6} = m_0 \alpha_5 \int_0^t \exp(-\alpha_6(t - \tau))(p - p_0) d\tau.$$

Iterative processes for the identification determination of the sought quantities $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$ and α_7 look as follows [26, 27]:

$$\alpha_i^{k+1} = \alpha_i^k - \lambda_k \frac{\partial J(\alpha_1^k, \alpha_2^k, \alpha_3^k, \alpha_4^k, \alpha_5^k, \alpha_6^k, \alpha_7^k)}{\partial \alpha_i}, \quad i = \overline{1, 7}. \quad (17)$$

Here λ_k are the steps of the iterative process (either have stable values or are selected using a special procedure, which is the establishment of the best direction of change in the pressure gradient in each iteration step).

For each case, the pressure gradients are determined using relation (17). The iterative process (17) is performed by selecting the initial values for the unknown parameters α_k , k_1 , γ_k , β_r , m_1 , γ_m and s_0 . In the initial iteration, zero values can be selected for them. As a result of the implemented iteration, for each subsequent index of the iterative cycle, the value of the functional $J(\alpha_1^k, \alpha_2^k, \alpha_3^k, \alpha_4^k, \alpha_5^k, \alpha_6^k, \alpha_7^k)$ is determined and their difference from the values obtained in the previous step is calculated. The iteration continues until a specified minimum accuracy value is reached. In this case, the unknown parameters α_k , k_1 , γ_k , β_r , m_1 , γ_m and s_0 are considered determined. To ensure the stability of the iterative process, the value of the regularization coefficient is set depending on the value of δ , which indicates the accuracy of the functional calculation [6, 19].

3. Calculation example

To test the proposed identification method, its justification was carried out on the basis of solving the model problem (1)–(6) in the case of gas filtration to a well in a creep-deformable formation, when the values of the identified parameters α_k , k_1 , γ_k , β_r , m_1 , γ_m and s_0 are known in advance. For the theoretical model of the identification problem, a hypothetical model of a gas formation with the following initial data was selected:

$$\begin{aligned} p_0 &= 40 \text{ MPa}; m_0 = 0.2; k_0 = 0.2 \cdot 10^{-12} \text{ m}^2; h = 10 \text{ m}; R_\kappa = 1000 \text{ m}; \\ q_g &= 0.25 \cdot 10^6 \text{ m}^3/\text{day}; \varepsilon = 0.0001; \beta = 0.735; \beta_r = 2.5 \cdot 10^{-3} \text{ MPa}^{-1}; \\ \alpha_k &= 0.01 \text{ MPa}^{-1}; k_1 = 5 \cdot 10^{-7} (\text{MPa} \cdot \text{sec})^{-1}; \gamma_k = 5 \cdot 10^{-5} (\text{MPa} \cdot \text{sec})^{-1}; \\ m_1 &= 3.4 \cdot 10^{-8} (\text{MPa} \cdot \text{sec})^{-1}; \gamma_m = 4.3 \cdot 10^{-6} \text{ sec}^{-1}; s_0 = 0.12; \\ \mu_g &= 0.0054(p/p_0)^2 + 0.0114(p/p_0) + 0.0105 \text{ MPa} \cdot \text{sec}; \\ z(p) &= -0.1845(p/p_0)^3 + 0.9458(p/p_0)^2 - 0.72(p/p_0) + 0.9972. \end{aligned}$$

To identify the values of these parameters based on actual field data, the well's bottomhole pressure values obtained from the problem solution were taken as their actual values measured under field conditions, and the initial approximate values of the parameters being determined during the iterations were set to zero. In each iteration, the values of the functional calculated for the given and determined values of the identified parameters were compared.

