UDC 622.279.5
DOI: 10.15587/2706-5448.2020.215074

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RESEARCH OF THE INFLUENCE OF THE PATTERN ARRANGEMENT OF INJECTION WELLS ON THE GAS RECOVERY FACTOR WHEN INJECTING CARBON DIOXIDE INTO RESERVOIR

The object of research is gas and gas condensate reservoirs, which is being developed under the conditions of the manifestation of the water drive of development and the negative effect of formation water on the process of natural gas production. In order to improve the existing technologies for the development of natural gas fields in the conditions of the manifestation of the water drive of development of productive reservoirs, a study was carried out using the main tools of hydrodynamic modeling Eclipse and Petrel from Schlumberger (USA). On the basis of a three-dimensional digital model of gas condensate reservoirs, the influence of the pattern arrangement of injection wells on the coefficient of natural gas extraction during the injection of carbon dioxide into productive reservoirs on the border of a gas-water contact was investigated. The study was carried out for a different number of injection wells (4, 6, 8, 12, 16 wells), which are evenly spaced along the perimeter of the initial gas-water contact. According to the results of the calculations, it was found that the production of formation water decreases with an increase in the pattern arrangement of the well. In the case of using 4 wells to inject carbon dioxide into a productive reservoir, the comulative production of formation water at the end of development amounted to 169.71 th.m^3. With an increase in the number of injection wells to 16, the comulative production of produced water decreased to 0.066 m^3. This result is achieved due to a more complete coverage of the perimeter of gas content with carbon dioxide and the creation of an artificial barrier between water and natural gas, which leads to a more effective blocking of the movement of produced water into productive reservoirs. According to the results of statistical processing of the calculated data, the optimal value of the number of injection wells was determined when injecting carbon dioxide into the reservoir. The optimal value of the number of injection wells at the time of the breakthrough of carbon dioxide into the first production well is 7.86 (8) wells. The maximum value of the number of injection wells according to the results of statistical processing is 6.8 (7) wells. The final gas recovery factor for the given optimal injection value is 61.88 %. On the basis of the calculations, the technological efficiency of using as an agent for injecting carbon dioxide at the boundary of the gas-water contact was established in order to prevent selective watering of productive reservoirs and production wells.

Keywords: *3D model of the field, gas condensate reservoir, water drive, trapped gas, injection of carbon dioxide.*

Received date: 20.05.2020
Accepted date: 22.06.2020
Published date: 31.10.2020

1. Introduction

The overwhelming majority of hydrocarbon fields, which today provide the main production of natural gas, have entered or are entering the final stage of development. The main features of the final stage of development are the selective water incroachment of productive reservoirs and production wells [1, 2].

The main reasons for the water flooding of production wells are usually the selective movement of formation water through highly permeable interlayers and the overflow of water in the leaky behind the casing from other horizons [3].

As the reservoir energy is depleted, the gas-water contact moves, which leads to a decrease in the gas-saturated thickness of the reservoirs, the appearance of water in the production of producing wells and a decrease in gas flow rates [4].

When designing the development of natural gas fields, information on the movement of contour and bottom waters is important. The nature of the movement of the gas-water contact is significantly affected by the heterogeneity of the productive section, which mainly consists of rocks characterized by variability of reservoir properties both in thickness and in area [5, 6].

Determination of the position of the gas-water contact in the conditions of the manifestation of the water drive of the development of productive reservoirs is an urgent task of control, without which the rational development of productive reservoirs is impossible.

When designing a rational system for the development of productive reservoirs of depleted gas and gas condensate reservoirs, various technologies are used to enhanc hydrocarbon recovery. The feasibility and effectiveness

of the selected methods and technologies depends solely on the ratio of non-watered and watered productive area of the field.

A promising method for increasing of hydrocarbon recovery factor from depleted fields with significant reserves of trapped gas is to displace it by injecting non-hydrocarbon gases (nitrogen, carbon dioxide, etc.) into productive reservoirs.

