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IMPROVING THE DEVELOPMENT PROCESS OF TWO HYDRODYNAMICALLY ISOLATED LAYERS WITH DIFFERENT PERMEABILITIES UNDER JOINT DEVELOPMENT CONDITIONS USING A SINGLE WELL GRID

The object of research is the filtration processes observed in the process of joint development of two hydrodynamically isolated different permeability layers by a single well grid. The subject of research is the interaction of different permeability, hydrodynamically isolated layers (upper low permeability k_1 and lower high permeability k_2) in the process of development of a two-layer deposit in the presence of an impermeable membrane between the layers.

The research solved the problem of the influence of the permeability ratio on the final values of gas flow rates, layer pressure, gas recovery coefficients and the duration of the deposit development.

The work is aimed at studying the features of gas recovery from two different permeability layers with an impermeable membrane, which are developed by a single well grid.

During the research, the influence of the permeability ratio of the layers ($n = k_2/k_1$) of the two-layer deposit on the final gas recovery coefficient was determined. It was established that with an increase in the value of n, the high permeability layer is depleted more intensively and is disconnected from development faster. Thus, at the final stage of development for $n = 10$ in a high-permeability layer, the layer pressure is 3.00 MPa, and in a low-permeability layer – 4.77 MPa. The gas recovery coefficient for a low-permeability layer for $n = 10$ is only 83.94%, and for a high-permeability layer – 90.11%. Increasing gas recovery can be achieved by transferring wells to simultaneous-separate operation at a certain stage of development, by carrying out treatments of bottomhole zones of low-permeability layers.

The results obtained can be effectively used in the joint development of two hydrodynamically isolated different-permeability layers with joint development by a single well grid. This allows to increase the gas recovery coefficient and the efficiency of further development of two different-permeability layers with an impermeable membrane.

Keywords: *field, modeling, permeability, gas recovery coefficient, layer pressure, gas flow rate, impermeable membrane.*

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1. Introduction

The current state of the Ukrainian oil and gas industry is characterized by the fact that most natural hydrocarbon deposits are at the stage of depletion. This requires the introduction of new technologies to support planned hydrocarbon production. This period is characterized by a significant decrease in layer pressure, waterlogging of productive layers and a progressive decrease in well rates. In conditions of a shortage of investment resources and the high cost of drilling new wells, the intensification of the use of the existing well fund by involving the development of multi-layer deposits is of particular importance.

Simultaneous exploitation of several hydrodynamically isolated layers by a single well grid is a highly effective technological solution. This ensures the optimization of capital investments and a reduction in the project payback period.

The practical implementation of the technology of joint development of layers by a single well grid is accompanied by a number of complex scientific and technical challenges. First of all, they are caused by the significant geological and physical heterogeneity of the productive section, which creates the prerequisites for uneven production of hydrocarbon reserves. The most critical factor is the difference in the filtration-capacity properties (FCP) of the combined layers. With a significant difference in the permeabilities of the layers, the phenomenon of interference occurs. In the case when a high-permeability layer provides the main production of hydrocarbons, the low-permeability layer is exploited inefficiently. As a result, this leads to a decrease in the final gas recovery coefficient [1, 2].

Therefore, the priority scientific task is to create hydrodynamic models capable of predicting the mutual influence of hydrodynamically isolated layers in the process of their joint development, which will allow determining the optimal parameters of well operation for each specific scenario.

The problem of effective further development of multi-layer deposits remains one of the most complex and relevant tasks of today. The complex structure of such deposits, characterized by significant layer-by-layer heterogeneity and different energy regimes of individual interlayers, requires a detailed research of the interaction of the "layer – well" system. Analysis of world experience and fundamental works shows that ignoring the individual characteristics of each layer leads to significant errors in predicting hydrocarbon production [3, 4].

In paper [5], the transient characteristics of multi-layer deposits were investigated and, in their researches, they demonstrated the dependence of the gas flow rate of an individual layer on the value of the product of permeability and layer thickness (*kh*) of each interlayer. In multi-layer deposits, it is the ratio *kh* that determines not only the current production, but also the dynamics of interlayer flows. In layers with higher permeability, the pressure decrease occurs faster, which creates a pressure gradient between the layers and can lead to the phenomenon of "reverse flow" of gas into less permeable layers during well shutdown.

In [6], all the key operational characteristics of layered systems without interlayer flows operating in the depletion mode (pseudo-steady filtration) were investigated. In particular, it was found that the absence of hydrodynamic communication between the layers leads to an autonomous decrease in the layer pressure in each of them. This causes uneven depletion of the energy of the layers, where the rate of pressure decrease is inversely proportional to the gas reserves in a particular layer.

In [7], a model was developed to reconcile production data from a layered system without flows in the depletion mode, using a combination of material balance equations and pseudo-steady flow equations for each individual layer. This approach allowed the total production from the well to be divided into partial flows of each layer, which makes it possible to estimate the initial hydrocarbon reserves and the productivity coefficient for each layer separately.

In [8], layer properties and gas reserves for layered layers without overflows under variable bottomhole pressure were estimated. The main task of these researches was to perform a retrospective analysis (History Matching) of actual production data, which made it possible to identify the energy state of each layer separately. This is critically important for choosing the optimal strategy for further development of deposits that are at the final stage of hydrocarbon extraction.

The impact of heterogeneity on dynamic reserves using the material balance method for multi-layered deposits was analyzed in [9]. It was found that without taking into account the individual characteristics of each layer, the material balance method is subject to change. At the initial stages of field development, dynamic reserves are overestimated. At a later stage, when less permeable layers come into operation, dynamic reserves are underestimated.

The dynamic reserves of a multilayer gas field were investigated in [10], on the basis of which it was established that due to the significant number of thin layers and their high heterogeneity, traditional methods of material balance give an error of up to 15–20%. A method for taking into account the nonlinear pressure drop in the system was proposed, which made it possible to specify the volumes of drained reserves for each operational object under conditions of active manifestation of the water pressure regime.

