Mining of Mineral Deposits
Volume 19 (2025), Issue 3, 14-21

https://doi.org/10.33271/mining19.03.014

Influence of the relative opening of the gas-bearing formation on the process of watering wells in reservoirs with bottom water

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Abstract

Purpose. The research aims to study the influence of gas-bearing reservoir relative opening on the patterns of well water-flooding process in deposits with bottom water.

Methods. Using the Petrel&Eclipse software, the influence of different values of the relative reservoir opening (0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9) on the deposit mining indicators in the 5^{th}, 10^{th} and 15^{th} years of mining has been studied. The paper examines options for operating wells with a reservoir depression of 1.25 MPa (5% of the initial pressure) and 2.5 MPa (10% of the initial pressure).

Findings. The research results are presented in the form of tables and graphical dependences of the studied parameters on the relative reservoir opening in the 5^{th}, 10^{th} and 15^{th} years of deposit mining at different reservoir depressions. According to the research results, at a reservoir depression of 1.25 MPa, the optimal value of the relative reservoir opening is 0.6. In the 15^{th} year of deposit mining, the reservoir pressure decreases from the initial value of 25 to 3.2 MPa, gas flow rate changes from 133.2 to 36.35 thousand m^3/day, and gas recovery factor is 85.66%. At a reservoir depression of 2.5 MPa, the optimal value of the relative reservoir opening is 0.4. In the 15^{th} year of deposit mining, the reservoir pressure decreases from 25 to 2.5 MPa, gas flow rate changes from 178 to 27.46 thousand m^3/day, and gas recovery factor is 90.46%. Thus, the choice of opening and depression parameters significantly influences the efficiency of deposit mining.

Originality. Based on the results of the conducted research for the conditions of the analyzed example, the optimal value of the relative reservoir opening has been obtained, which varies within 0.4-0.6 at a reservoir depression of 1.25-2.5 MPa (5 and 10% of the initial pressure).

Practical implications. Using the conducted research results, it will be possible to select the optimal parameters of relative reservoir opening to minimize water-flooding of the well and increase gas recovery efficiency. This will help to prolong the water-free period of well operation and substantiate the feasibility of using technologies for joint mining of gas and water from wells in difficult hydrogeological conditions.

Keywords: *deposit, well, gas, water, reservoir opening, reservoir pressure, gas flow rate, gas recovery factor*

1. Introduction

The problem of water cone formation in gas wells is one of the key issues in ensuring efficient and long-term operation of gas deposits with bottom water. The water cone occurrence leads to water breakthrough into the wellbore, which in turn reduces gas flow rate, complicates well operations and increases well maintenance costs. Therefore, determining the conditions under which water breakthrough occurs, as well as the critical water-free gas flow rate, is extremely important for developing optimal well operation modes [1]-[4].

Today, there is a significant amount of theoretical and applied research that can be conditionally divided into two main groups: those that consider steady-state conditions and are aimed at assessing the ultimate water-free gas flow rate, and those that study transient processes, focusing on the time of water breakthrough and the dynamics of water cone development [5], [6]. One of the key factors influencing the water cone formation is the relative reservoir opening, that is, the ratio of the productive interval opened part to the total gas-bearing layer thickness. This parameter determines the distribution of depression along the reservoir, shapes the fluid movement conditions in the zone around the well and significantly influences the critical water-free gas flow rate [1]-[3]. Low opening can increase the critical gas flow rate and reduce the water breakthrough probability, while high opening, on the contrary, accelerates the cone-forming process.

Despite the existence of numerous theoretical and empirical studies in this area, the issue of choosing the optimal relative reservoir opening to prevent water inflows remains open [5], [7]-[10].

The cone-forming process is an important aspect of gas deposit mining, as it determines the gas extraction efficiency from the deposit and affects the well stability during the entire period of its operation [5], [11]. Cone-forming process describes changes in the geometry of the gas extraction zone around the well caused by gradual gas withdrawal from the

Received: 11 February 2025. Accepted:7 June 2025. Available online: 30 September 2025

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

deposit. This phenomenon reflects a change in pressure in the surrounding layers and the development of a low-pressure zone, or cone, around the well.

Paper [12] discusses in detail the main aspects of cone-forming process in gas wells, starting with the physical principles underlying this process and ending with practical aspects such as modeling and predicting.

The main factors that determine the rate of cone-forming process include reservoir permeability, porosity, initial deposit pressure and gas extraction intensity [11], [13], [13].

Mathematical models that take into account the gas reservoir properties and gas extraction conditions are used to accurately predict the cone-forming process. Such models help not only to calculate the time until the cone reaches the well bottomhole, but also to optimize gas extraction parameters to ensure stable well operation [8], [15], [16].

An important aspect of gas deposit mining is predicting cone development. This makes it possible to make decisions at the early stages on methods of gas extraction intensification (increase in well flow rate) or the introduction of reservoir pressure maintenance technologies [3], [5], [12].

