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GAS RESERVES CALCULATION BASED ON THE RESULTS OF RESERVOIR PRESSURE DISTRIBUTION MODELING

The object of this study is the gas-bearing layer B-26 of the Zakhidne-Radchenkivs'ke gas condensate field (Ukraine). A bottleneck in the process of exploration and experimental and industrial operation of the Zakhidne-Radchenkivs'ke gas condensate field was the ambiguous data on extractive reserves (values that were calculated by different authors range from 14 thousand to 424 million m^3). At present, the field is mothballed, which is why the use of a new approach to calculating the initial gas reserves could be useful for deciding to start developing a single productive layer B-26.

During the study, such theoretical research methods were used as the system analysis of the information used, numerical modeling based on the combined finite-element-difference method, the methods of visual representation of the information received, as well as analytical methods. The method of calculating gas reserves proposed in this work combines a volumetric method and the simulation of filtration processes using a combined finite-element-difference method. The latter makes it possible to take into consideration the structure of the reservoir, which is heterogeneous in terms of permeability, and to adequately, at the quantitative level, to describe the distribution of non-stationary reservoir pressure around the extractive well. By applying an analytical formula based on the values of average reservoir and downhole pressures, the radii of the well's feed circuit at different stages of the reservoir development have been calculated. Thus, the active area (and volume) of the reservoir can be determined, according to which the extractive reserves of the deposit are calculated. The mining reserves of the Zakhidne-Radchenkivs'ke field, estimated in this way, amount to 174 million m^3 of gas.

The method for calculating reserves proposed in this study could prove useful for deciding on the further development of the Zakhidne-Radchenkivs'ke gas condensate field. Combining the volumetric method with the results of modeling filtration processes is an operational method for calculating the reserves of the reservoir, opened by one mining well. In this case, the application of the combined finite-element-difference method makes it possible to take into consideration the complex heterogeneous structure of the reservoir and predict the distribution of reservoir nonstationary pressures around the extractive well.

The current study that used the Zakhidne-Radchenkivs'ke gas condensate field in Ukraine as an example is interesting when calculating the reserves of layers of complex structure all over the world, whereby the productive reservoir is opened by a single mining well.

Keywords: *gas-bearing layers, extractive reserves, volumetric method, finite-element-difference method, distribution of reservoir pressure.*

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1. Introduction

Reserves are an important parameter for exploration and development of oil and gas fields, as well as experimental and industrial operation of wells [1]. At different stages of exploration and development of productive deposits, ideas about geological conditions and rules of development are constantly changing, as well as the parameters necessary for calculating gas reserves are refined. Therefore, the calculation and evaluation of reserves is an important task throughout the life cycle of the development of a reservoir [2].

It is important to systematically apply various methods for estimating reserves in order to select an appropriate technique for developing a gas reservoir [3]. At the initial stage, the starting geological reserves that form the basis of the project and the plan for the development of the gas field are estimated. Initial geological reserves can be determined by a volumetric method. During the implementation of the development plan, it is necessary to determine the production reserves to define the location of the well. Usually, gas reserves are calculated by a volumetric method taking into consideration the coefficient of gas production of a reservoir [1]. In large-scale development, the extractive reserves of collectors are calculated using a material balance method [4]; at the middle and late stages of development – numerical modeling is used [5].

On the other hand, an important factor in assessing the initial extractive gas reserves is the consideration of the heterogeneous structure of a reservoir [6]. In this event, computer simulation methods prove useful, which make it possible to get an idea of filtration processes in a productive layer. This information could be used to estimate the initial extractive reserves of the gas deposit of a heterogeneous structure.