When designing the development of hydrocarbon fields with the injection of carbon dioxide into productive reservoirs, it is important to select the rate and cyclicity of the periods of its injection, the number and system of placement of injection and production wells in the gas-bearing area, the distance between them and the technological drives of their operation.

In this paper, the influence of the pattern arrangement of injection wells on the gas recovery factor when injecting carbon dioxide into productive reservoirs on the edge of the gas-water contact is investigated. The study was carried out using the main hydrodynamic modeling tools Eclipse and Petrel from Schlumberger (USA) on the example of a digital three-dimensional model of a gas condensate reservoir.

2. The object of research and its technological audit

The object of research is gas and gas condensate reservoirs developed under the conditions of the manifestation of the water drive of development and the negative effect of formation water on the process of natural gas production.

Under the conditions of the manifestation of the water drive of development, in the process of moving formation water into the gas-saturated horizons, significant volumes of natural gas are trapped. Given the low current of hydrocarbon recovery factors in an active water-pressure system, there is a need to search for new methods of regulating the process of promoting formation water and the development of optimal ways to extract residual hydrocarbon reserves. In order to improve the existing technologies for field development, it is advisable to carry out additional research aimed at minimizing the harmful effects of edge waters on the natural gas production process.

3. The aim and objectives of research

The aim of this research is to study the effect of the pattern arrangement of injection wells on the natural gas recovery factor when injecting carbon dioxide into productive reservoirs on the verge of gas-water contact using numerical modeling.

To achieve this aim, it is necessary to complete the following objectives:

1. Establish the optimal number of injection wells for injection the dioxide into the productive reservoir on the verge of the initial gas-water contact for the conditions of a particular reservoir.

2. Investigate the effect of the optimal number of wells on the natural gas recovery factors when injecting carbon dioxide into a productive reservoir and during depletion development.

4. Research of existing solutions of the problem

A significant number of natural gas fields have entered the late stages of development and are characterized by selective watering of productive reservoirs of production wells. As a result of the selective movement of formation water by the most permeable interlayers, formation water is pinched by the formation water of areas of the productive layer with high gas saturation [7].

Based on the results of numerous studies, the mechanism of the behavior of trapped gas by formation water in a porous medium has been revealed [8, 9]. Based on the results of the studies [10, 11], scientists have developed new and improved existing technologies for the development of fields in the conditions of the manifestation of the water drive of development. Considering the significant heterogeneity of the productive of hydrocarbon reservoirs, both in area and in thickness, the developed technologies can be ineffective. The nature of the distribution of reservoir properties of the reservoir introduces significant uncertainty in the process of substantiating the optimal technology for further development of the field under conditions of active water drive.

Today, the direction of increasing the hydrocarbon production in gas and gas condensate reservoirs, which is characterized by a water drive of development, remains promising by regulating the development process of such fields, by injecting non-hydrocarbon gases into productive reservoirs.

One of the successful technologies for increasing the hydrocarbon production is the injection of carbon dioxide into productive reservoirs. Theoretical and experimental studies of the process of injection of carbon dioxide in order to displace the residual gas confirm its technological efficiency.

In [12, 13], the results of laboratory studies on the displacement of residual gas by carbon dioxide, nitrogen and flue gases from horizontal models of a homogeneous and heterogeneous reservoir are presented. The results of laboratory studies confirm the high technological efficiency of using non-hydrocarbon gases to displace residual gas from productive reservoirs. The highest gas recovery factor was obtained in experiments in the case of using carbon dioxide as injection agent.

Numerous laboratory and experimental studies have confirmed that carbon dioxide dissolves well in formation water. Due to its high solubility, carbon dioxide will expand and dissolve in the formation water, which slows down further movement towards the gas-saturated part of the reservoir [14, 15].

The simulation results show that due to the injection of carbon dioxide, the inflow and advancement of formation water becomes controlled, which provides significantly higher of hydrocarbon recovery factors [16, 17].