The problem of water cone formation in gas wells has been studied for more than eighty years, starting with the classic works of Muskat and Wyckoff [4], who were the first to formulate an analytical dependence for critical water-free gas flow rate, taking into account the hydrodynamic imperfection of the well. Their model showed that the relative reservoir opening is one of the key parameters affecting the height of the water cone rise and the ultimate gas flow rate without water inflow. According to their conclusions, reducing the opening helps to increase the resistance of the well to water breakthrough.

Further research, in particular the work of Wheatley [17], has found that the Muskat and Wyckoff [4] model somewhat overestimates critical flow rates because it neglects the influence of an already formed cone on reservoir pressure distribution. He also highlights that the well radius has less influence than the degree of its relative reservoir opening. More precise dependences for assessing the critical gas flow rate, which take into account not only the opening but also the reservoir depression parameters, were proposed in further studies [17], [18]. The authors have found that with a relative reservoir opening within 0.2-0.6, the discrepancy between the upper and lower limits of the critical flow rate reaches 30-40%, and with an opening of more than 0.9, it exceeds 50%.

The authors in [13], using in combination model [4] and Arthurs graphs [19], tested its effectiveness using the example of a real field. They concluded that models that take into account the degree of relative opening more accurately describe the behavior of the water cone in an industrial environment. In [10], the authors emphasized the role of vertical pressure gradient and found that the critical flow rate can be achieved even when only a third of the reservoir thickness is opened, which contradicts previous assumptions about the need to completely cover the water-bearing part.

Studies [20] present a nomogram for determining breakthrough time and critical flow rate, which is based on experimental and model studies. This work has once again confirmed that the relative reservoir opening is a critical parameter that should be taken into account when designing and operating wells in gas deposits with bottom water.

Summarizing the above, it can be argued that the relative reservoir opening significantly affects both the initial cone formation and the dynamics of its development. Choosing the optimal opening allows not only to increase the efficiency of field mining, but also to minimize the risks of water inflow. However, a number of simplifications and contradictory results remain in the available publications, indicating the relevance of further research in this direction.

The purpose of this research is to study the influence of gas-bearing reservoir relative opening on the patterns of well water-flooding process in deposits with bottom water. To do this, the following tasks should be solved:

– to conduct theoretical studies of the influence of gas-bearing reservoir relative opening on the cone-forming process and gas recovery factor;

– to identify the characteristic peculiarities of the well water-flooding process in deposits with bottom water at different values of gas-bearing reservoir relative opening and to substantiate the optimal value of the relative reservoir opening for the conditions of the analyzed example.

2. Research methods

The influence of the relative reservoir opening on the cone-forming process was studied by numerical modeling using the Petrel&Eclipse software packages. The Petrel software environment is an integrated platform for modeling collector structure and properties. Petrel implements grid construction tools of various dimensions, including local grid refinement, which allows you to model dynamic processes with the required accuracy, while maintaining an acceptable level of computational complexity. After forming a geological model that takes into account the distribution of physical properties in the reservoir volume, the data is exported for further dynamic modeling.

Eclipse is a leading simulator used for hydrodynamic modeling of flows of multiphase systems (gas, oil, water) in a porous media. Eclipse 100 implements complete 3D non-stationary filtration models that allow for the consideration of complex processes of phase interaction, capillary forces, and other physical phenomena occurring in the reservoir. The use of Eclipse simulator makes it possible to model the dynamics of pressure changes, production flow rates and the development of water cones during the entire field operation period.

A square-shaped gas deposit with a square side of 2000 m was used as the modeling object. The deposit is mined through a single vertical well located in the center and is characterized by geological-physical parameters typical of gas fields with bottom water. The deposit is 2030 m deep, with a gas-water contact (GWC) at a depth of 2020 m. Initial reservoir pressure is 25 MPa; reservoir temperature – 70°C; open porosity coefficient – 0.15; initial gas saturation coefficient – 0.8; permeability coefficient: across and along the bedding (along the X and Y axes) – 100 mD, in the vertical direction (along the Z axis) – 10 mD; thickness of the productive reservoir – 30 m (gas-bearing part – 20 m, water-bearing part – 10 m); the aquifer is unlimited in length, with initial gas reserves of 536401 thousand m^3.

Based on these parameters, a 3D geological model of the reservoir was built in the Petrel software package. At the first stage, a grid of 50×50×10 cells was created, covering the entire deposit area. Local Grid Refinement is used to more accurately reproduce cone-forming processes near the well, which allows to more accurately determining the distribution of pressures and fluid saturation in the zone of the greatest dynamics. Local Grid Refinement created an additional grid of much smaller cells in the immediate vicinity of the well, allowing more accurate modeling of pressure gradients, fluid saturation, and phase movement in the zone of maximum hydrodynamic changes. This local refinement significantly improves the quality of the cone-forming modeling, as the most intense gas-water interaction occurs in these zones, and a classical grid with larger cells would not be able to capture the subtle physical processes with sufficient accuracy. The model takes into account the distribution of porosity and permeability, respectively, taking into account the reservoir anisotropy.