2. The object of research and its technological audit

The object of this study is the gas-bearing layer B-26 of the Zakhidne-Radchenkivs'ke gas condensate field (Ukraine). Evaluation of initial extractive gas reserves is a promising task as in the process of exploration and experimental and industrial operation of the field, ambiguous data were acquired, first of all, on extractive reserves [7]. The estimated values of the initial extractive gas reserves at the Zakhidne-Radchenkivs'ke gas condensate field are very different from each other (from 14 thousand to 424 million m^3) [7–9]. At present, the field is mothballed, so another assessment of the initial reserves would be useful for deciding to start developing a productive layer B-26 of the Zakhidne-Radchenkivs'ke gas condensate field.

3. The aim and objectives of research

The purpose of this study is to calculate gas reserves at the Zakhidne-Radchenkivs'ke gas condensate field based on the results of modeling the reservoir pressure around the well No. 205 using the combined finite-element-difference method.

To accomplish the aim, the following tasks have been set:

1. State mathematically a nonstationary filtration problem.
2. Apply the combined finite-element-difference method [6] to solve the stated problem.
3. Use the resulting modeled reservoir pressure distribution field to calculate the radius of the well's feed circuit.
4. Calculate the active area of the layer B-26 along the radius of the feed circuit of a single well No. 205, which would make it possible to estimate the extractive gas reserves.

4. Research of existing solutions to the problem

Methods for calculating gas reserves are divided into volumetric, pressure drop [10], isobar maps [1]. There is also a method of material balance, which is usually used in large-scale development of deposits [3, 4]. The basic method is volumetric, which can be used to calculate both absolute initial (geological) and industrial (extractive) gas reserves [11]:

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

where V_e is the initial extractive gas reserves reduced to atmospheric pressure and standard temperature, million m^3; $V_r = S_r \cdot h$ is the reservoir volume, m^3; S_r is the area of the reservoir, m^2; h is the effective gas-saturated thickness of the reservoir, m; m is the coefficient of open porosity; β is the gas saturation coefficient; $(P_r\alpha - P_{res}\alpha_{res})/P_{st}$ is the baric coefficient used to reduce the volume of free gas contained in the deposit to standard conditions; P_r is the reservoir pressure in the deposit, MPa; P_{res} is the residual pressure, which is set in the deposit when the pressure on an extractive wellbore is equal to standard, 0.101325 MPa; α, α_{res} are the corrections to the deviation of hydrocarbon gases from the Boyle-Mariotte law for pressures P_r ($\alpha = 1/Z$) and P_{res} ($\alpha_{res} = 1$); P_{st} is the pressure under standard conditions ($P_{st} = 0.101325$ MPa); f is the correction for temperature to reduce the volume of gas to the standard temperature, $f = T_{st}/T_r$.

For the first time, gas reserves at the Zakhidne-Radchenkivs'ke field were credited to the State Balance in 2005. As of 01.01.2010, the initial total gas reserves decreased by 92.56 % compared to those listed on the State Balance Sheet [7]. The main reason for the actual failure to confirm the volume of gas reserves was a change in ideas about the structural and tectonic model of the structure of the Zakhidne-Radchenkivs'ke field [12].

To calculate the initial mining reserves at the Zakhidne-Radchenkivs'ke deposit, all known methods were used but the obtained values are very different (from 14 thousand to 424 million m^3) [8, 9]. The value of the reserves at the Zakhidne-Radchenkivs'ke gas condensate field has not been confirmed several times; at present, it is difficult to assess their true value. But most authors accept the value of gas reserves at the Zakhidne-Radchenkivs'ke gas condensate field to be within about hundreds of millions m^3 [7–9].

To make a decision on the further development of the Zakhidne-Radchenkivs'ke gas condensate field, it is important to assess the initial extractive reserves based on a new approach to the calculation of reserves. For example, by combining a volumetric method with the results of mathematical modeling of filtration processes in the layer B-26 [6].

5. Methods of research

Theoretical research methods include system analysis of the information used, numerical modeling based on the combined finite-element-difference method [6, 13], methods of visual representation of the information received, analytical methods.

