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Article

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APPROVAL OF THE COMBINED RESERVE CALCULATION METHOD (CHERVONOZAYARSKE GAS FIELD AS AN EXAMPLE)

The object of the study is the calculation of the producing reserves of the gas-bearing reservoir. Increasingly, published studies provide justification for the possibility of restoring reserves in old depleted gas fields by gas flow from deep horizons. Given the possibility of resuming producing gas reserves, the issue of clarifying their volume in the reservoirs of fields at a late stage of development is promising.

In the course of the study, theoretical research methods were used: a system analysis of the inreservoir used, numerical modeling based on a combined finite element-difference method, methods for visualizing the inreservoir obtained, and analytical methods.

The method proposed in the paper for refining gas reserves combines the volumetric method and modeling of filtration processes using a combined finite element-difference method. The latter makes it possible to take into account the reservoir structure that is heterogeneous in terms of permeability and adequately describe the distribution of non-stationary reservoir pressure around the production well on a quantitative level. By applying an analytical formula based on the values of average reservoir and bottomhole pressures, the radii of the well feed contour were calculated for different periods of reservoir development. Thus, the active area (and volume) of the reservoir is determined, according to which the calculations of the producing reserves of the field are carried out.

The study was carried out on the example of the Chervonozayarske Gas Field (Ukraine) for the reservoir V-26-T-1a, discovered by one production well 468-B(D). The recoverable reserves of the V-26-T-1a reservoir calculated in this way are 597.69 million m^3 of gas. At the same time, the error relative to the value indicated in the Atlas of Ukrainian Fields is 4.63 %.

The method of calculating reserves proposed in this study is useful for refining the reserves of depleted fields. The combination of the volumetric method with the results of simulation of filtration processes is an operational method for calculating the reserves of a reservoir discovered by one production well. At the same time, the use of a combined finite element-difference method makes it possible to take into account the complex heterogeneous structure of the reservoir and predict the distribution of reservoir non-stationary pressures around the production well.

Keywords: *reserves calculation, volumetric method, gas-bearing reservoirs, filtration processes, depleted fields, reservoir pressure.*

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1. Introduction

Reserves are an important parameter in the exploration and development of oil and gas fields, as well as in the pilot operation of wells [1]. At different stages of exploration and development of productive deposits, ideas about geological conditions and development rules are constantly changing, and the parameters necessary for calculating gas reserves are being refined. An opinion is also being developed about the possibility of renewing depleted reserves by flowing gas from lower horizons along tectonic faults [2]. Therefore, the calculation and evaluation of reserves is a fundamental task throughout the life cycle of reservoir development [3].

It is important to systematically apply different methods for calculating reserves to select an appropriate method for developing a gas reservoir [4]. At the initial stage of development, the initial geological reserves are estimated using the volumetric method. In large-scale development, recoverable reservoir reserves are calculated using the material balance method [5]; at the middle and late stages of development, numerical modeling is used [6].

In addition, the fundamental factor in assessing the initial gas production reserves is to take into account the heterogeneous structure of the reservoir [7]. In this situation, computer simulation methods are in demand, allowing getting an idea of the filtration processes in the reservoir.

This inreservoir can be used to estimate the original producing reserves of a heterogeneous gas reservoir.

Therefore, to increase the accuracy of calculating producing reserves, it is possible to combine the volumetric method with the results of mathematical modeling of filtration processes using a combined finite element difference method.

2. The object of research and its technological audit

The object of research is the calculation of the producing reserves of the gas-bearing reservoir. Published studies are increasingly providing justification for the possibility of restoring reserves in old depleted gas fields by gas flow from deep horizons [2, 8]. Taking into account the possibility of renewal of producing gas reserves, it is important to clarify their volume in the reservoirs of fields at a late stage of development.

3. The aim and objectives of research

The aim of research is to estimate the gas reserves of a productive reservoir based on a combined method that combines the volumetric method and the results of reservoir pressure modeling around the well.

To achieve the aim, the following objectives must be completed:

1. Formulate the mathematical formulation of the non-stationary filtration problem.
2. Simulate the filtration process around the well by solving the formulated problem using the combined finite element difference method [7].
3. Apply the reservoir pressure distribution fields obtained as a result of modeling to calculate the radius of the well feed contour.
4. Calculate the active area of the reservoir along the radius of the feed contour of the producing well, which will allow estimating the producing gas reserves.