In order to improve the existing technologies for the development of one of the fields in Mexico, characterized by a water drive of development of productive reservoirs, the process of displacement of residual trapped gas by formation water by various injection agents was simulated. Dry gas, carbon dioxide, nitrogen and flue gases were used as injection agents. The results obtained indicate that the most effective option is with the injection of carbon dioxide. Thanks to the introduction of this technology, part of the trapped gas is extracted by water. In the zones of injection of carbon dioxide, formation pressure sharply increases and an additional hydrodynamic barrier is created, which complicates the movement of formation water into productive formations and provides significantly higher coefficients of hydrocarbon recovery [18].

Theoretical and experimental studies of the injection process of non-hydrocarbon gases with the aim of displacing residual gas and slowing down the movement of formation

ISSN 2664-9969

water into productive reservoirs confirm their effectiveness. However, the issues of using injection agents that would provide the greatest effect have not yet been investigated.

The results of the laboratory and theoretical studies carried out indicate that the final natural gas recovery factor under the conditions of the manifestation of a water drive of development mode when injecting non-hydrocarbon gases into productive reservoirs depends on:

– duration of the injection period of non-hydrocarbon gas;
– heterogeneity degree of the reservoir both in thickness and in area;
– layouts of production and injection wells by area of deposits;
– pattern arrangement of injection wells.

To improve the existing technologies for the development of natural gas fields and increase the final gas recovery factor by injecting carbon dioxide into the productive reservoir, it is advisable to conduct additional research using hydrodynamic modeling tools.

5. Methods of research

To carry out studies to increase the gas recovery factor in conditions of the manifestation of a water drive of development of productive reservoirs and to improve existing technologies for developing fields in such conditions, the main tools of hydrodynamic modeling Eclipse and Petrel from Schlumberger (USA) were used.

The study was carried out on the basis of a synthetic 3D model of a gas condensate reservoir. To reproduce the physical processes that take place in the reservoir during the injection of non-hydrocarbon gases, a compositional PVT model was created using the PVTi module and the Eclipse software [19, 20].

The gas condensate reservoir is being developed for depletion using 5 production wells. The gas flow rate of the producing well is 50 th.m^3/day. Injection of carbon dioxide is carried out at a rate of 50 th.m^3/day per well. The distance between the production wells is 400 m.

The study was carried out to inject carbon dioxide into a productive reservoir using 4, 6, 8, 12, 16 injection wells, evenly spaced at the boundary of the initial gas-water contact. The distance between the wells is 1100, 800, 600, 400, 300 meters, respectively. Development of the productive reservoir is carried out until the moment of breakthrough of carbon dioxide into the last production well.

In the course of the research, for the option with the injection of non-hydrocarbon gas into productive reservoirs, the moment of carbon dioxide breakthrough into each of the production wells was recorded. In order to assess the magnitude of the effect obtained from the introduction of the technology under study in the development of the productive reservoir for depletion, the production wells were stopped at the same time as in the development of the reservoir with the injection of carbon dioxide.

Carrying out research for a different number of injection wells determines a different duration of the production wells operation period until the breakthrough of carbon dioxide into the production wells. Taking into account the above, for each development option of a reservoir with injection of carbon dioxide, a depletion development option was calculated in accordance with the duration of the production wells operation period, due to different pattern arrangement of the injection wells.

Based on the studies carried out, the calculation of the main technological indicators of the development of the productive reservoir at the time of the breakthrough of carbon dioxide into one of the production wells was carried out according to the amount of produced formation water at the time of its breakthrough. The research results were processed in the form of graphical dependencies of the studied parameters at the time of the breakthrough of carbon dioxide into one of the production wells, depending on the pattern arrangement of the injection wells.

6. Research results

The results of the studies performed indicate a significant effect on the gas recovery factor of the pattern arrangement of injection wells.

Analyzing the results of modeling the development of productive reservoirs, it was found that when carbon dioxide is injected at the boundary of the initial gas-water contact, the formation pressure is maintained at a higher level compared to the development of reservoirs for depletion.

The dynamics of reservoir pressure over time for a different number of injection wells with carbon dioxide injection is shown in Fig. 1.