This study was carried out for the gas reservoir at the Zakhidne-Radchenkivs'ke field. In the mathematical statement of the problem, the following assumptions are accepted: the effective thickness of the reservoir is a constant value and much smaller than the horizontal size of it, in which case the problem is considered two-dimensional. The permeability, porosity, viscosity, and super-compressibility coefficient of the gas, the initial reservoir pressure, as well as debit, are known and time-constant quantities. The problem assumes a single-phase flow (gas), then [6]:

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

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

$$k_b gradP^2 = \alpha(P^2 - P_b^2), \quad (4)$$

where (2) is the piezo conductivity equation; (3) is the initial condition; (4) is the boundary condition for the infiltration of fluid at the boundaries of the region in question; k_b is the

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gas phase permeability, m^2; μ is the dynamic viscosity of gas, Pa·s; m is the porosity of the gas-bearing layer, μm^2; P_0 is the initial pressure of the porous layer, Pa; α is the fluid infiltration coefficient at the boundaries of the region in question, m; P_b is the pressure at the boundaries of the region in question, Pa.

In this paper, to solve flat (two-dimensional) non-stationary problems of piezo conductivity, taking into consideration the heterogeneous distribution of permeability within the collector reservoir, a combined finite-element method is used [6, 13]. This method is implemented in the Fortran programming language. The algorithm for calculating the system of equations (2) to (4) by the finite-element-difference method is described in [6].

To solve the system of equations (2) to (4), the simulated area is split into 81 finite eight-node elements. The result of solving the Leibenzon piezo conductivity equation using the combined finite-element-difference method is the derived pressure values at all nodal points of the finite-element grid. According to the found nodal value, the pressure is determined at an arbitrary point of the hydrocarbon reservoir of the studied region at a predefined time.

The average reservoir pressure is determined by isobar maps (pressure distribution fields in Fig. 1). That is, the area between each two neighboring isobars is determined and the average reservoir pressure in this area is calculated as the arithmetic mean of the pressure values of the two adjacent isobars. This value is multiplied by the area between the isobars and summarized. The total amount is divided by the total area within which the calculation is carried out. The average reservoir pressure determined in this way is weighted average in the area of the reservoir.

The results of modeling the distribution of reservoir pressure around the well make it possible to draw conclusions about the radius of its feed circuit by applying an analytical formula for determining the debit of a gas well [11]. Since the debit value is known, one can derive the value of the radius of the well feed circuit:

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

where Q is the debit of the well, thousand m^3/s; μ is the coefficient of dynamic viscosity of gas, mPa·s; P_{atm} is the atmospheric pressure, 0.101325 MPa; k is the permeability coefficient, μm^2; h is the effective capacity of the reservoir, m; r_w is the reduced radius of the well, m; $P_{av.r}$ is the average reservoir pressure according to the results of modeling; P_{wel} is the wellbore pressure based on the results of modeling.

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

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

where r_w is the well radius by chisel, mm; C_1 and C_2 are the coefficients of imperfection in the degree and nature of opening, respectively.

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

where $\bar{h} = h_{op}/h_{ef}$ is the relative opening of the reservoir by the well; $\delta = 1.6(1-\bar{h}^2)$; $\bar{r}_w = r_w/h$ is the relative radius of the well.

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

where n is the number of perforation holes; R_0 is the hole radius; h_{ef} is the effective thickness of the layer.

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

Reserve calculation is carried out by the value of the radius of the well's feed circuit, which is determined by the values of pressures obtained as a result of modeling of filtration processes. That is, the calculated values of reserves are obtained on the basis of pressure values, which, in turn, are calculated by the combined finite-element-difference method.

Extractive reserves from the reservoir opened by one well No. 205 can be calculated according to formula (1), where:

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

where R_c is the radius of the feed circuit, m.

To calculate the coefficient of super-compressibility of gas, we use the analytical method according to [14]. This is a method based on the equation of the state of the gas with virial coefficients, which does not take into consideration the factor of eccentricity of molecules (that is, it is recommended for non-polar substances and for a mixture of gas with a molar concentration of high-boiling components less than 10 %). The value of the reduced pressure should be no more than 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]:

$$b_{mix}^* = \sum_{i=1}^{n} b_i^* x_i, \; a_{mix}^* = \sum_{i=1}^{n} a_i^* x_i. \quad (12)$$

The coefficients of equation (10) would determine its notation in the form of a cubic one, calculated using an online calculator for solving cubic equations [15], which produces one real root.