In [11], the backpressure equation (BPE) for wells exploiting layered gas layers with or without hydrodynamic connection is presented. As a result of the researches, it was proven that for such systems the classical power exponent *n* in the inflow equation is not a constant, but varies depending on the degree of depletion of each layer. The proposed equation allows to correctly model the nonlinear behavior of the inflow under conditions of significant permeability contrast, taking into account the redistribution of pressures between the layers through the wellbore.

In paper [12], all the key operational characteristics of multilayer deposits without interlayer crossflows operating in the depletion mode were studied. It was found that in layers without interlayer crossflows (no-crossflow), each layer is depleted at its own rate, which directly depends on its permeability and pore volume. This leads to the fact that over time, highly permeable layers are depleted faster, and the main production is transferred to less permeable layers.

An integrated workflow for assessing and understanding well performance in "mature" multi-layer gas fields was developed in [13]. This approach is based on a combination of Decline Curve Analysis (DCA). This algorithm allows for rapid identification of layers that have stopped operating due to waterlogging or low layer pressure, and for making informed decisions regarding repair and isolation work or intensification of hydrocarbon inflow.

Thus, the analysis of the above researches shows that most existing models are based on well operation under constant bottomhole pressure. This does not fully reflect the real specifics of multi-layer gas field development. Therefore, it is advisable to study the features of joint development by a single well grid of a two-layer gas field, represented by hydrodynamically isolated layers with significantly different filtration and capacity properties (differently permeable layers).

The object of research is the filtration processes observed in the process of joint development of two hydrodynamically isolated different permeability layers by a single well grid.

The aim of research is to improve the process of development of two hydrodynamically isolated different permeability layers in the conditions of joint development of a single well grid.

To do this, it is necessary to solve the following objectives:

- to investigate the influence of the permeability ratio of two hydrodynamically isolated different permeability layers on the values of layer pressure and the final gas recovery coefficient;
- to investigate the influence of the permeability ratio of two hydrodynamically isolated different permeability layers on the duration of the gas recovery process.

The implementation of the studied approach will allow oil and gas institutions to more accurately predict the dynamics of depletion of multi-layered deposits, optimize the parameters of joint production of hydrocarbons from different permeability layers and increase the gas recovery coefficient.

2. Materials and Methods

The research of the patterns of joint development by a single well grid of a two-layer gas field with hydrodynamically isolated different permeability layers was carried out using the example of a heterogeneous model of a square-shaped gas deposit with a side of a square of 2000 m.

The main parameters of the field: average depth – 2085 m; initial layer pressure in the middle of the first layer 1 – 29.87 MPa; initial layer pressure in the middle of the second layer 2 – 29.96 MPa; layer temperature in the middle of the first layer 1 – 69.59°C; layer temperature in the middle of the second layer 2 – 69.78°C; initial gas saturation coefficient – 0.8.

The deposit consists of two layers, the effective gas-saturated thickness is 80 m, the thickness of each layer is 40 m. Between the two layers there is an impermeable membrane 5 m thick (the entire thickness of the layer is 85 m). The permeability of the first (upper) low-permeable layer 1 across and along the bedding (along the *X* and *Y* axes) is in different calculation options, respectively – 10; 12.5; 16.7; 25; 50; 100 mD; in the vertical direction (along the *Z* axis) – 1.0; 1.25; 1.67; 2.5; 5.0; 10 mD; the porosity coefficient is 0.12. The permeability of the second (lower) high-permeable layer *2* across and along the bedding (along the *X* and *Y* axes) is 100 mD; in the vertical direction (along the *Z* axis) – 10 mD; porosity coefficient – 0.12.

The field is developed by five wells (Fig. 1): four wells located in a square grid with a distance between them of 2000 m and one central well.

Pump-compressor pipes with an internal diameter of 0.062 m are lowered to the middle of the upper layer *1* to a depth of 2020 m.

The technological mode of operation of the wells is a constant gas flow rate with a transition to a constant pressure mode at the wellhead after reaching the minimum permissible wellhead pressure of 1.5 MPa.

The initial flow rate of one well from both layers was 200 thousand m^3/day. The initial gas flow rates from individual layers are given in Table 1.

The initial gas reserves of each layer are 3934568320 m^3 (3.935 billion m^3). The research was performed using licensed software Petrel & Eclipse (SLB, France).

To analyze the forecasting of joint development indicators by a single well grid of two-layer deposits with different permeability layers, studies of the influence of the heterogeneity of the layers n were performed. The nature of the heterogeneity indicator directly affects the dynamics of layer pressure, the final gas recovery rate and the duration of the layer development period.

Fig. 1 shows the distribution of permeability across layers in a two-layer gas deposit.

Table 1

Initial gas flows from individual layers

No.	k_1, mD	k_2, mD	$N = k_2/k_1$	q_1, thousand m^3/day	q_2, thousand m^3/day
1	100	100	1	100.0	100.0
2	50	100	2	71.0	129.0
3	25	100	4	46.5	153.5
4	16.7	100	6	35.4	164.6
5	12.5	100	8	29.0	171.0
6	10	100	10	24.5	175.5