After completing the geological model construction, the data were saved and exported to the Eclipse simulator for further hydrodynamic modeling. Calculations in Eclipse were performed with the E100 module using a complete 3D non-stationary gas and water filtration model.

Such a step-by-step approach – from the construction of a geological model to detailed hydrodynamic modeling – allows obtaining a comprehensive and accurate picture of reservoir processes, necessary for further analysis and decision-making.

The operation of wells was modeled for different values of reservoir depression, taking into account water inflow from the bottom water, reduction of reservoir pressure, changes in gas flow rate and accumulated production. The duration of modeling was 15 years, which made it possible to assess long-term trends in the development of water cones and gas production efficiency.

The numerical modeling results were analyzed using the built-in Petrel tools, as well as with subsequent data processing in Microsoft Excel program. This approach made it possible to analyze the sensitivity of the deposit to changing operating conditions, in particular, the influence of different relative opening values of the gas-bearing reservoir on the cone-forming process and to determine under which parameters the maximum gas recovery factor is achieved during water breakthrough to the well bottomhole.

The use of a comprehensive modeling methodology in Petrel & Eclipse software complexes ensured high accuracy and reproducibility of the results, which confirms its applicability for predicting the efficiency of gas field mining with bottom water. The proposed methodology can be applied to similar fields to predict mining efficiency and optimize technical parameters of well operation.

Figure 1 shows the general scheme of the deposit in 3D and in section.

Mining of the deposit started on 01.01.2025 through one production well. Two options for operating a well with a constant reservoir depression of 1.25 MPa (5% of the initial pressure) and 2.5 MPa (10% of the initial pressure) are considered. The well was operated with a specified constant reservoir depression (1.25 or 2.5 MPa) until water appeared in the reservoir products (water cone rising to the lower holes of the perforation interval), after which the well was stopped. In the absence of water-flooding, the well was operated with a constant reservoir depression until the pressure at the wellhead decreased to the specified minimum value (1.2 MPa).

Subsequently, the well was operated with constant wellhead pressure. After the reservoir pressure decreased to 0.1 of the initial pressure, the deposit mining was stopped.

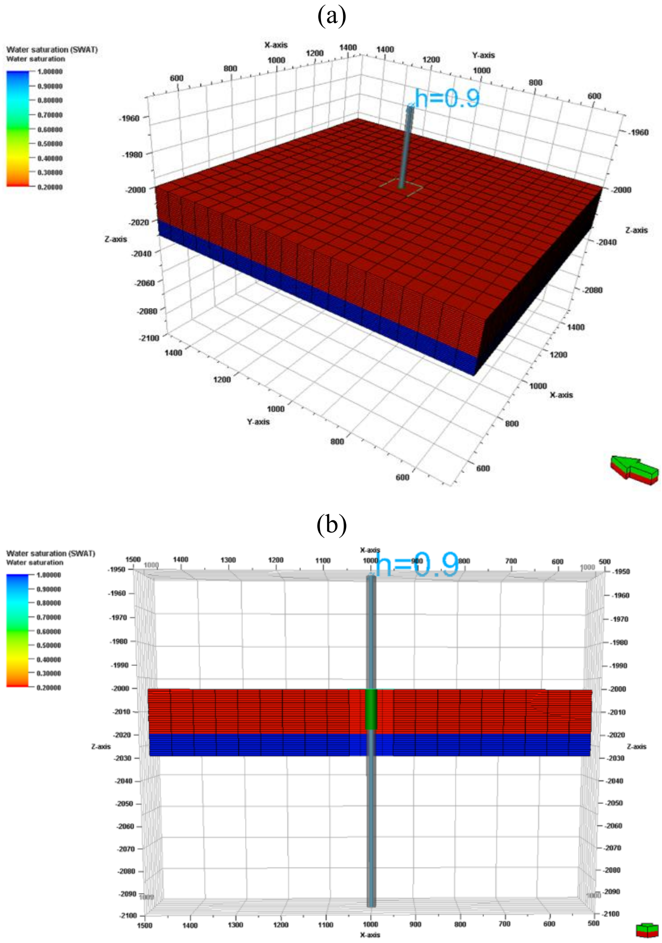

Figure 1. General scheme of the deposit: (a) 3D; (b) in section

To study the dynamics of the cone-forming process, the main mining indicators were recorded throughout the entire modeling period: gas flow rates, pressure changes and accumulated production.

3. Results and discussion

The results of the research in the 5th, 10th and 15th years of deposit mining at a constant reservoir depression of 1.25 MPa (5% of the initial pressure) are summarized in Table 1. At a constant reservoir depression of 2.5 MPa (10% of the initial pressure), the results are summarized in Table 2 and are shown as dependences of reservoir pressure (Fig. 2), gas flow rate (Fig. 3) and gas recovery factor (Fig. 4) on the relative opening of gas-bearing reservoir for different reservoir depression values (5 and 10% of the initial pressure). Table 3 shows the duration of well operation for different values of gas-bearing reservoir relative opening and depression (5 and 10% of the initial pressure).