Thus, based on modeling the distribution of pressure in the reservoir, we determine the value of the radius of the well's feed circuit. Based on the resulting R_c, it is possible to calculate the extractive reserves of the reservoir opened by one mining well.

6. Research results

The initial data for the results of this study are given in Table 1. At a distance of 660 m from well No. 205, the zonal heterogeneity of the porous medium is set, which is assigned by a negative value of permeability (we simulate the influence of exploration well No. 203 [7] on changing the collector properties of the reservoir). Also, for the maximum approximation of the reservoir model to actual conditions, the negative values of permeability in places of tectonic disturbances were set [12].

According to [7, Table 3.1], the diameter of the operational column of well No. 205 is 168 mm. Therefore, it is quite likely that the productive thickness of the B-26 reservoir was chiseled, at a diameter of 215.9 mm (the choice of the nearest normalized chisel diameter according to GOST 20692-80). Then the diameter of the well on chisel d_w=215.9 mm, respectively, the radius r_w=107.95 mm. Reservoir B-26 was shot with cumulative punches Spiral Shogan 2 1/8″ (manufactured by CoreLab, America) in the range of 2914–2907 at 20 hole/m and in the range of 2923–2929 at 10 hole/m [7]. In total: 170 perforation holes n with a probable radius of R_0=5 mm. The calculation of the consolidated radius according to formulas (6) to (8) is given in Table 2.

The critical parameters of the gas in well No. 205 at the Zakhidne-Radchenkivs'ke gas condensate field are given in Table 3, where x_i is the molar share of the i-th gas component; P_{abs} and T are the critical parameters of the i-th component of gas (tabular values); $P_{cr.i}=x_i \cdot P_{abs}$ and $T_{cr.i}=x_i \cdot T$ are the pseudocritical parameters of the i-th component of the gas.

The results of our study in Fig. 1 show a change in the distribution of reservoir pressure near the extractive well depending on the amount of permeability and the type of isotropy of the gas-bearing reservoir ($P_{av.r}$ and P_w – the value of the average reservoir and wellbore pressure, respectively, MPa).

According to the results of modeling, after 6 months, the average reservoir pressure decreased from 29.82 to 10.89 MPa (the difference between Fig. 1, *a* and Fig. 1, *d*), which indicates a significant decrease in gas filtration within the range of the well.

Table 1

Initial data for modeling

Title, designation	Value	Measurement unit
The area of the gas-bearing formation S	1.2	km^2
Porosity coefficient m	0.16	–
Initial formation pressure p_0	$30.22 \cdot 10^6$	Pa
Reservoir temperature T_r	369.15	K
Coefficient of dynamic viscosity of gas μ at P_0 and T_r	$0.025 \cdot 10^{-3}$	Pa·s
Coefficient of super compressibility Z at P_0 and T_r	0.95	–
The compression ratio of the rock skeleton β_2	10^{-10}	Pa^{-1}
The average flow rate of the production well Q	160	thousand m^3/day
Effective gas-saturated layer thickness h_{ef}	10.4	m
The total thickness of the productive layer B-26 h_{op}	13.3	m
Permeability coefficient	2.315	μm^2
The gas saturation coefficient of the formation	0.74	s

Table 2

Calculation of the reduced radius of well No. 205

$\bar{h} = h_{op}/h_{ef}$	$\delta = 1.6(1-\bar{h}^2)$	$\bar{r}_w = r_w/h$	C_1	C_2	r_r, m
0.7820	0.6217	0.0082	2.1741	0.0122	0.012