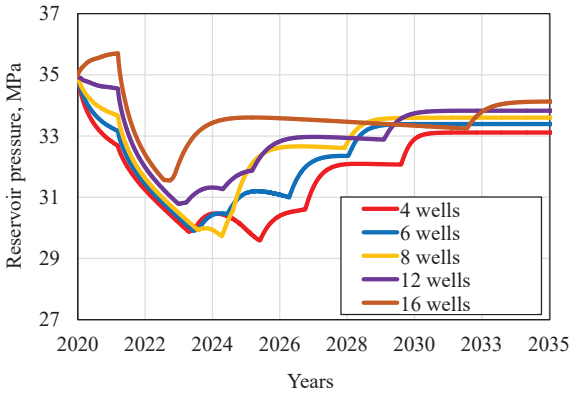


Fig. 1. Dynamics of reservoir pressure over time during injection of carbon dioxide for a different number of injection wells

Analyzing the results, it is necessary to pay attention to the nature of the dependences of the dynamics of reservoir pressure in time. The resulting nature of the change in reservoir pressure over time is due to the shutdown of production wells due to the breakthrough of carbon dioxide, or watering. Also, a significant influence on the nature of the formation pressure change is active in the water drive system and the movement of formation water into productive reservoirs, due to which there is a partial compensation of the value of the average formation pressure in the process of developing the productive formation.

Based on the results of the calculations, it was found that an increase in the number of injection wells from 4 to 8 at the time of the breakthrough of carbon dioxide in producing wells significantly affects the average reservoir pressure in productive reservoirs. However, the subsequent increase in the number of injection wells leads to an increase in the average reservoir pressure in productive reservoirs. When providing a distance ratio of 2.75:1 between production and injection wells, the maximum value of reservoir pressure is reached at the moment of breakthrough of carbon dioxide into the production wells.

Dependences of reservoir pressure on the number of injection wells at the time of the breakthrough of carbon dioxide into the producing wells and during the development of the reservoir for depletion are shown in Fig. 2.

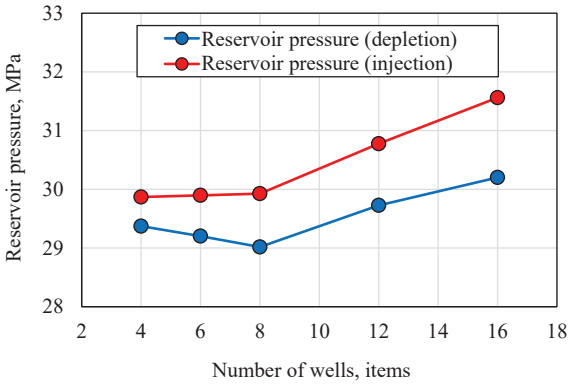


Fig. 2. Dependences of reservoir pressure on the number of injection wells at the moment of breakthrough of carbon dioxide into production wells and during the development of a reservoir for depletion

Analyzing the breakthrough time of carbon dioxide in the production wells, it was found that an increase in the number of injection wells from 4 to 8 wells leads to an increase in the time of carbon dioxide breakthrough into the production wells from 44 to 47 months. The next compaction of the grid of injection wells from 8 to 16 wells leads to a sharp decrease in the breakthrough time from 47 to 34 months.

Based on the simulation results, it should be noted the volumes of produced water depending on the pattern arrangement of injection wells with the injection of carbon dioxide at the initial gas-water contact. According to the results obtained, it was found that the production of formation water decreases with an increase in the pattern arrangement of the well grid. In the case of using 4 wells to inject carbon dioxide into a productive reservoir, the accumulated production of formation water amounted to 169.71 th.m^3. With an increase in the number of injection wells to 16, the altimate comulative water production decreased to 0.066 m^3.

The dynamics of cumulative production of formation water over time during injection of carbon dioxide for different numbers of injection wells is shown in Fig. 3.

On the basis of the analysis of the main technological indicators of the development of the productive capacity for depletion and with the injection of carbon dioxide into the productive reservoirs, it was found that the introduction of the technology for injecting non-hydrocarbon gas at the gas-water contact boundary leads to a reduction in the production of water. According to the results of modeling the process of injection of carbon dioxide, there is a slowdown in the advancement of formation water into productive reservoirs, which leads to a greater reliability of the production capabilities of the field.