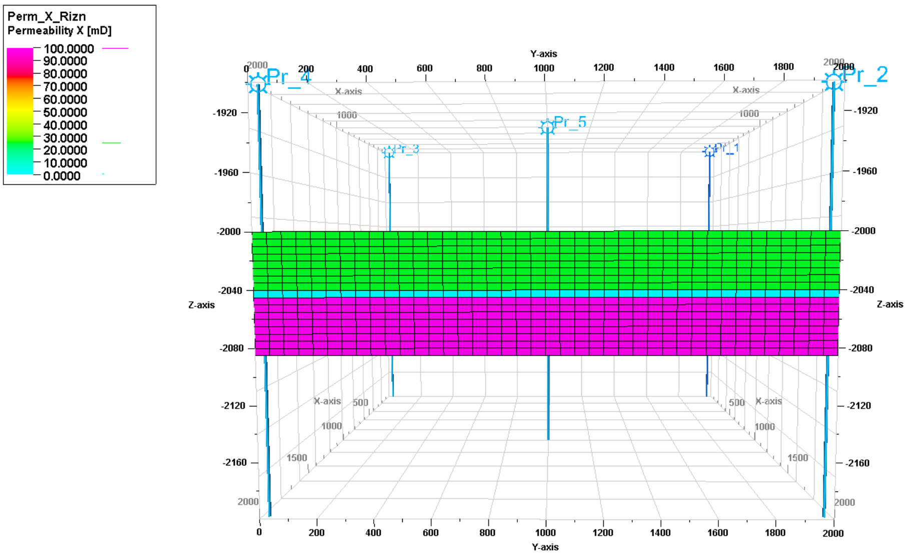


Fig. 1. Distribution of permeability by layers in a two-layer gas field

The development of the deposit was started on 01.01.2023 using five production wells. The development of the deposit was carried out to exhaustion under the technological mode of operation of the wells of constant gas flow, and in case of impossibility of its provision due to a decrease in layer energy – by switching to a constant wellhead pressure mode (1.5 MPa). The research results were recorded at the time of reduction of layer pressure to 0.1 of the initial pressure P_{in2} in the lower high-permeability layer *2*; at the time of reduction of layer pressure to 0.1 of the initial pressure P_{in1} in the upper low-permeability layer *1*; at the time of reaching a gas flow rate in one well of 10 thousand m^3/day and at the time of reaching a gas flow rate in one well of 5 thousand m^3/day.

Using the research results, graphical dependences of the dynamics of layer pressure and gas recovery coefficient for different values of the layer permeability ratio ($n = k_2/k_1$) and graphical dependences of layer pressure and gas recovery coefficient on the layer permeability ratio at the time of reducing the layer pressure to $0.1P_{in2}$ in the lower layer *2*; at the time of reducing the layer pressure to $0.1P_{in1}$ in the upper layer *1*; at the time of achieving a gas flow rate in one well of 10 thousand m^3/day and at the time of achieving a gas flow rate in one well of 5 thousand m^3/day.

3. Results and Discussion

3.1. Investigation of the influence of the permeability ratio of two hydrodynamically isolated differently permeable layers on the values of layer pressure and final gas recovery coefficient

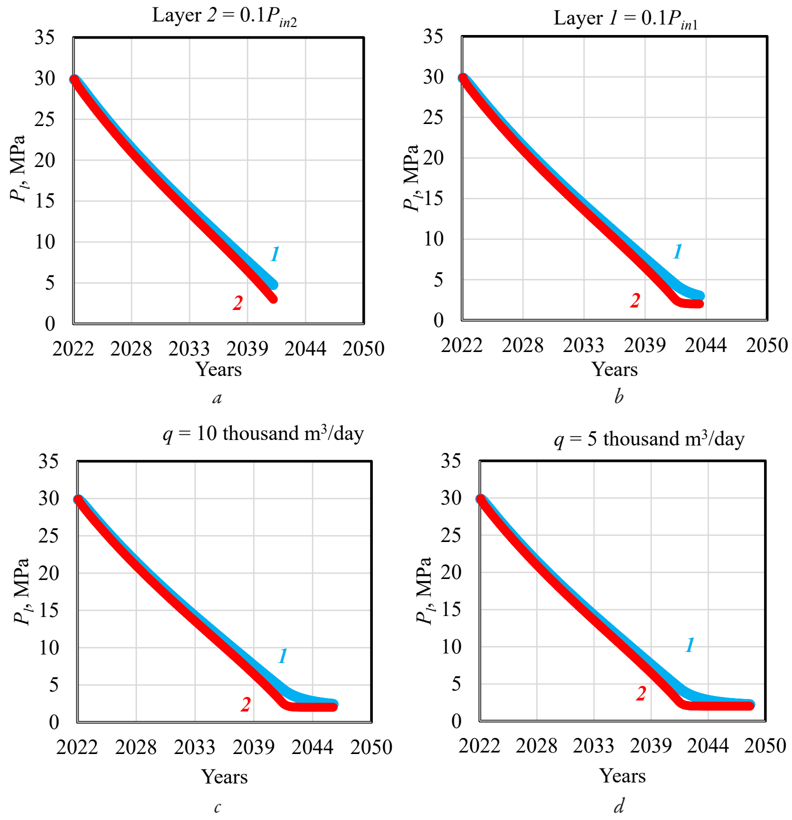
Fig. 2 shows the dynamics of layer pressure for a layer permeability ratio of $n = 10$, and Fig. 3 – for the ratio of layer permeabilities $n = 2$ at the moment of decreasing the layer pressure to $0.1P_{in2}$ in the lower layer *2*, at the moment of decreasing the layer pressure to $0.1P_{in1}$ in the upper layer *1*, at the moment of reaching the gas flow rate in one well of 10 thousand m^3/day and at the moment of reaching the gas flow rate in one well of 5 thousand m^3/day.

Analysis of dependencies (Fig. 2, 3) indicates a depletion process in a two-layer deposit with different permeability layers, which has two stages. The first stage corresponds to the period of operation of wells with a constant gas flow rate, and the second stage – the operation of wells with a constant wellhead pressure. At the time of the field's development, the layer pressure in the lower layer *2* was 29.92 MPa, and in the upper layer *1* – 29.856 MPa.

The main feature of the results obtained is the obtained regularity that with a significant difference in permeabilities ($n = 2$ and $n = 10$) the dynamics of layer pressure changes in both layers has the same nature. However, the duration of the field development is different. During the field development, the layer pressure decreases faster in the high-permeability layer *2* and slower in the low-permeability layer *1*. An important difference in the results is that with the heterogeneity of $n = 10$, the moment of transition to the constant wellhead pressure regime occurs 8 months earlier than with $n = 2$. This indicates a faster depletion of the high-permeability layer.