In the studied options, depending on the values of reservoir depression ΔP and relative reservoir opening $h_{relative}$, the initial well flow rate varies from 22.2 thousand m^3/day at ΔP = 1.25 MPa and $h_{relative}$ = 0.1 to 400 thousand m^3/day at ΔP = 2.5 MPa and $h_{relative}$ = 0.9. When operating wells with a reservoir depression of 1.25 MPa, depending on the value of the relative reservoir opening $h_{relative}$, water appears in reservoir products over the following period of time: at $h_{relative}$ = 0.9 in 1 month, at $h_{relative}$ = 0.8 in 4 months, at $h_{relative}$ = 0.7 in 1.5 years (Table 3).

Table 1. Results of the research in the 5th, 10th and 15th years of deposit mining at a constant reservoir depression of 1.25 MPa (5% of the initial pressure)

Relative reservoir opening, $h_{relative}$	Reservoir pressure, MPa			Gas flow rate, thousand m³/day				Gas recovery factor, %		
	5th year	10th year	15th year	Initial flow rate, q_{init}	5th year	10th year	15th year	5th year	10th year	15th year
0.1	22.79	20.79	18.96	22.2	21.65	20.99	20.19	7.47	14.73	21.74
0.2	20.73	17.18	14.14	44.4	41.97	38.6	34.55	14.72	28.45	40.91
0.3	18.85	14.09	10.03	66.6	60.57	51.80	41.75	21.72	40.89	56.80
0.4	17.12	11.45	7.28	88.8	77.18	60.20	42.47	28.42	51.85	69.22
0.5	15.52	9.17	4.96	111.0	91.58	63.90	40.08	34.80	61.26	78.60
0.6	14.04	7.23	3.21	133.2	103.59	63.70	36.32	40.83	69.14	85.66
0.7	20.48	20.48	20.48	155.4	0	0	0	15.34	15.34	15.34
0.8	23.70	23.70	23.70	177.6	0	0	0	3.93	3.93	3.93
0.9	24.62	24.62	24.62	199.8	0	0	0	1.13	1.13	1.13

Table 2. Results of the research in the 5th, 10th and 15th years of deposit mining at a constant reservoir depression of 2.5 MPa (10% of the initial pressure)

Relative reservoir opening, $h_{relative}$	Reservoir pressure, MPa			Gas flow rate, thousand m³/day				Gas recovery factor, %		
	5th year	10th year	15th year	Initial flow rate, q_{init}	5th year	10th year	15th year	5th year	10th year	15th year
0.1	20.83	17.36	14.40	44.4	41.96	38.60	34.51	14.72	28.44	40.90
0.2	17.31	11.76	7.68	88.8	77.14	60.14	42.44	28.41	51.83	69.18
0.3	14.30	7.65	3.69	133.2	103.51	63.66	36.29	40.81	69.09	85.59
0.4	11.72	4.77	2.50	178	120.17	58.39	27.46	51.71	80.98	90.46
0.5	14.05	14.05	14.05	222	0	0	0	41.65	41.65	41.65
0.6	20.36	20.36	20.36	266	0	0	0	16.02	16.02	16.02
0.7	22.39	22.39	22.39	311	0	0	0	8.50	8.50	8.50
0.8	23.95	23.95	23.95	355	0	0	0	2.95	2.95	2.95
0.9	24.55	24.55	24.55	400	0	0	0	0.94	0.94	0.94

Table 3. Duration of well operation for different values of gas-bearing reservoir relative opening and depression (5 and 10% of the initial pressure)

Relative reservoir opening, $h_{relative}$	Duration	
	Constant reservoir depression of 1.25 MPa (5% of the initial pressure)	Constant reservoir depression of 2.5 MPa (10% of the initial pressure)
0.1	15	15
0.2	15	15
0.3	15	15
0.4	15	13 years and 2 months
0.5	15	3 years and 2 months
0.6	15	3 years and 1 month
0.7	1.5 years	11 months
0.8	4 months	5 months
0.9	1 month	1 month and 14 days

During the studied period of time (15 years), the reservoir interval with a relative opening $h_{relative} \leq 0.6$ is not water-flooded.

In the operating conditions of a well with a reservoir depression of 1.25 MPa, the reservoir pressure (Table 1, Fig. 2a) gradually decreases with an increase in the relative reservoir opening and reaches a minimum value at a relative reservoir opening $h_{relative} = 0.6$ (14.04 MPa – in the 5th year, 9.17 MPa – in the 10th year, 3.21 MPa – in the 15th year of deposit mining). At values of $h_{relative} > 0.6$, the reservoir pressure gradually increases with increasing relative reservoir opening, and for all studied values of the deposit mining duration, the reservoir pressure curves are plotted on the same line. The increase in reservoir pressure at $h_{relative} > 0.6$ is explained by the inflow of edge reservoir water into the deposit.