4. Research of existing solutions to the problem

The calculation of gas reserves is of key importance during the entire field development cycle [1, 3]. To estimate the initial producing reserves of a deposit, the material balance method is usually used [4, 9]. The use of the material balance requires a fairly accurate determination of the initial and current values of the reservoir pressure [5], the dependence of the physical parameters of the reservoir fluid, such as the volume factor, gas or condensate content, and the coefficient of elasticity on pressure [10]. Therefore, this method is not always applicable due to the lack of necessary initial inreservoir [6]. The method of calculating reservoir pressure reduction reserves [11] does not give satisfactory results in the presence of excellent pressure gradients due to low permeability or anisotropic distribution. A simplified balance model of depletion of deposits [5] allows one to take into account the zonal heterogeneity of the environment when calculating reserves. But the main condition for the calculation is the absence of interlayer flows. At the same time, the use of the finite element difference method makes it possible to take into account fluid infiltration through the reservoir boundaries [7].

A well-known method is the volumetric one, which can be used to calculate both absolute initial (geological) and industrial (producing) gas reserves [12, 13]:

$$V_p = V_r m\beta \frac{P_r\alpha - P_{res}\alpha_{res}}{P_{st}} f, \quad (1)$$

where V_p – initial producing gas reserves reduced to atmospheric pressure and standard temperature, million m^3; $V_r = S_r \cdot h$ – reservoir volume, m^3; S_r – reservoir area, m^2; h – the effective gas-saturated thickness of the reservoir, m; m – the coefficient of open porosity; β – the gas saturation coefficient; $\frac{P_r\alpha - P_{res}\alpha_{res}}{P_{st}}$ – baric coefficient used to bring the volume of free gas contained in the deposit to standard conditions; P_f – reservoir pressure in the deposit, MPa; P_{res} – residual pressure established in the deposit, when the pressure at the mouth of the production well is equal to the standard, 0.101325 MPa; α, α_{res} – corrections for the deviation of hydrocarbon gases from the Boyle-Mariotte law for pressures P_r ($\alpha = 1/Z$, where Z is the gas compressibility factor) and P_{res} ($\alpha_{res} = 1$); P_{st} – pressure under standard conditions ($P_{st} = 0.101325$ MPa); f is the correction for temperature to bring the volume of gas to the standard temperature, $f = T_{st}/T_r$.

To clarify the value of the producing reserves of depleted gas reservoirs, it is of interest to use a combined method for calculating reserves, which combines the volumetric method and the results of mathematical modeling of the distribution of reservoir pressures [7].

5. Methods of research

Theoretical research methods include a system analysis of the inreservoir used, numerical modeling based on the combined finite element-difference method [7], methods of visual representation of the inreservoir obtained, and analytical methods.

The study was carried out on the example of the Chervonozayarske Gas Field (Ukraine). In the mathematical formulation of the problem, the following assumptions are made. The effective reservoir thickness is constant and much less than the horizontal dimensions of the reservoir, in this case the problem is considered as two-dimensional. Permeability, porosity, viscosity and gas compressibility factor, initial reservoir pressure, flow rate are known and constant values over time. The task is calculated for a single-phase flow (gas). Then [7]:

$$\frac{\partial P^2}{\partial t} = \frac{kP_0}{\mu m}\left(\frac{\partial^2 P^2}{\partial x^2} + \frac{\partial^2 P^2}{\partial y^2}\right) + \gamma; \quad (2)$$

$$P(t=0) = P_0; \quad (3)$$

$$k_b \operatorname{grad} P^2 = \alpha(P^2 - P_b^2), \quad (4)$$

where (2) – the piezoconductivity equation; (3) – initial condition; (4) – the limiting condition for fluid infiltration at the boundaries of the area under consideration; k – the permeability of the gas phase, m^2; μ – the dynamic viscosity of the gas, Pa·s; m – the porosity of the gas-bearing reservoir, fractions of units; P_0 – the initial pressure of the porous layer, Pa; α – the fluid infiltration coefficient at the boundaries of the area under consideration, m; P_b – the pressure at the boundaries of the area under consideration, Pa; k_b – the

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permeability of the gas phase at the boundaries of the area under consideration, m^2.