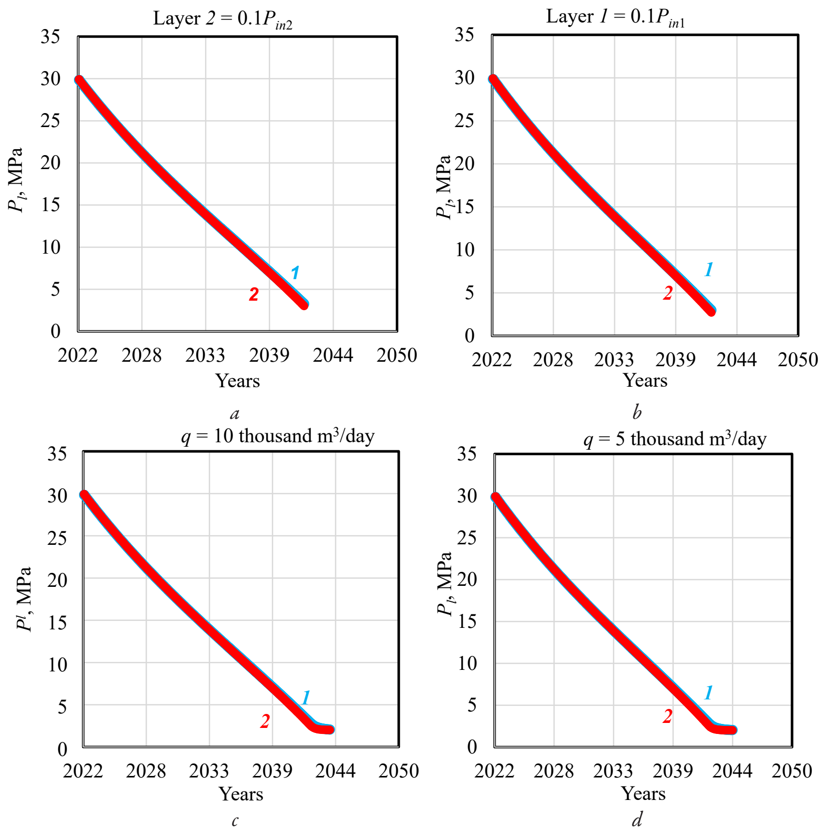
The obtained research results are consistent with the classical dependencies of underground hydro-gas mechanics, i. e., layers with high permeability are depleted first. However, the obtained researches, unlike the usual analytical dependencies, take into account specific economic profitability (reducing the flow rate to 10 and 5 thousand m^3/day). This allows for more accurate prediction of the development indicators of multi-layer deposits with different permeability layers.

The modeling of the development processes was performed with an initial difference in layer pressures of 0.073 MPa and in the absence of active flow between the layers through a low-permeability membrane. The research results are limited by the values of the layer heterogeneity ($n = 2$ and $n = 10$).



a *b* *c* *d*

Fig. 2. Dynamics of layer pressure for the ratio of layer permeability $n = 10$:
a – at the moment of decreasing layer pressure to $0.1P_{in2}$ in the lower layer *2*; *b* – at the moment of decreasing layer pressure to $0.1P_{in1}$ in the upper layer *1*; *c* – at the moment of reaching a gas flow rate in one well of 10 thousand m^3/day; *d* – at the moment of reaching a gas flow rate in one well of 5 thousand m^3/day; *1* – upper layer; *2* – lower layer

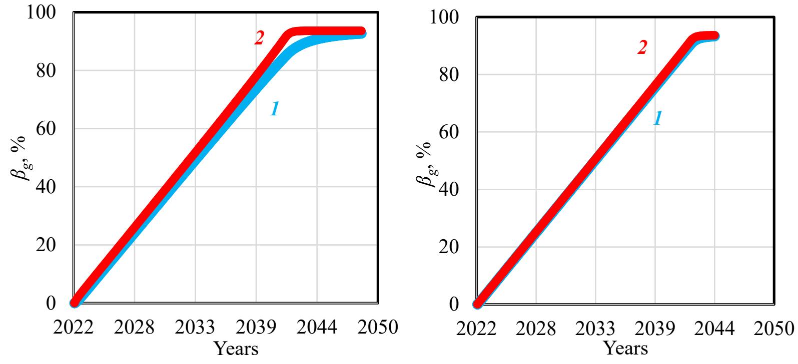


a *b* *c* *d*

Fig. 3. Dynamics of layer pressure for the ratio of layer permeability $n = 2$:
a – at the moment of decreasing layer pressure to $0.1P_{in2}$ in the lower layer *2*; *b* – at the moment of decreasing layer pressure to $0.1P_{in1}$ in the upper layer *1*; *c* – at the moment of reaching a gas flow rate in one well of 10 thousand m^3/day; *d* – at the moment of reaching a gas flow rate in one well of 5 thousand m^3/day; *1* – upper layer; *2* – lower layer

Fig. 4 shows the dynamics of the gas recovery coefficient for the values of the layer permeability ratio $n = 2$ and $n = 10$ at the time of reaching a gas flow rate of 5 thousand m^3/day in one well.

The results of research into the regularities of the process of developing a two-layer gas field with different permeability layers with an impermeable membrane between them under different characteristics of the layers at the moment of reducing the layer pressure to $0.1P_{in2}$ in the lower layer *2*; at the moment of reducing the layer pressure to $0.1P_{in1}$ in the upper layer *1*; at the moment of reaching a gas flow rate in one well of 10 thousand m^3/day and at the moment of reaching a gas flow rate in one well of 5 thousand m^3/day are given in Table 2 and shown in Fig. 5, 6.



a *b*

Fig. 4. Dynamics of gas recovery coefficient at the moment of reaching a gas flow rate in one well of 5 thousand m^3/day:
a – $n = 10$; *b* – $n = 2$; *1* – upper layer; *2* – lower layer

Table 2

Research results into the regularities of the process of developing a two-layer gas field with different permeability layers with an impermeable membrane