Figure 1 shows the dependence of the relative error of the calculated functional values (as a percentage) on the iteration number. As can be seen from the figure, at an iteration number of $n = 10$, functional (11) takes on a minimum value, almost equal to zero. This corresponds to the values of the identified parameters being close to their true values, adopted for them when solving the theoretical problem of gas filtration toward a well in a creep-deformable reservoir. This is also evident, for example, in the nature of the curves given in fig. 2, which depict the calculation results obtained for the identified parameters α_k and s_0 over iterations. Thus, as the number of iterations increases, the values of the identified parameters approach their true values. In this case, other identified parameters also achieve iterative approximation to their values known from the model.

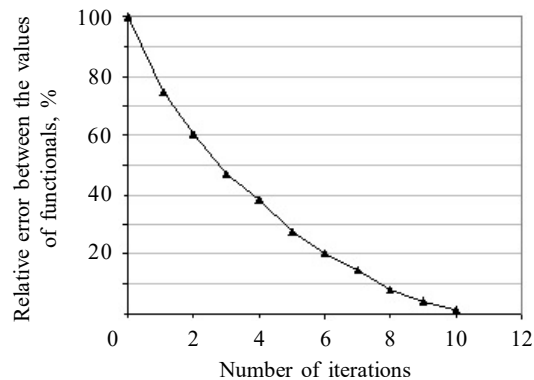


Fig. 1. Dependence of the relative error of the values of the calculated functionals on the number of iterations

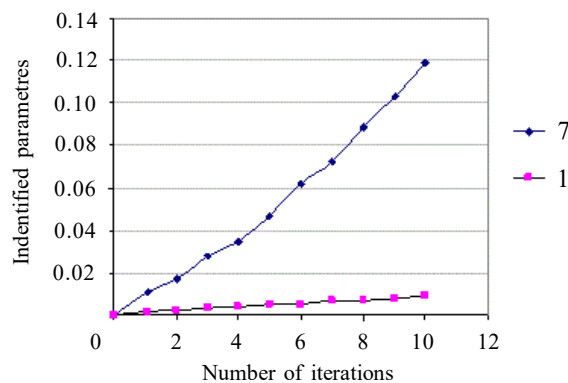


Fig. 2. Approach of the identified parameters α_k (1) and s_0 (7) to their true values over

Conclusion

Thus, taking into account creeping deformation of rocks, the identification problem has been solved, allowing for an adequate assessment of the permeability, porosity, and residual permeability coefficients of a deep-seated gas field developed in a depletion mode. The possibility of determining the desired parameters based on actual field data using optimization theory methods has been demonstrated, and an appropriate determination procedure has been proposed.

References

1. Ametov I.M., Basniev K.S. Filtration of liquid and gas in creeping media [Filtratsiya zhidosti i gaza v polzuchikh sredakh]. *Proceedings of the USSR Academy of Sciences. Fluid Dynamics* [Izvestiya AN SSSR. Mekhanika zhidkosti i gaza]. 1981. Vol. 16. No 4. P. 150–153 (In Russian).
2. Mirzadzhanzade A.H., Kuznecov O.L., Basniev K.S., Aliev Z.S. *Fundamentals of Gas Production Technology* [Osnovy tekhnologii dobychi gaza]. Moscow. Nedra Publ. 2003. 879 p. (In Russian).
3. Kuliev A.M., Kazymov B.Z. *Deformation of Rocks and its Influence on their Filtration-capacity Properties and on the Processes of Filtration and Development of Oil and Gas Deposits* [Deformatsiya gornyykh porod i ee vliyanie na ikh filtratsionno-emkostnye svoystva i na protsessy filtratsii i razrabotki mestorozhdeniy nefi i gaza]. Baku. Elm Publ. 2009. 88 p. (In Russian).