The algorithm for calculating the system of equations (2)–(4) by the finite element difference method is described in [7].

To solve the system of equations (2)–(4), the simulated area is divided into 81 finite eight-node elements. As a result of solving the Leibenson piezoconductivity equation using the combined finite element difference method, let's obtain the pressure value at all nodal points of the finite element mesh. Based on the found nodal values, the pressure is determined at an arbitrary point in the hydrocarbon reservoir of the study area at a given point in time.

Area-weighted reservoir pressure is determined from isobar maps (pressure distribution fields in Fig. 1).

The results of modeling the reservoir pressure distribution around the well allow to draw conclusions about the radius of its supply contour by applying an analytical formula for determining the flow rate of a gas well [12]. Since the value of the flow rate is known, from here it is possible to find out the value of the radius of the well feed contour:

$$Q=\frac{\pi kh(P_{\text{av.}r}^2-P_b^2)}{\mu P_{atm}\ln\frac{R_c}{r_w}}\Rightarrow \ln R_c=\frac{Q\mu P_{atm}}{\pi kh(P_{\text{av.r}}^2-P_b^2)}+\ln r_w, \quad (5)$$

where Q – the flow rate of the well, thousand m^3/s; μ – the coefficient of dynamic viscosity of the gas, mPa·s; R_{atm} – atmospheric pressure, R_{atm}=0.101325 MPa; k – the permeability coefficient, μm^2; h – the effective thickness of the reservoir, m; r_w – the summary radius of the well, m; $P_{av.r}$ – average reservoir pressure based on simulation results; P_b – bottom hole pressure according to simulation results; R_c – the radius of the power circuit, m.

The summary radius of the well is determined according to [14]:

$$r_s=r_w e^{-(C_1+C_2)}, \quad (6)$$

where r_w – the radius of the well along the bit, mm; C_1 and C_2 are imperfection coefficients according to the degree and nature of disclosure, respectively:

$$C_1=\frac{1}{\bar{h}}\ln\bar{h}+\frac{1-\bar{h}}{\bar{h}}\ln\frac{\delta}{\bar{r}_c}+\frac{1}{\bar{h}}, \quad (7)$$

where $\bar{h}=h_o/h_{ef}$ – the relative opening of the reservoir by the well; $\delta=1.6(1-\bar{h}^2)$; $\bar{r}_c=r_c/h$ – the relative radius of the well;

$$C_2=\frac{h_{ef}}{nR_0}+\frac{h_{ef}^2}{3n^2R_0^3}, \quad (8)$$

where n – the number of perforations; R_0 – the hole radius; h_{ef} – effective reservoir thickness.

The coefficient of dynamic viscosity of gas at atmospheric pressure is calculated from the known composition of the gas, the calculation is made at reservoir temperature, and then recalculated at reservoir pressures according to [14].

Calculation of reserves is carried out by the value of the radius of the well feed contour, determined by the pressure values obtained as a result of simulation of filtration processes. That is, the calculated values of the reserves are obtained on the basis of pressure values, which, in turn, are calculated by the combined finite element-difference method.

Recoverable reserves from a reservoir discovered by one well can be calculated using formula (1). Wherein:

$$S_r=\pi R_c^2, \quad (9)$$

where S_r – the reservoir area from which reserves can be extracted, m^2.

To calculate the coefficient of gas supercompressibility, let's use the analytical method according to [14]. This is a method based on the equation of state of a gas with virial coefficients, which does not take into account the factor of acentricity of molecules (i. e., it is recommended for non-polar substances and for a gas mixture with a molar concentration of high-boiling components less than 10 %). The value of the reduced pressure should not exceed 15:

$$Z=\frac{1}{1-h}-\frac{a^{*2}}{b^*}\cdot\frac{h}{h+1}, \quad (10)$$

where

$$h=\frac{Pb^*}{Z},$$

$$b^*=0.0867\frac{T_{cr}}{P_{cr}T},$$

$$a^{*2}=0.4278\frac{T_{cr}^{2.5}}{P_{cr}T^{2.5}}. \quad (11)$$

The coefficients of the equation for the mixture are determined from the formulas [14]:

$$b_m^*=\sum_{i=1}^n b_i^* x_i,$$

$$a_m^*=\sum_{i=1}^n a_i^* x_i. \quad (12)$$

The coefficients of equation (10) predetermine its entry in the form of a cubic solution of cubic equations calculated using an online calculator [15] with one real root.