At the moment of reduction of layer pressure to $0.1P_{in2}$ in the lower layer *2*									
$n = k_2/k_1$, times	Layer *1*, k_1, mD	Layer *2*, k_2, mD	Layer *1*		Layer *2*		Field development time, months	Gas flow rate, thousand m^3/day	
			β_{g1}, %	P, MPa	β_{g2}, %	P_1, MPa		Layer *1*	Layer *2*
1	100	100	90.11	3	90.11	3	233	100	100
2	50		89.07	3.266	90.11	3	232	96.54	103.46
4	25		87.62	3.717	90.11	3	230	93.00	107.00
6	16.7		86.23	4.12	90.11	3	228	90.66	109.34
8	12.5		85.07	4.427	90.11	3	227	88.74	111.46
10	10		83.94	4.772	90.11	3	225	87.66	112.34
At the moment of reduction of layer pressure to $0.1P_{in1}$ in the upper layer *1*									
$n = k_2/k_1$, times	Layer *1*, k_1, mD	Layer *2*, k_2, mD	Layer *1*		Layer *2*		Field development time, months	Gas flow rate, thousand m^3/day	
			β_{g1}, %	P, MPa	β_{g2}, %	P_1, MPa		Layer *1*	Layer *2*
1	100	100	90.11	3	90.11	3	233	100	100
2	50		90.11	3	91.266	2.712	234	94.42	98.84
4	25		90.11	3	92.901	2.223	238	65.06	47.16
6	16.7		90.11	3	93.456	2.057	243	43.36	10.18
8	12.5		90.11	3	93.582	2.02	248	34.20	2.52
10	10		90.11	3	93.621	2.01	255	26.86	0.44
At the moment of reaching the gas flow rate in one well q = 10 thousand m^3/day									
$n = k_2/k_1$, times	Layer *1*, k_1, mD	Layer *2*, k_2, mD	Layer *1*		Layer *2*		Field development time, months	Gas flow rate, thousand m^3/day	
			β_{g1}, %	P, MPa	β_{g2}, %	P_1, MPa		Layer *1*	Layer *2*
1	100	100	93.546	2.029	93.546	2.029	252	5	5
2	50		93.2	2.075	93.601	2.015	256	8.58	1.78
4	25		92.81	2.189	93.621	2.010	263	9.54	0.46
6	16.7		92.57	2.262	93.621	2.010	272	9.68	0.32
8	12.5		92.29	2.345	93.621	2.010	279	9.80	0.20
10	10		92.19	2.375	93.623	2.000	285	10	$12 \cdot 10^{-4}$
At the moment of reaching the gas flow rate in one well q = 5 thousand m^3/day									
$n = k_2/k_1$, times	Layer *1*, k_1, mD	Layer *2*, k_2, mD	Layer *1*		Layer *2*		Field development time, months	Gas flow rate, thousand m^3/day	
			β_{g1}, %	P, MPa	β_{g2}, %	P_1, MPa		Layer *1*	Layer *2*
1	100	100	93.612	2.017	93.612	2.017	256	2.5	2.5
2	50		93.33	2.038	93.621	2.01	262	4.24	0.76
4	25		93.15	2.093	93.623	2.00	275	5	0
6	16.7		93.00	2.136	93.623	2.00	288	5	0
8	12.5		92.86	2.179	93.623	2.00	300	5	0
10	10		92.71	2.225	93.623	2.00	310	5	$6 \cdot 10^{-5}$

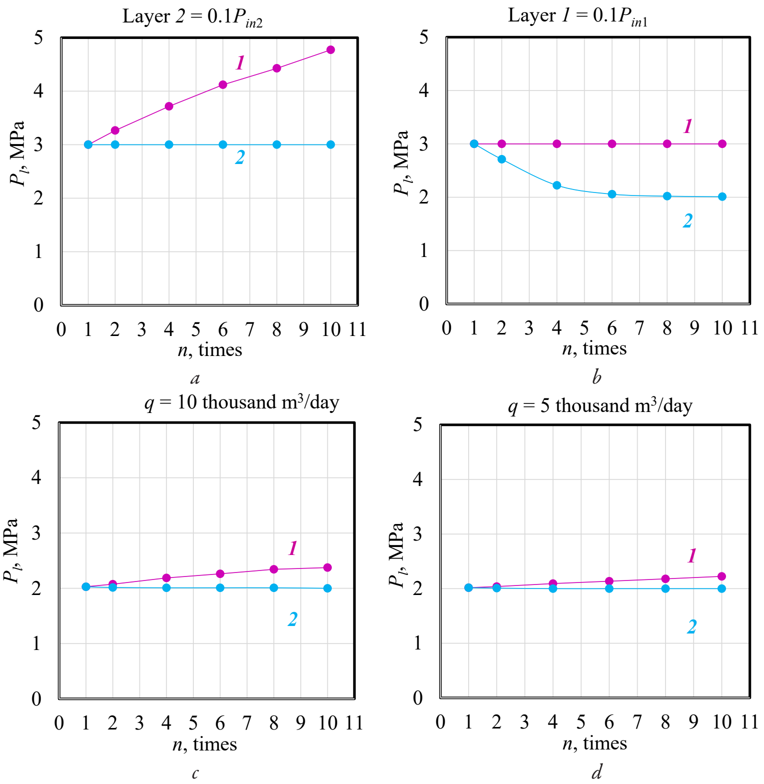


Fig. 5. Dependences of layer pressure on the ratio of layer permeability:
a – at the time of reducing layer pressure to 0.1P_{in2} in the lower layer *2*; *b* – at the time of reducing layer pressure to 0.1P_{in1} in the upper layer *1*; *c* – at the time of achieving a gas flow rate in one well of 10 thousand m^3/day; *d* – at the time of achieving a gas flow rate in one well of 5 thousand m^3/day; *1* – upper layer; *2* – lower layer