4. Dzhahalov G.I., Ibragimov T.M., Aliyev A.A., Gorshkova E.V. *Modeling and Research of Filtration Processes in Deep-Lying Oil and Gas Fields* [Modelirovanie i issledovanie filtratsionnykh protsessov v glubokozalegayushchikh neftegazovykh mestorozhdeniyakh nefti i gaza]. Baku. Elm Publ. 2018. 382 p. (In Russian).
5. Molokovich Yu.M. *Non-Equilibrium Filtration and its Application in Oilfield Practice* [Neravnovesnaya filtratsiya i ee primeneniye v neftepromyslovoy praktike]. Moscow. CentrLitNefteGaz Publ. 2006. 214 p. (In Russian).
6. Abasov M.T., Dzhahalov G.I., Ibragimov T.M., Mamedov A.M. *Hydrogasdynamics of Deep-Lying Deformable Reservoirs of Oil and Gas Fields* [Gidrogazodinamika glubokozalegayushchikh deformiruemyykh kollektorov neftegazovykh mestorozhdeniy]. Baku. Nafta-Press. 2012. 530 p. (In Russian).
7. Guliyev A., Kazimov B. Numerical modeling of development of oil deposit with system of wells taking into account the relaxation of deformation of rocks. *Problems of Cybernetics and Informatics (PCI): IV International Conference*. Baku. 12–14 Sept. 2012. P. 135–138. <https://doi.org/10.1109/ICPCI.2012.6486399>.
8. Kazymov B.Z. Influence of the relaxation deformation of rocks on the characteristics of nonisothermal filtration of live crude in the stratum. *J. Eng. Phys. Thermophys.* 2018. Vol. 91. No 6. P. 1539–1542. <https://doi.org/10.1007/s10891-018-1890-0>.
9. Kazymov B.Z. Numerical schemes for solving the problem of gas inflow to a well system in a relaxation-deformable gas reservoir. *Computational Mathematics and Mathematical Physics*. 2026. Vol. 66. No 4. P. 758–764.
10. Kazymov B.Z. Variation in oil recovery during oil filtration in reservoirs with relaxation-deformable porous media. *J. Eng. Phys. Thermophys.* 2026. Vol. 99. Iss. 2. P. 446–449.
11. Feyzullayev Kh.A., Khalilov M.S., Kazymov B.Z. Identification of collector properties of relaxational-deformable gas stratum based on the development history data [Identifikatsiya kollektorskikh svoystv relaksatsionno-deformiruemogo gazovogo plasta na osnove dannykh istorii razrabotki]. *Differentsialnye Uravneniya i protsessy upravleniya*. 2023. Iss. 1. P. 1–11. <https://doi.org/10.21638/11701/spbu35.2023.101> (In Russian).
12. Stefanov Yu.P., Bakeev R.A. Nonlinear properties and rheology of rocks. *AIP Conference Proceedings*. 2020. Vol. 2310. Iss. 1. Article No 020325. <https://doi.org/10.1063/5.0034774>.
13. Stefanov Yu.P. Some nonlinear rock behavior effects [Nekotorye nelineynye efekty povedeniya gornykh porod]. *Phys Mesom [Fizicheskaya mezomekhanika]*. 2016. Vol. 19. Iss. 6. P. 54–61 (In Russian).
14. Kazymov B.Z. Procedure for determining the dynamic characteristics of a gas reservoir with a creeping porous medium. *Fluid Dynamics*. 2018. Vol. 53. Iss. 2. P. 34–37. <https://doi.org/10.1134/S0015462818060058>.
15. Kazymov B.Z. Numerical modelling of development of the gas deposit by system of arbitrarily located well taking into account creeping deformation of rocks. *SOCAR Proceedings*. 2012. No 3. P. 42–46. <https://doi.org/10.5510/OGP20120300122>.
16. Kazymov B., Mammadov A. Determination of the developing indicators of gas layers whose rocks are creeping deformation during operation by inclined wells. *5th International Conference on Problems of Cybernetics and Informatics (PCI)*. Baku. Azerbaijan. 20–30 Aug. 2023. P. 1–3. <https://doi.org/10.1109/PCI60110.2023.10326010>.
17. Guliyev A.M., Efendiyev R.M., Kazimov B.Z. The influence of rock creep on oil recovery of deposits developed in the natural mode [Vliyaniye polzuchesti gornykh porod na nefteotdachu zalezhey, razrabatyvaemykh v estestvennom rezhime]. *SOCAR Proceedings*. 2012. Iss. 3. P. 32–37. <https://doi.org/10.5510/OGP20120300120> (In Russian).
18. Yang W., Gamage R.P., Huang C., Luo G., Guo J., Wang Sh. Loading history effect on creep deformation of rock. *Energies*. 2018. Vol. 11. Iss. 6. P. 1462-1 – 1462-20. <https://doi.org/10.3390/en11061462>.
19. Yang L., Zhaojie X., Zhe C., Haijun J. Progress and development directions of deep oil and gas exploration and development in China. *China Petroleum Exploration*. 2020. Vol. 25. No 1. P. 45–57. <https://doi.org/10.3969/j.issn.1672-7703.2020.01.005> (In Chinese).
20. Wang H., Ji B., Lv C., Zhang L. The stress sensitivity of permeability in tight oil