Thus, based on modeling the pressure distribution in the reservoir, let's determine the value of the radius of the well feed circuit. Based on the obtained R_c, it is possible to calculate the recoverable reserves of the reservoir discovered by one production well.

6. Research results

The initial data for the results of the study are given in Table 1. For the maximum approximation of the reservoir model to real conditions, excellent permeability values were set in the place of tectonic excitation [16].

Let's assume that the opening of the productive stratum of the V-26-T-1a horizon of the Chervonozayarske Gas Field was carried out with a bit with a diameter of 215.9 mm. Then the diameter of the well along the bit is d_w=215.9 mm, respectively, the radius is r_w=107.95 mm. The coefficient of imperfection by the nature of the opening will have to be neglected due to the lack of inreservoir on the perforation of the bottom hole.

The summary radius of well 468-B(D) is calculated in Table 2.

The critical and pseudocritical parameters of the gas well 468-B(D) of the Chervonozayarske Gas Field are calculated in Table 3, where x_i – the mole fraction and gas component; R_{abs} and T are critical parameters and gas components (table values); $P_{cr.i}=x_i{\cdot}P_{abs}$ and $T_{cr.i}=x_i{\cdot}T$ – pseudocritical parameters of the i-th gas component.

The results of the study in Fig. 1 shows the change in the distribution of reservoir pressure near the production well ($P_{av.f}$ and P_b – the value of the average reservoir and bottom hole pressure, respectively, MPa). Fig. 1 does not show the entire reservoir area of 3.76 km^2 (1939×1939 m), but a zone close to the well (with an area of 950×950 m), where there is an intense pressure change.

The recalculation of the coefficient of dynamic gas viscosity according to the instructions [14] for various values of average reservoir pressures is given in Table 4.

The calculation of the value of the radius of the supply loop for different periods of well operation 468-B(D) according to the formula (5) is given in Table 5.

Recoverable reserves from reservoir V-26-T-1a by well 468-B(D), calculated by formula (1), are given in Table 6.

Table 1

Initial data for modeling

Name, designation	Value	Units
Gas reservoir area S	3.76	km^2
Porosity factor m	0.11	–
Initial reservoir pressure P_0	$42.1{\cdot}10^6$	Pa
Reservoir temperature T_r	386	K
Coefficient of dynamic gas viscosity μ at P_0 and T_f	$0.027{\cdot}10^{-3}$	Pa·s
Compression coefficient of the rock skeleton β_2	10^{-10}	Pa^{-1}
Average well production rate Q	60.3	thousand m^3/day
Effective gas-saturated reservoir thickness h_{ef}	3.7	m
The total thickness of the productive layer h_{calc}	56	m
Permeability coefficient	0.3	μm^2
Reservoir gas saturation coefficient	0.72	s

Table 2

Calculation of the summary radius of the well 468-B(D)

$\bar{h} = h_{calc}/h_{ef}$	$\delta = 1.6(1-\bar{h}^2)$	$\bar{r}_c = r_c/h$	C_1	r_s, м
0.066	1.593	0.0019	54.84	0.0015

Table 3

Calculation of pseudo-critical parameters of gas well 468-B(D)

Gas composition	x_i, %	Critical parameters		Pseudocritical parameters	
		P_{abs}, kgf/cm^2	T, K	$P_{cr.i}$, kgf/cm^2	$T_{cr.i}$, K
CH_4	0.9612	46.95	190.55	45.1283	183.1567
C_2H_6	0.0116	49.76	306.43	0.5772	3.5546
C_3H_8	0.0203	43.33	369.82	0.8796	7.5073
n-C_4H_{10}	0.0012	38.71	425.16	0.0465	0.5102
i-C_4H_{10}	0.0004	37.19	408.13	0.0149	0.1633
n-C_5H_1	0.0003	34.35	469.65	0.0103	0.1409
i-C_5H_{12}	0.0002	34.48	460.39	0.0069	0.0921
CO_2	0.0040	75.27	304.20	0.3011	1.2168
N_2	0.0004	34.65	126.26	0.0139	0.0505
He	0.0004	2.34	5.20	0.0009	0.0021
–	–	–	–	P_{cr}=46.9796 kgf/cm^2 or 4.6071 MPa	T_{cr}=196.3944 K