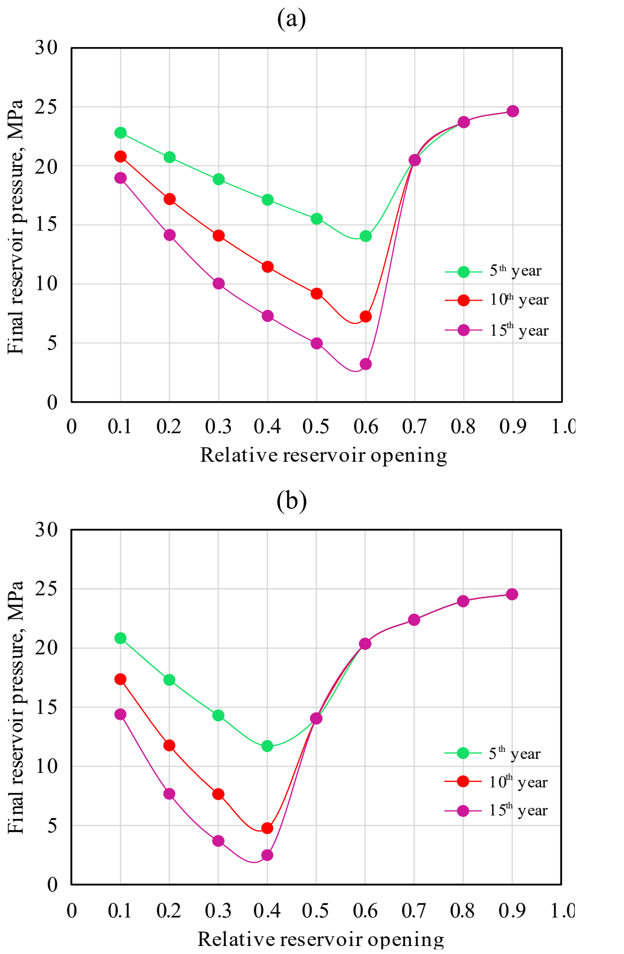

Figure 2. Dependences of the final reservoir pressure in the 5th, 10th and 15th years of deposit mining on the relative reservoir opening at constant reservoir depression: (a) 5%; (b) 10%

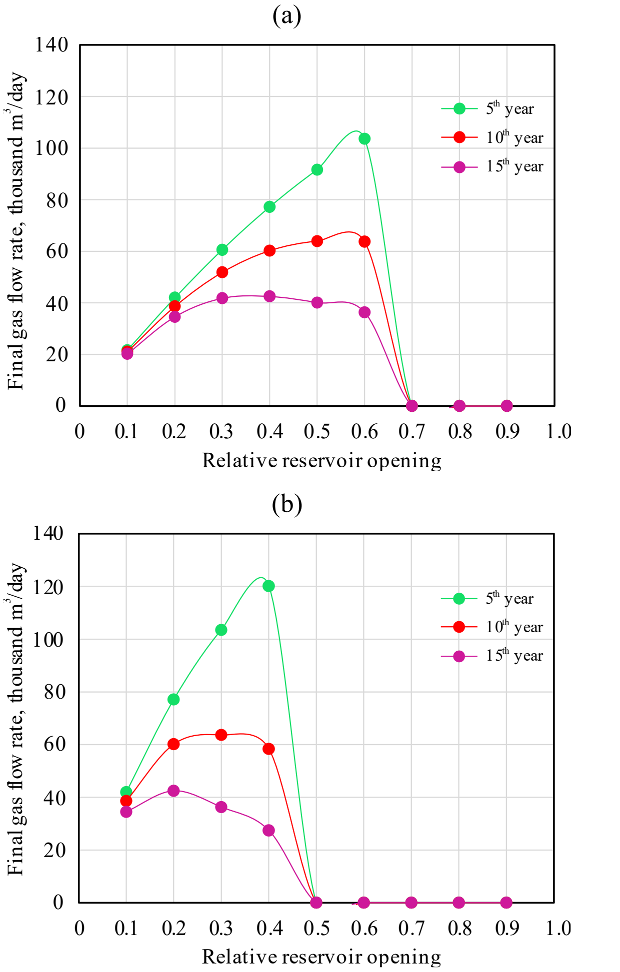

Figure 3. Dependences of the final gas flow rate in the 5th, 10th and 15th years of deposit mining on the relative reservoir opening at constant reservoir depression: (a) 5%; (b) 10%