reservoirs. *Energy Explor. Exploit.* 2019. Vol. 37. No 4. P. 1364–1376. <https://doi.org/10.1177/0144598719855819>.

21. Malinin N.N. *Applied Theory of Plasticity and Creep: Textbook for Universities [Prikladnaya teoriya plastichnosti i polzuchesti. Uchebnoe posobie dlya universitetov]*. Moscow. Yurayt Publ. 1975. 400 p. (In Russian).

22. Abasov M.T., Jalalov G.I., Feyzullayev Kh.A. Identification of parameters of the hydrodynamic model of a gas condensate reservoir. *News of the Azerbaijan National Academy of Sciences (ANAS): Earth Sciences Series*. 2008. Vol. 2. P. 78–90.

23. Zhukov V.S., Pleshkov I.V. The influence of water saturation on changes in the physical properties of a reservoir [Vliyanie vodonasyshchennosti na izmenenie fizicheskikh svoystv porod-kollektorov]. *Gas Science Bulletin. [Vesti gazovoy nauki]*. 2018. Vol. 37. Iss. 5. P. 121–128 (In Russian).

24. Cheremisin N.A., Tolstolytkin D.V., Rzaev I.A. Direct method for calculating critical water saturation using results of capillary surveys [Pryamoy metod rascheta kriticheskoy vodonasyshchennosti po rezul'tatam kapillyarnykh issledovaniy]. *Neftegaz Territoriya [Territoriya neftegaz]*. 2021. No 11-12. P. 46–52 (In Russian).

25. Zakirov S.N. *Theory and Design of Development of Gas and Gas Condensate Fields [Teoriya i proektirovanie razrabotki gazovykh i gazokodensatnykh mestorozhdeniy]*. Moscow. Nauka Publ. 1989. 333 p. (In Russian).

26. Tikhonov A.N., Goncharky A.V., Stepanov V.V., Yagola A.Q. *Numerical Methods for Solving Ill-Posed Problems [Chislennyye metody nekorrektnykh zadach]*. Moscow. Nauka Publ. 1990. 229 p. (In Russian).

27. Vasiliev F.P. *Methods for Solving Extremal Problems. Minimization in Function Spaces: Regularization and Approximation Techniques [Metody resheniya ekstremalnykh zadach: Zadachi minimizatsii v funktsionalnykh prostranstvakh, regulyarizatsiya, approksimatsiya]*. Moscow. Nauka Publ. 1980. 400 p. (In Russian).

Список литературы

1. Аметов И.М., Басниев К.С. Фильтрация жидкости и газа в ползучих средах. *Изв. АН СССР. Механика жидкости и газа*. 1981. №4. С. 150–153.

2. Мирзаджанзаде А.Х., Кузнецов О.Л., Басниев К.С., Алиев З.С. *Основы технологии добычи газа*. М.: Недра, 2003. 879 с.

3. Кулиев А.М., Казымов Б.З. Деформация горных пород и ее влияние на их фильтрационно-емкостные свойства и на процессы фильтрации и разработки месторождений нефти и газа. Баку: Элм, 2009. 88 с.