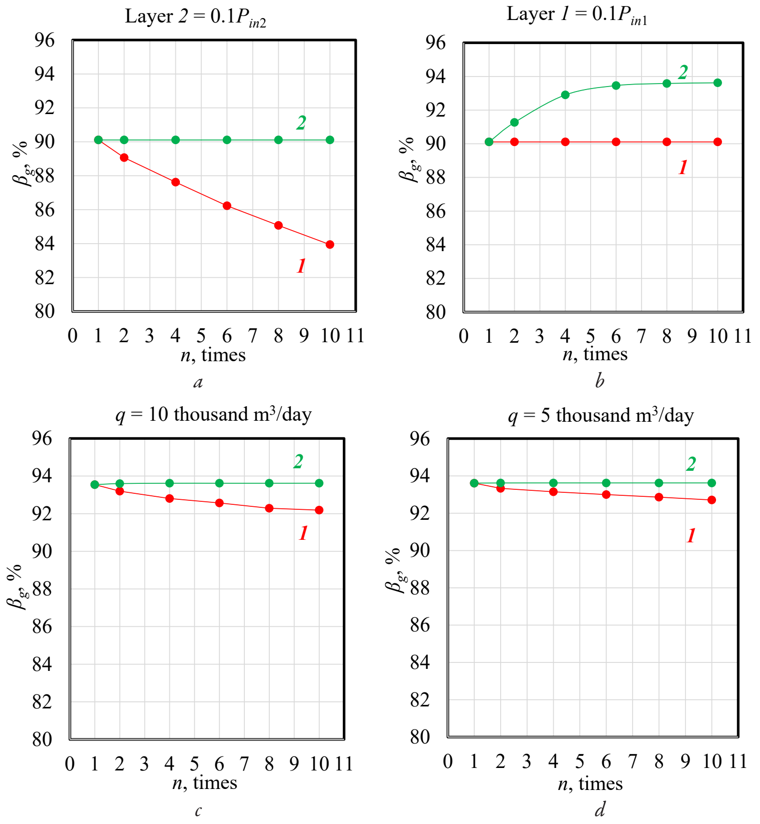


Fig. 6. Dependences of the final gas recovery coefficient on the ratio of layer permeability:
a – at the time of reducing layer pressure to 0.1P_{in2} in the lower layer *2*; *b* – at the time of reducing layer pressure to 0.1P_{in1} in the upper layer *1*; *c* – at the time of achieving a gas flow rate in one well of 10 thousand m^3/day; *d* – at the time of achieving a gas flow rate in one well of 5 thousand m^3/day; *1* – upper layer; *2* – lower layer

Based on the presented results, the influence of the permeability ratio of individual layers $n = k_2/k_1$ on the final values of the layer pressure, gas recovery coefficient and gas flow rate and the duration of field development at fixed points in time was estimated (Table 2, Fig. 5, 6).

The research results show that in a high-permeability layer, the layer pressure decreases much faster than in a low-permeability layer. According to the results of the calculations, the gas inflow from the lower layer *2* stops at $n = 2$, when the layer and bottomhole pressures practically equalize ($P_{l2} = 2.000$ MPa, $P_{bot2} = 1.998$ MPa). On the specified date, the ratio between the bottomhole pressures in the two layers obeys the barometric formula (Laplace-Babinet equation [14]).

At minimum gas flow rates (5 thousand m^3/day), the highly permeable layer *2* completely stops working already at heterogeneity $n \geq 2$ (the flow rate decreases to zero or is $6 \cdot 10^{-5}$ thousand m^3/day). At higher gas flow rates (10 thousand m^3/day), the highly permeable layer *2* continues to work, but at high heterogeneity values $n = 10$, the gas flow rate also decreases ($12 \cdot 10^{-4}$ thousand m^3/day). At the moment of decreasing the layer pressure in the lower layer *2* to $0.1P_{in2}$ from the initial pressure (3 MPa), the gas recovery coefficient from this layer is 90.11%. With an increase in the ratio n from 1 to 10, the gas flow rate from the lower layer *2* increases from 100 to 112.34 thousand m^3/day, and from the upper layer *1* decreases from 100 to 87.66 thousand m^3/day, the gas recovery rate from the upper layer 1 decreases from 90.11 to 83.94%. The duration of the field development decreases from 233 to 225 months. At the time of the decrease in the layer pressure in the upper layer *1* to $0.1P_{in1}$ from the initial pressure (3 MPa), the gas recovery rate from this layer is 90.11%. With an increase in the ratio n from 1 to 10, the gas flow rate from the lower layer *2* decreases from 100 to 0.44 thousand m^3/day, and from the upper layer *1* – from 100 to 26.86 thousand m^3/day, the gas recovery ratio from the lower layer *2* increases from 90.11 to 93.621%. The duration of the field development increases from 233 to 255 months.

After the actual stop of the high-permeability layer *2*, the development continues at the expense of the low-permeability layer *1*. This leads to a decrease in the total bottomhole pressure, which creates additional depression. Additional depression contributes to partial drainage of residual gas from the high-permeability layer *2*.

For a two-layer field with different permeability layers, there is a certain critical value of the layer heterogeneity. At this value, the development of the high-permeability layer *2* is completely stopped at a given wellhead pressure.

Unlike general theoretical dependencies, the researches have established precise limits. For example, with a total gas flow rate from one well from both layers of 10 thousand m^3/day and $n = 4$, the gas flow rate from high-permeability layer *2* is 0.46 thousand m^3/day. At the same time, the gas flow rate from low-permeability layer *1* is 9.54 thousand m^3/day.

The research results indicate the absence of gas flows between the layers during their development by a common grid of wells. The layer pressure decreases more intensively in high-permeability layer *2* and this layer is disconnected from development faster. Thus, the relationship between the two layers occurs only through the wellbore due to the interference of bottomhole pressures.

The obtained results mainly confirm the well-known statements of the development of oil and gas fields, which indicate the uneven extraction of hydrocarbons during joint exploitation.

Known methods consider layers with averaged parameters or analyze the development process without taking into account the hydrostatic pressure of the gas column. In contrast to these methods, the Laplace-Babine equation is used in the work. This equation makes it possible to take into account gravitational forces in the wellbore. The research results show that at the time of reaching a gas flow rate of 10 thousand m^3/day from one well for $n = 10$, the gas recovery coefficient decreases from 93.612 to 92.71%. This indicates gas losses due to imperfect joint development of two layers with different permeability.