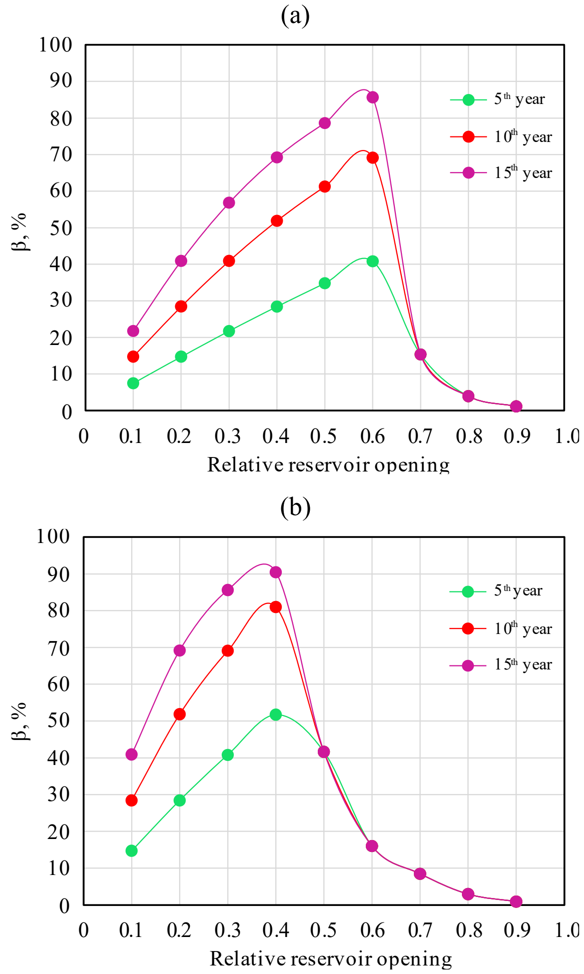

Figure 4. Dependences of the gas recovery factor in the 5th, 10th and 15th years of deposit mining on the relative reservoir opening at constant reservoir depression: (a) 5%; (b) 10%

At a reservoir depression of ΔP = 1.25 MPa, the final gas flow rate at the considered time points (5, 10, 15 years) initially increases with an increase in the relative reservoir opening, reaching a maximum value at $h_{relative}$ = 0.6, and then sharply decreases to zero at relative reservoir opening of 0.7, 0.8, 0.9 (Fig. 3a). The absence of gas extraction at $h_{relative}$ > 0.6 is due to well operation stoppage due to water-flooding.

The current gas recovery factor during the operation of a well with a reservoir depression of 1.25 MPa initially increases with an increase in the relative reservoir opening and reaches a maximum value at $h_{relative}$ = 0.6, which is: for the 5th year – 40.83%; for the 10th year – 69.14%; for the 15th year – 85.66% (Fig. 4a). Subsequently, the current gas recovery factor decreases sharply with an increase in the relative reservoir opening and is: at $h_{relative}$ = 0.7-15.34%; at $h_{relative}$ = 0.8-3.93%; at $h_{relative}$ = 0.9-1.13%. For all the considered time points, the values of the current gas recovery factor at $h_{relative}$ > 0.6 coincide.

Thus, within the considered deposit mining period (15 years), when operating a well with a reservoir depression of 1.25 MPa, the optimal value of the relative reservoir opening is 0.6. At this value of $h_{relative}$, at the end of the 15th year of deposit mining, the reservoir pressure decreases to 3.21 MPa, which is close to the ultimate value (0.1 P_{init} = 2.5 MPa), a fairly high gas flow rate (36.32 thousand m^3/day) is still maintained and a high current gas recovery factor is achieved (85.66%).

For the considered reservoir depression in the first 1.5 years, only intervals with a relative reservoir opening of 0.7, 0.8, 0.9 are water-flooded (Table 3). Intervals with a lower relative reservoir opening ($h_{relative}$ < 0.7) are not water-flooded for 15 years.

With a relative reservoir opening of 0.6, continuing to operate a well with a reservoir depression of 1.25 MPa until it is watered or depleted will allow for a higher gas recovery factor than that achieved in the 15th year of mining.

When operating a well with a reservoir depression of 2.5 MPa (10% of the initial pressure), the dependences of reservoir pressure, final gas flow rate and gas recovery factor on relative reservoir opening in the 5th, 10th and 15th years of deposit mining are similar to the corresponding dependences obtained when operating a well with a reservoir depression of 1.25 MPa (5% of the initial pressure), with some exceptions. With an increase in the relative reservoir opening, the reservoir pressure for all studied values of the deposit mining duration gradually decreases to the value of $h_{relative}$ = 0.4 and then increases (Fig. 2b). Starting from a relative reservoir opening $h_{relative}$ = 0.5, the depen-dences of reservoir pressure on the relative reservoir ope-ning are plotted on the same line. For a relative reservoir opening of 0.4, the reservoir pressure decreases to 11.72 MPa in the 5th year of deposit mining, to 4.77 MPa – in the 10th year, and to 2.5 MPa – in the 15th year. That is, in the 15th year of deposit mining, the reservoir pressure decreases to 0.1 of the initial pressure and the deposit mining is stopped due to depletion. It should be noted that the well is operated at a constant reservoir depression mode of ΔP = 2.5 MPa until 01.11.2036, after which it is switched to operating mode with constant wellhead pressure $P_{wellhead}$ = 1.2 MPa. The well is operated until 01.03.2038, when the reservoir pressure decreases to 0.1 of the initial pressure.