4. Джалалов Г.И., Ибрагимов Т.М., Алиев А.А. *Моделирование и исследование фильтрационных процессов в глубокозалегающих нефтегазовых месторождениях нефти и газа*. Баку: Элм, 2018. 382 с.

5. Молокович Ю.М. *Неравновесная фильтрация и ее применение в нефтепромышленной практике*. М.: ЦентрЛитНефтеГаз, 2006. 214 с.

6. Абасов М.Т., Джалалов Г.И., Ибрагимов Т.М., Мамедов А.М. *Гидрогазодинамика глубокозалегающих деформируемых коллекторов нефтегазовых месторождений*. Баку: Нафта-Пресс, 2012. 530 с.

7. Guliyev A., Kazimov B. Numerical modeling of development of oil deposit with system of wells taking into account the relaxation of deformation of rocks. *Problems of Cybernetics and Informatics (PCI): IV International Conference*. Baku. 12–14 Sept. 2012. P. 135–138. <https://doi.org/10.1109/ICPCI.2012.6486399>.

8. Kazymov B.Z. Influence of the relaxation deformation of rocks on the characteristics of nonisothermal filtration of live crude in the stratum. *Journal of Engineering Physics and Thermophysics*. 2018. Vol. 91. No 6. P. 1539–1542. <https://doi.org/10.1007/s10891-018-1890-0>.

9. Kazymov B.Z. Numerical schemes for solving the problem of gas inflow to a well system in a relaxation-deformable gas reservoir. *Computational Mathematics and Mathematical Physics*. 2026. Vol. 66. No 4. P. 758–764.

10. Kazymov B.Z. Variation in oil recovery during oil filtration in reservoirs with relaxation-

deformable porous media. *Journal of Engineering Physics and Thermophysics*. 2026. Vol. 99. Iss. 2. P. 446–449.

11. Фейзуллаев Х.А., Халилов М.С., Казымов Б.З. Идентификация коллекторских свойств релаксационно-деформируемого газового пласта на основе данных истории разработки. *Дифференциальные уравнения и процессы управления*. 2023. Т. 1. С. 1–11. <https://doi.org/10.21638/11701/spbu35.2023.101>.

12. Stefanov Yu.P., Bakeev R.A. Nonlinear properties and rheology of rocks. *AIP Conference Proceedings*. 2020. Vol. 2310. Iss. 1. Article No 020325. <https://doi.org/10.1063/5.0034774>.

13. Стефанов Ю.П. Некоторые нелинейные эффекты поведения горных пород. *Физическая мезомеханика*. 2016. Т. 19. №6. С. 54–61.

14. Kazymov B.Z. Procedure for determining the dynamic characteristics of a gas reservoir with a creeping porous medium. *Fluid Dynamics*. 2018. Vol. 53. Iss. 2. P. 34–37. <https://doi.org/10.1134/S0015462818060058>.

15. Kazymov B.Z. Numerical modelling of development of the gas deposit by system of arbitrarily located well taking into account creeping deformation of rocks. *SOCAR Proceedings*. 2012. No 3. P. 42–46. <https://doi.org/10.5510/OGP20120300122>.

16. Kazymov B., Mammadov A. Determination of the developing indicators of gas layers whose rocks are creeping deformation during operation by inclined wells. *5th International Conference on Problems of Cybernetics and Informatics (PCI)*. Baku. Azerbaijan. 20–30 Aug. 2023. P. 1–3. <https://doi.org/10.1109/PCI60110.2023.10326010>.

17. Кулиев А.М., Эфендиев Р.М., Казымов Б.З. Влияние ползучести горных пород на нефтеотдачу залежей, разрабатываемых в естественном режиме. *SOCAR Proceedings*. 2012. №3. С. 32–37.

18. Yang W., Gamage R.P., Huang C., Luo G., Guo J., Wang Sh. Loading history effect on creep deformation of rock. *Energies*. 2018. Vol. 11. Iss. 6. P. 1462-1 – 1462-20. <https://doi.org/10.3390/en11061462>.