Table 3

Calculation of pseudocritical parameters of gas well No. 205

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	0.83051	46.95	190.55	38.9924	158.2537
C_2H_6	0.05340	49.76	306.43	2.6572	16.3634
C_3H_8	0.01531	43.33	369.82	0.6634	5.6619
n-C_4H_{10}	0.00103	38.71	425.16	0.0399	0.4379
i-C_4H_{10}	0.00077	37.19	408.13	0.0286	0.3143
C_5H_{12+}	0.00020	34.35	469.65	0.0069	0.0939
N_2	0.06053	34.65	126.26	2.0974	7.6425
CO_2	0.03794	75.27	304.20	2.8557	11.5413
O_2	0.00031	51.80	154.78	0.0161	0.0480
–	–	–	–	P_{cr}=47.3576 kgf/cm^2 or 4.6442 MPa	T_{cr}=200.3569 K

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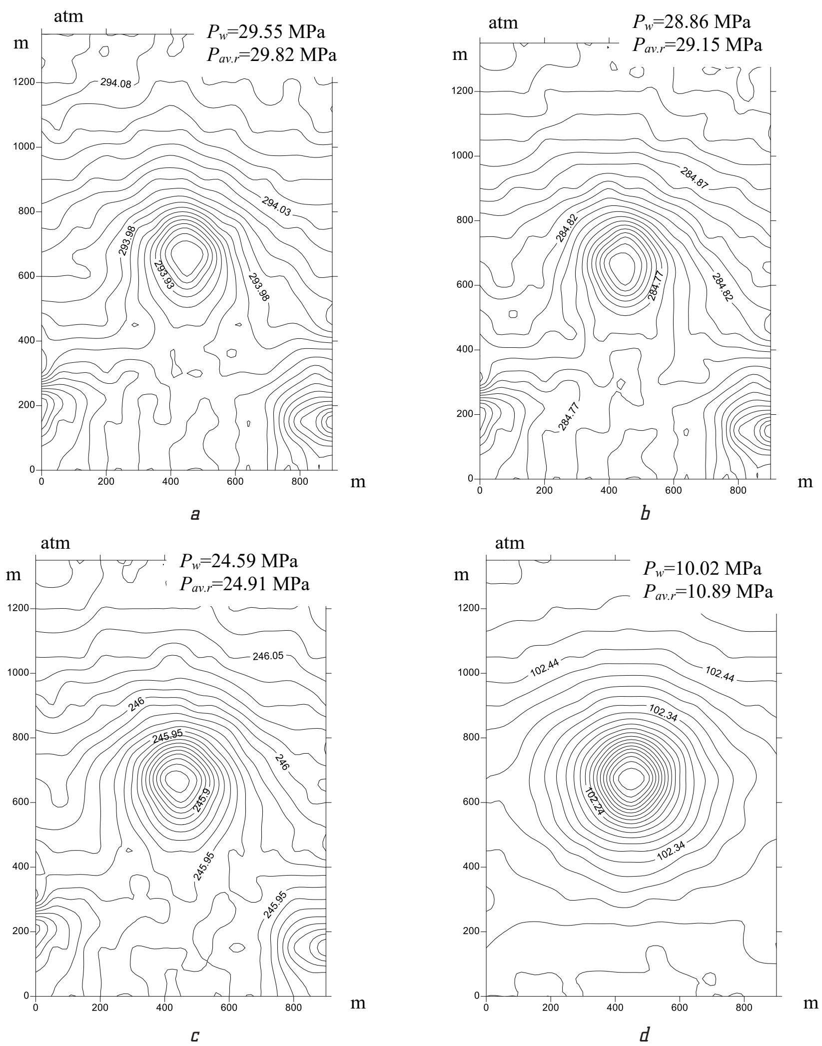

Fig. 1. Pressure distribution fields around well No. 205 at different operation duration: *a* – 10 days; *b* – 1 month; *c* – 3 months; *d* – 6 months

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

The calculation of the value of the radius of the feed circuit at different service life of well No. 205 according to formula (5) is given in Table 5.