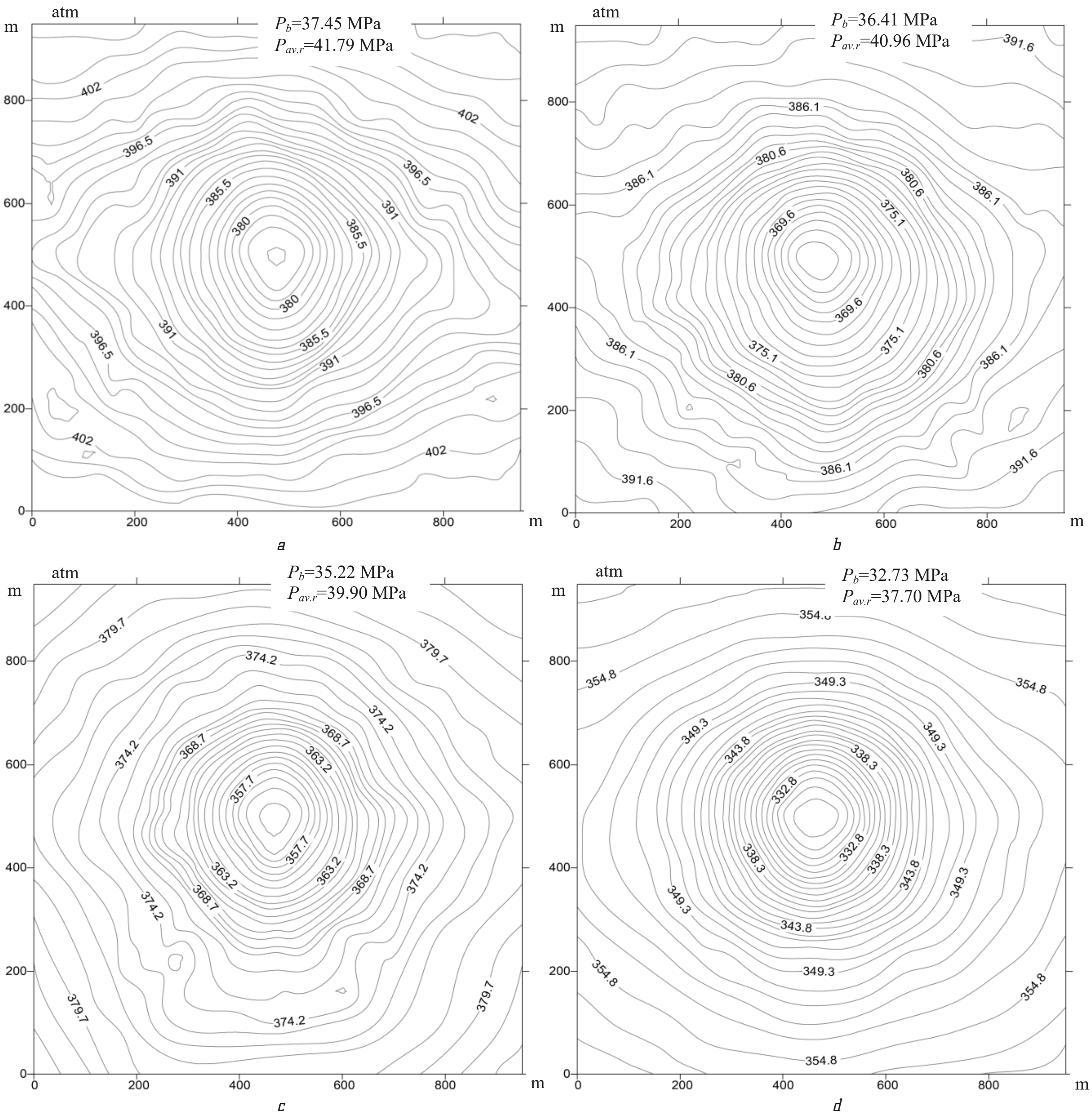

Fig. 1. Pressure distribution fields around well 468-B(D) at different operating times: *a* – 10 days; *b* – 50 days; *c* – 100 days; *d* – 200 days