At a reservoir depression of 2.5 MPa, the gas flow rate gradually increases with the increase in the relative reservoir opening and reaches its maximum value at $h_{relative}$ = 0.4: 120.17 thousand m^3/day – in the 5th year of deposit mining; 58.39 thousand m^3/day – in the 10th year of deposit mining; 27.46 thousand m^3/day – in the 15th year of deposit mining (Table 2, Fig. 3b). With $h_{relative}$ > 0.4, gas flow rate in the 5th, 10th and 15th years of deposit mining sharply decreases to 0 at relative reservoir openings of 0.5; 0.6; 0.7; 0.8; 0.9.

When operating wells with a reservoir depression of 2.5 MPa, the gas recovery factor initially increases with an increase in the relative reservoir opening to 0.4 and is: in the 5th year of deposit mining – 51.71%, in the 10th year of deposit mining – 80.98% and in the 15th year of deposit mining – 90.46% (Fig. 4b).

The last value of the gas recovery factor is the maximum for the considered example, since the deposit is completely depleted and the reservoir pressure drops to 0.1 of the initial pressure. At $h_{relative}$ > 0.4, with an increase in the relative reservoir opening, the gas recovery factor gradually decreases to 0.94% at $h_{relative}$ = 0.9 and has the same value for all the studied mining periods. With a relative reservoir opening value of 0.4, the well is operated for 13 years and 2 months. At the end of this period, the reservoir pressure decreases to the specified minimum value of 2.5 MPa (0.1 of the initial pressure). For the values of relative reservoir opening of 0.1, 0.2, 0.3, the reservoir pressure in the 15th year of deposit mining is higher than the minimum value (Table 2).

Therefore, when operating wells with a reservoir pressure of 2.5 MPa for 13 years and 2 months, the optimal value of the relative reservoir opening is 0.4. With this value of $h_{relative}$, at the end of the study period of deposit mining, the reservoir pressure decreases to 2.5 MPa, gas flow rate is 27.46 thousand m^3/day, and gas recovery factor is 90.46%.

The performed research results indicate a significant influence of the relative reservoir opening in the wells on the mining process characteristics of a gas deposit with bottom water. As the gas-bearing reservoir relative opening increases, the initial gas flow rate increases, which makes it possible to reduce the number of wells required to ensure a given level of gas production and intensify the process of deposit mining. However, at the same time, the rate of decrease in reservoir pressure and gas flow rate increases, and the water-flooding of wells with cones of bottom water accelerates. The optimal value of the relative reservoir opening should be selected based on the results of modeling the mining process of a particular deposit under various options.

The given dependences of the gas recovery factor on the relative reservoir opening at a constant reservoir depression of 5 and 10% of the initial pressure (Fig. 4) are explained by the fact that with an increase in the relative gas-bearing reservoir opening, more efficient interaction of wells with the reservoir is simultaneously possible.

Different values of the gas recovery factor for the same mining period (until the minimum pressure is reached) with different relative openings of the gas-bearing reservoir are explained by several main factors related to the hydrodynamic peculiarities of the interaction between the well and the reservoir:

– reservoir drainage efficiency – greater reservoir opening, in particular due to the longer length of perforation channels, the use of hydraulic fracturing or drilling horizontal wells, improves the hydrodynamic contact between the well and the productive interval of the reservoir. This provides increased drainage capacity, intensifies the reduction of reservoir pressure in the bottomhole zone and contributes to a more uniform gas recovery throughout the entire deposit thickness;

– uniformity of mining – with less relative opening of the gas-bearing reservoir, most of the reservoir remains insufficiently drained, which leads to the formation of zones with limited extraction – the so-called “dead” zones. In such zones, in particular in areas remote from the well, gas is not fully extracted, even under conditions of reaching the minimum pressure in the bottomhole zone;

– hydrodynamic resistance – lower relative opening of the gas-bearing reservoir means higher resistance to the movement of gas to the well, especially in low-permeability collectors. As a result, there is a slow gas recovery from the peripheral zones of the productive interval;

– the time factor is also critical when assessing the effectiveness of deposit mining. In conditions of insufficient productive reservoir opening, it takes significantly longer to achieve a comparable degree of gas recovery. However, the implementation of long operating cycles is often limited by economic or technical factors, which reduces the overall mining efficiency.

According to the conducted research results, the choice of the optimal value of relative reservoir opening is influenced by the technological mode of well operation, in particular, the value of reservoir depression, at which the highest gas recovery factor will be achieved during the water-free period of well operation.

In conditions of reservoir energy depletion, the water-free period of well operation at the appropriate value of the gas-bearing reservoir relative opening can be extended by changing the technological mode of their operation, for example, by switching from the mode of constant reservoir depression to the mode of constant wellhead pressure. It is advisable to use technologies for joint gas and water extraction from water-flooded wells in case of a bottom water cone occurrence.

4. Conclusions

The mining of gas deposits with bottom water is accompanied by deformation of the gas-water interface with the formation of water cones below the well bottomhole. The top of the cone is placed on the axis of the well. The height of the cone rise mainly depends on the vertical permeability of the reservoir and reservoir depression. Under certain conditions, the water cone rises to the bottomhole of the well, which leads to water-flooding.