According to our calculations (Table 5), the radius of the feed circuit of well No. 205 at the beginning of its operation (t=10 days) is 438.25 m and expands over time (at t=180 days, R_c=725.79 m).

Extractive reserves from layer B-26 in well No. 205, calculated according to formula (1), are given in Table 6.

Thus, the initial gas reserves at the Zakhidne-Radchenkivs'ke field are equal to V_e=174 million m^3 of gas. As one can see from Table 6, the value of the radius of the feed circuit depends on the well operation duration, but the initial gas reserves remain unchanged. Confirmation of the existence of a single value of extractive reserves (V_e=174 million m^3 of gas) under different well operation durations is a self-verification of the calculation.

Table 4

Calculation of the viscosity of gas in well No. 205 at reservoir pressures

Well operation time t, day	Average reservoir pressure P_r, MPa	$P_p=P_r/P_{cr}$	μ, sP (calculated from [14])
10	29.82	6.42	0.02486
30	29.15	6.28	0.02462
90	24.91	5.36	0.02292
180	10.89	2.34	0.01686

Table 5

Value of the radius of the well No. 205 feed circuit

Operation time of well No. 205, day	Average reservoir pressure according to the simulation results $P_{av.r.i}$, MPa	Wellbore pressure according to the simulation results $P_{wel.i}$, MPa	Coefficient of dynamic viscosity of gas μ_i, mPa·S	Value of the radius of the feed circuit of well $R_{c.i}$, m
10	29.82	29.55	0.02504	438.25
30	29.15	28.86	0.02474	443.25
90	24.91	24.59	0.02384	479.83
180	10.89	10.02	0.01966	725.79

Table 6

Calculation of gas reserves at the Zakhidne-Radchenkivs'ke field

Operation time of well No. 205, day	Average reservoir pressure according to the simulation results $P_{av.r.i}$, MPa	Coefficient of gas super compressibility Z_i	$\alpha_i = 1/Z_i$	Value of the radius of the feed circuit of well $R_{c.i}$, m	Gas reserves, $V_{e.i}$, million m^3
10	29.82	0.9458	1.057	438.25	174
30	29.15	0.9391	1.065	443.25	174
90	24.91	0.9054	1.104	479.83	174
180	10.89	0.8816	1.134	725.79	174

7. SWOT analysis of research results

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

Weaknesses. The weak side of the combined method of calculating extractive gas reserves is the possibility of its application for layers opened by one mining well.

Opportunities. In the future, it is of interest to devise a methodology for calculating gas reserves for multi-reservoir deposits, as well as in the presence of two or more extractive wells.

Threats. This level of research does not require additional costs when implementing the results.

8. Conclusions

1. The mathematical statement of the non-stationary heterogeneous problem of gas filtration given in our work includes the following:

– the non-stationary heterogeneous equation of Leibenzon piezo conductivity;

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

– the boundary condition that takes into consideration the infiltration of fluid across the boundaries of the studied area.

2. To solve the non-stationary heterogeneous filtration problem of Leibenzon, a combined finite-element-difference method was used [6, 13], which makes it possible to take into consideration the heterogeneous distribution of filtration and capacitive characteristics of the reservoir (within the framework of this study, the zonal heterogeneity was given by a negative value of the permeability coefficient). With the help of the applied method, it is possible to describe adequately at the quantitative level the distribution of pressure in the gas-saturated reservoir opened by the mining well.

3. Using the fields of the distribution of reservoir pressure derived from modeling, we have calculated the value of the radius for the well's feed circuit. According to calculations, the radius of the feed circuit of well No. 205 at the beginning of its operation (t=10 days) is 438.25 m and expands over time (at t=180 days, R_c=725.79 m).

4. Based on the radius of the feed circuit of single well No. 205, the active area and volume of the B-26 reservoir have been calculated. Using a volumetric method for calculating reserves in combination with the results of the simulation has made it possible to estimate gas reserves at V_e=174 million m^3.

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