3.2. Investigation of the influence of the permeability ratio of two hydrodynamically isolated different permeability layers on the duration of the gas production process

Fig. 7 shows the dependence of the duration of the field development period on the permeability ratio of the layers at fixed points in time.

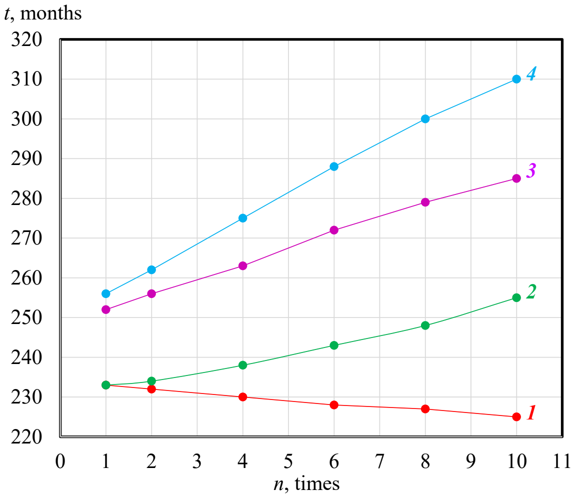


Fig. 7. Dependences of the duration of the field development period on the ratio of layer permeabilities at fixed points in time: *1* – at the time of reduction of the layer pressure to $0.1P_{in1}$ in the lower layer *2*; *2* – at the time of reduction of the layer pressure to $0.1P_{in1}$ in the upper layer *1*; *3* – at the time of reaching the gas flow rate in one well of 10 thousand m^3/day; *4* – at the time of reaching the gas flow rate in one well of 5 thousand m^3/day

According to the research results (Fig. 7), the duration of the field development increases with an increase in the degree of heterogeneity of the layers in terms of permeability. The increase in the duration of the field development at fixed points in the researches with an increase in n is due to the fact that the low-permeable layer *1* determines a long period of the final stage of development, which requires long-term operation of the wells at low wellhead pressures.

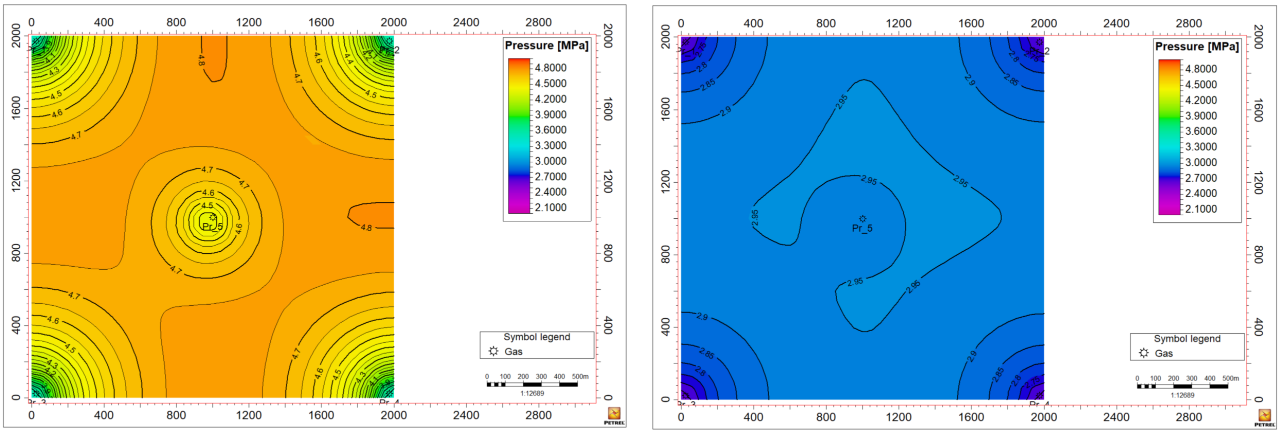
Fig. 8 shows pressure distribution maps for the upper layer 1 and the lower layer *2* at the moment of decreasing the layer pressure to $0.1P_{in2}$ in the lower layer *2* for the ratio of layer permeabilities $n = 10$, and Fig. 9 shows pressure distribution maps for the upper layer *1* and the lower layer *2* at the moment of reaching a gas flow rate from one well of 5 thousand m^3/day for the ratio of layer permeabilities $n = 10$.

Visualization of the 3D distribution of layer pressure in Fig. 8 confirms the significant unevenness of the depletion of the field: while the lower layer *2* (Fig. 8, *b*) is almost completely depleted to a level of 3 MPa ($0.1P_{in2}$), high pressure zones (over 4.7 MPa) remain in the upper layer *1* (Fig. 8, *a*).

The depression funnels formed on the isobar maps indicate that due to the low permeability of layer *1*, filtration flows do not have time to compensate for gas withdrawal. This leads to the localization of significant residual reserves outside the well drainage zones. This clearly demonstrates the need to revise the well grid or implement inflow intensification methods specifically for the upper layer *1* to equalize the degree of depletion of both layers.

Unlike the usual calculations given in the table, the work obtained three-dimensional graphical dependencies that clearly show the zones where unextracted gas is located in the low-permeability layer.