19. Yang L., Zhaojie X., Zhe C., Haijun J. Progress and development directions of deep oil and gas exploration and development in China. *China Petroleum Exploration*. 2020. Vol. 25. No 1. P. 45–57. <https://doi.org/10.3969/j.issn.1672-7703.2020.01.005> (In Chinese).

20. Wang H., Ji B., Lv C., Zhang L. The stress sensitivity of permeability in tight oil reservoirs. *Energy Exploration & Exploitation*. 2019. Vol. 37. No 4. P. 1364–1376. <https://doi.org/10.1177/0144598719855819>.

21. Малинин Н.Н. *Прикладная теория пластичности и ползучести*. М.: Машиностроение, 1975. 400 с.

22. Abasov M.T., Jalalov G.I., Feyzullayev Kh.A. Identification of parameters of the hydrodynamic model of a gas condensate reservoir. *News of the Azerbaijan National Academy of Sciences (ANAS): Earth Sciences Series*. 2008. Vol. 2. P. 78–90.

23. Жуков В.С., Плешков И.В. Влияние водонасыщенности на изменение физических свойств пород-коллекторов. *Вести газовой науки*. 2018. Т. 37. № 5. С. 121–128.

24. Черемисин Н.А., Толстолыткин Д.В., Рзаев И.А. Прямой метод расчета критической водонасыщенности по результатам капиллярных исследований. *Территория нефтегаз*. 2021. №11-12. С. 46–52.

25. Закиров С.Н. *Теория и проектирование разработки газовых и газоконденсатных месторождений*. М.: Недра, 1989. 333 с.

26. Тихонов А.Н., Гончарский А.В., Степанов В.В., Ягола А.Г. *Численные методы некорректных задач*. М.: Наука, 1990. 229 с.

27. Васильев Ф.П. *Методы решения экстремальных задач: Задачи минимизации в функциональных пространствах, регуляризация, аппроксимация*. М.: Наука, 400 с.

**ОПРЕДЕЛЕНИЕ ПОРИСТОСТИ, ПРОНИЦАЕМОСТИ
И НАЧАЛЬНОЙ КРИТИЧЕСКОЙ ВОДОНАСЫЩЕННОСТИ
ГЛУБОКОЗАЛЕГАЮЩЕГО ПОЛЗУЧЕ-ДЕФОРМИРУЕМОГО
ГАЗОВОГО МЕСТОРОЖДЕНИЯ**

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При разработке нефтяных и газовых месторождений составляющие их породы подвергаются сложным деформациям, что, в свою очередь, приводит к изменению пористости и проницаемости пластов по закономерностям, отклоняющимся от линейно-упругих моделей. Поскольку эффективная разработка глубокозалегающего газового месторождения в значительной степени зависит от петрофизических свойств вмещающих пород, для грамотного проектирования разработки необходимо всесторонне учитывать эти свойства. Однако чрезвычайная сложность пластовой системы и происходящих в ней процессов затрудняет формулировку и изучение таких вопросов с точки зрения получения положительных практических результатов. Выявить эти свойства в соответствии с пластовыми условиями можно прежде всего путем решения соответствующих обратных задач подземной гидрогазодинамики. В связи с этим в настоящей статье предлагается вычислительный метод определения пористости, проницаемости и начальной критической водонасыщенности глубокозалегающих газовых месторождений, породы которых подвергаются ползучим деформациям. Метод основан на сопоставлении данных об истории разработки месторождения, полученных в ходе полевых наблюдений, с результатами решения соответствующей прямой задачи по определению зависящего от времени изменения пластового давления, в том числе забойного. Предлагаемый подход позволяет оценить коэффициенты проницаемости, пористости и остаточной водонасыщенности глубинного газового месторождения, разрабатываемого в режиме истощения, что крайне важно для оптимизации стратегии разработки и прогнозирования конечного коэффициента извлечения газа.

Ключевые слова: газовое месторождение, деформация, горная порода, ползучесть, идентификация.