Table 4

Gas viscosity calculation for well 468-B(D) at reservoir pressures

Well operation life *t*, days	Average reservoir pressure P_r, MPa	$P_{pr}=P_r/P_{cr}$	μ, cP (calculation according to [14])
10	41.79	9.07	0.027
50	40.96	8.89	0.027
100	39.90	8.66	0.028
200	37.70	8.18	0.029

Table 5

The value of the radius of the feed contour of the well 468-B(D)

Well life 468-B(D), days	Average reservoir pressure according to the results of modeling $P_{av.r.i}$, MPa	Bottom hole pressure according to the results of modeling $P_{b.i}$, MPa	Gas dynamic viscosity coefficient μ_i, mPa·s	The value of the radius of the well feed contour $R_{c.i}$, m
10	41.79	37.45	0.027	286.56
50	40.96	36.41	0.027	289.44
100	39.90	35.22	0.028	293.27
200	37.70	32.73	0.029	301.78

Table 6

Calculation of gas reserves of the Chervonozayarske Gas Field

Well life 68-B(D), days	Average reservoir pressure according to the results of modeling $P_{av.r.i}$, MPa	Gas supercompressibility factor Z_i	Correction $\alpha_i=1/Z_i$	The value of the radius of the well feed contour $R_{c.i}$, m	Gas reserves, $V_{g.r.}$, million m^3
10	41.79	0.9922	1.057	286.56	597.69
50	40.96	0.9821	1.065	289.44	597.69
100	39.90	0.9735	1.104	293.27	597.69
200	37.70	0.9608	1.134	301.78	597.69

The proof of the fact of the existence of one value of extractive reserves (V_e=597.69 million m^3 of gas) at any time t is a self-check of the calculation. The error in calculating the value of recoverable reserves by the proposed method relative to the value indicated in the Atlas of Ukrainian Fields [16] is 4.63 %. This indicates a good convergence of the results, and hence the possibility of using a combined method for calculating the reserves of gas deposits discovered by one production well.

7. SWOT analysis of research results

Strengths. Based on the study, it is possible to calculate the producing gas reserves using the volumetric method and the results of modeling the filtration processes around the well. The combined method for calculating reserves can be used as an operational method based on geophysical and laboratory data. Since inreservoir about the distribution of reservoir pressures is obtained by mathematical modeling of filtration processes, the combined method for calculating reserves does not require hydrodynamic studies of the well.

Weaknesses. The weak side of the combined method for calculating producing gas reserves is the possibility of its application only for reservoirs discovered by one production well.

Opportunities. In the future, it is of interest to create a methodology for calculating gas reserves for multilayer fields, as well as in the presence of two or more producing wells.

Threats. This level of research does not require additional costs for the implementation of the results.

8. Conclusions

1. The mathematical statement of the non-stationary inhomogeneous problem of gas filtration formulated in the course of the work includes:

– non-stationary inhomogeneous Leibenson piezoconductivity equation;

– initial condition (the value of the initial reservoir pressure is set);

– the limiting condition that takes into account fluid infiltration through the boundaries of the study area.

2. To solve the non-stationary inhomogeneous Leibenson filtration problem, a combined finite-element-difference method was applied [7]. This makes it possible to take into account the heterogeneous distribution of reservoir characteristics of the reservoir (in the framework of this study, zonal heterogeneity was set by a different value of the permeability coefficient at the site of tectonic disturbance of the reservoir). Using the applied method, it is possible to adequately describe the pressure distribution in a gas-saturated reservoir, opened by a production well, at a quantitative level.

3. Using the reservoir pressure distribution fields obtained as a result of modeling, the value of the radius of the well feed contour was calculated. According to calculations, the radius of the well 468-B(D) feed contour at the beginning of its operation (t=10 days) is 286.56 m and expands with time (at t=200 days R_c=301.78 m).

4. The active area (and volume) of the V-26-T-1a reservoir was calculated from the radius of the feed contour of a single well 468-B(D). The use of the volumetric method of reserves calculation in combination with the simulation results made it possible to estimate the producing gas reserves (V_e=597.69 million m^3 of gas).

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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