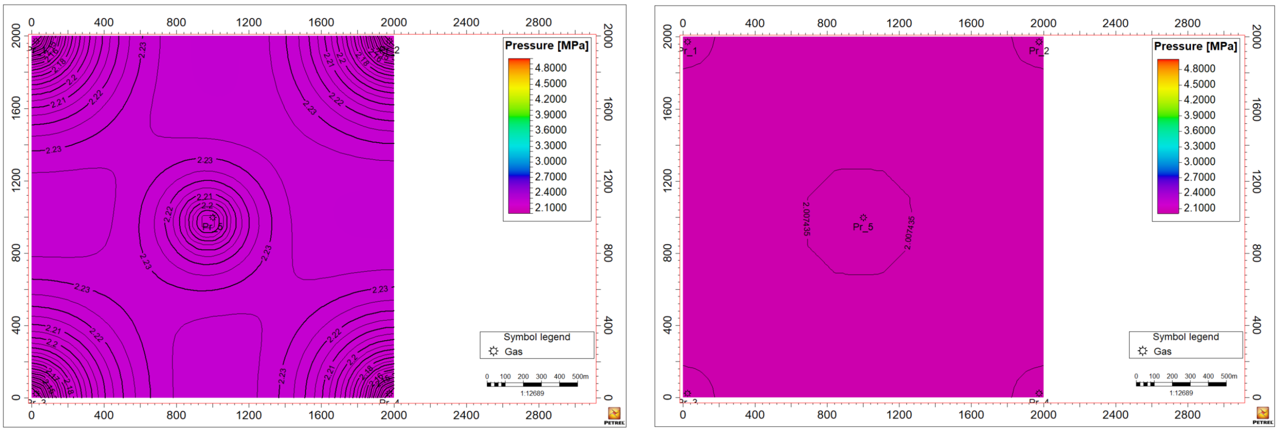
The obtained dependencies (Fig. 7) are consistent with the known principles of filtering the heterogeneity of multilayer deposits. The theoretical data state that with the joint exploitation of layers with heterogeneity of 4–10 times, low-permeability layers remain unextracted.



a

b

Fig. 8. Pressure distribution maps at the moment of layer pressure reduction to $0.1P_{in2}$ in the lower layer *2* for the layer permeability ratio $n = 10$: *a* – for the upper layer *1*; *b* – for the lower layer *2*



a

b

Fig. 9. Pressure distribution maps at the time of reaching a gas flow rate of 5 thousand m^3/day from one well for a ratio of layer permeability $n = 10$: *a* – for the upper layer *1*; *b* – for the lower layer *2*

The data of the research demonstrate the accuracy of the duration of the deposit development period for different degrees of heterogeneity of layers in terms of permeability. For the first time, pressure distribution maps were constructed for this model at the moment of reaching the critical gas flow rate (5 thousand m^3/day). This allows to estimate the residual unextracted gas reserves at the limit of the economically profitable gas flow rate.

Pressure distribution maps are constructed for a field with the same number of wells throughout the development period of a two-layer field. The 3D modeling was performed without taking into account the possibility of one or more wells being shut down for a certain period of time, which could affect the duration of development.

3.3. Limitations on the directions of research development

Practical significance: The obtained research results can be the basis for developing a new methodology for the development of two hydrodynamically isolated different permeability layers in the conditions of joint development by a single well grid. This methodology will allow to intensify the development of a two-layer field and increase the final gas recovery coefficient.

Research limitations: The conducted researches were based on the development period from 2023 to 2050 for a square-shaped deposit with certain values of the layer heterogeneity, which may somewhat limit the extrapolation of the results to other fields.

The proposed gas field model is built for conditions of an impermeable membrane between two different permeability layers. The research results do not take into account possible "lithological windows" or layer fractures. This could cause vertical gas migration.

These researches are limited by a specific initial layer pressure and different values of the layer permeability. In the case of deep deposits, the dynamics of the gas recovery coefficient can differ significantly.

This model is based on clean gas, which does not take into account the risks of retrograde condensate or breakthrough of bottom water. These factors quickly block the process of developing a low-permeability layer *1*.

A possible direction for increasing the gas recovery coefficient of a two-layer deposit is to transfer wells to simultaneous-separate operation. This will allow for each layer to separately regulate bottomhole pressures. It is also necessary to carry out treatments of the bottomhole zones of the layer in order to reduce the heterogeneity index n. In all wells, after their commissioning, it is necessary to carry out selective treatment of the bottomhole zone of the low-permeability layer (acid treatments, hydraulic fracturing, etc.) to increase the gas flow rate from this layer. It is important to ensure minimum values of the wellhead pressure by commissioning a booster compressor station, supplying gas to local consumers and using gas at the production site. It is advisable to consider the possibility of simultaneously – separately operating high-permeability and low-permeability layers in one well both from the beginning of the field development and after reducing the layer pressure by a certain amount.

Prospects for further research: A possible direction for further research is to optimize the well grid in the gas-bearing area. It would be advisable to develop recommendations for drilling side shafts with certain lengths of the horizontal section. This would allow to reveal certain high-pressure zones.

4. Conclusions

1. A model of two hydrodynamically isolated different-permeability (upper low-permeability and lower high-permeability) layers has been developed under the conditions of joint development by a single well grid. The researches have assessed the influence of the permeability ratio of individual layers $n = k_2/k_1$ on the final values of gas flow rates, layer pressure, gas recovery coefficients and the duration of field development. The obtained qualitative patterns indicate the early depletion of the high-permeability layer and uneven extraction of gas reserves for the ratio of layer permeabilities $n = 10$. At the late stage of field development for $n = 10$, the layer pressure in the high-permeability layer is 3.00 MPa, and in the low-permeability layer – 4.77 MPa. The gas extraction coefficient for the low-permeability layer for $n = 10$ is only 83.94%, while for homogeneous characteristics of the layers for $n = 1$ this indicator is 90.11%.

2. The features of gas extraction from two hydrodynamically isolated different-permeability layers under the conditions of joint development by a single well grid are investigated. The work substantiates a set of methods for intensifying hydrocarbon production (reducing pressure at the wellhead, performing bottomhole treatments of low-permeability layers, transferring wells to simultaneous-separate operation at a certain stage of field development), the choice of which is made on the basis of technical and economic calculations. It was established that an increase in the strata heterogeneity index significantly extends the period of the final stage of development to 310 months for $n = 10$ compared to 262 months for $n = 2$, which is due to the low intensity of gas inflow from the low-permeability layer. Forecast calculations confirmed the effectiveness of the proposed solutions, which ensures an increase in the final gas recovery ratio by 3.0–5.5%.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or other, that could influence the research and its results presented in this paper.

Financing

The research was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented paper.

Authors' contributions

Liliia Matiishyn: Conceptualization, Software, Writing – original draft, Visualization; ***Roman Kondrat***: Formal analysis, Writing – reviewing and editing.

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