When operating wells in deposits with bottom water, it is important to choose the optimal value of the relative opening of the gas-bearing reservoir $h_{relative}$ in the wells.

At high values of $h_{relative}$, the initial flow rate of wells increases, but the process of their water-flooding accelerates. At low $h_{relative}$ values, wells will be operated with low initial gas flow rates, which will require an increase in their number to fulfill a given gas production plan.

The paper, using the example of a hypothetical gas deposit with bottom water, operated through one well, examines the influence of different values of gas-bearing reservoir relative opening (0.1; 0.2; 0.3; 0.4; 0.5; 0. 6; 0.7; 0.8; 0.9) on the values of reservoir pressure, gas flow rate and gas recovery factor in the 5th, 10th and 15th years of deposit mining at reservoir depressions of 1.25 MPa (5% of the initial pressure) and 2.5 MPa (10% of the initial pressure).

At a reservoir depression of 1.25 MPa, the optimal value of the relative reservoir opening is 0.6. During the first 1.5 years, intervals with a relative reservoir opening of 0.7, 0.8 and 0.9 are water-flooded. Subsequently, the remaining intervals of the reservoir are not water-flooded until the end of the 15th year. At the end of the 15th year, with a relative reservoir opening of 0.6, the reservoir pressure decreases from 25 to 3.21 MPa, gas flow rate changes from 133.2 to 36.32 thousand m^3/day, and the current gas recovery factor is 85.66%.

At a reservoir depression of 2.5 MPa, the optimal value of the relative reservoir opening is 0.4. In this case, the first 3 years and 1 month, the intervals with a relative reservoir opening of 0.5; 0.6; 0.7; 0.8; 0.9 are water-flooded. Subsequently, until the end of the 15th year, water-flooding of other intervals does not occur. At the end of the 15th year, the reservoir pressure decreases from 25 to 2.5 MPa, gas flow rate changes from 178 to 27.46 thousand m^3/day, and the current gas recovery factor is 90.46%.

Therefore, the maximum value of the gas recovery factor of mining a gas deposit with bottom water can be achieved by choosing the optimal value of the gas-bearing reservoir relative opening in the wells and, accordingly, the technological mode of their operation. For the conditions of the described example, the optimal value of the gas-bearing reservoir relative opening varies within 0.4-0.6 at a reservoir depression of 1.25-2.5 MPa (5-10% of the initial pressure).

Author contributions

Conceptualization: LM; Formal analysis: RK; Software: LM; Visualization: LM; Writing – original draft: LM; Writing – review & editing: RK. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

We are grateful to our colleagues and reviewers for their continuous support, insightful feedback, and encouragement, all of which greatly contributed to the successful completion of this research.

Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Вплив відносного розкриття газоносного пласта на процес обводнення свердловин на покладах з підошовною водою

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Мета. Дослідження впливу відносного розкриття газоносного пласта на закономірності процесу обводнення свердловин на покладах з підошовною водою.

Методика. З використанням програми Petrel&Eclipse досліджено вплив різних значень відносного розкриття пласта (0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9) на показники розробки покладу на 5-й, 10-й і 15-й роки розробки. Розглянуто варіанти експлуатації свердловин з депресією на пласт 1.25 МПа (5% від початкового тиску) і 2.5 МПа (10% від початкового тиску).

Результати. Результати досліджень представлені у вигляді таблиць і графічних залежностей досліджуваних параметрів від відносного розкриття пласта на 5-й, 10-й і 15-й роки розробки покладу за різних депресій на пласт. Згідно з результатами досліджень, за депресії на пласт 1.25 МПа оптимальне значення відносного розкриття пласта становить 0.6. На 15-й рік розробки покладу пластовий тиск знижується з початкового значення 25 до 3.2 МПа, дебіт газу змінюється з 133.2 до 36.35 тис.м^3/добу, коефіцієнт газовилучення становить 85.66%. За депресії на пласт 2.5 МПа оптимальне значення відносного розкриття пласта дорівнює 0.4. На 15-й рік розробки покладу пластовий тиск знижується з 25 до 2.5 МПа, дебіт газу змінюється зі 178 до 27.46 тис.м^3/добу, коефіцієнт газовилучення складає 90.46%. Отже, вибір параметрів розкриття та депресії істотно впливає на ефективність розробки покладу.

Наукова новизна. За результатами проведених досліджень для умов розглянутого прикладу отримано оптимальне значення відносного розкриття пласта, яке змінюється в межах 0.4-0.6 за депресії на пласт 1.25-2.5 МПа (5 і 10% від початкового тиску).

Практична значимість. Використання результатів проведених досліджень дозволить вибрати оптимальні параметри відносного розкриття пласта для мінімізації обводнення свердловин і підвищення ефективності газовилучення. Це сприятиме продовженню безводного періоду експлуатації свердловин та обґрунтуванню доцільності застосування технологій спільного видобування газу і води зі свердловин у складних гідрогеологічних умовах.

Ключові слова: *поклад, свердловина, газ, вода, розкриття пласта, пластовий тиск, дебіт газу, коефіцієнт газовилучення*

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