Analyzing the concentration of carbon dioxide at the time of its breakthrough into production wells for different numbers of injection wells, it was found that an increase in the density of injection wells leads to a more complete coverage of the perimeter of gas content with carbon dioxide. Due to this, the blocking of water movement takes place over a larger area of the field, as a result of which a significant efficiency of the use of carbon dioxide is manifested in effectively blocking formation water.

The concentration of carbon dioxide at the moment of breakthrough into production wells using 8 and 16 injection wells is shown in Fig. 4.

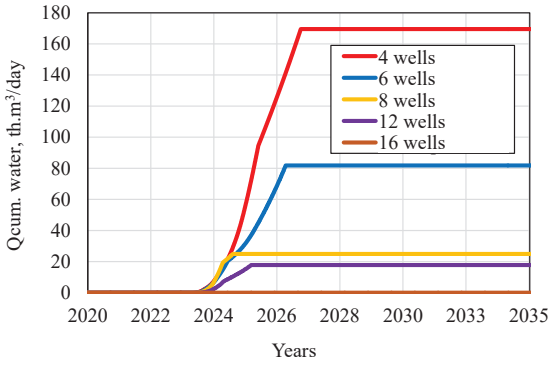
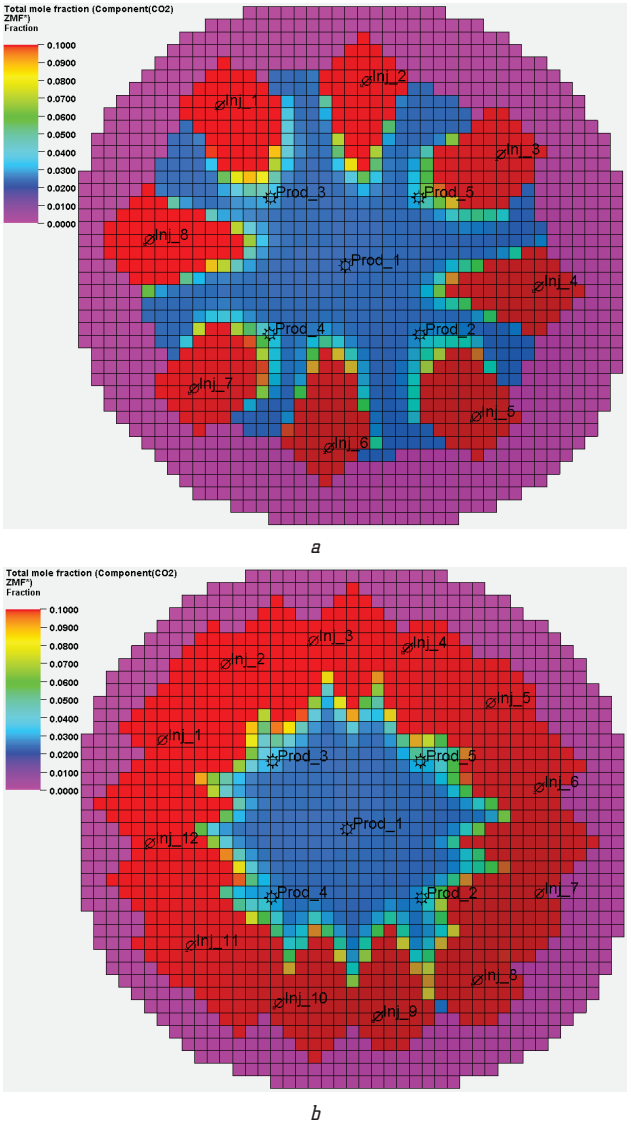


Fig. 3. Dynamics of cumulative production of formation water over time for a different number of injection wells during injection of carbon dioxide



a

b

Fig. 4. Concentration of carbon dioxide at the moment of breakthrough into production wells using: *a* – 8 injection wells; *b* – 16 injection wells

ISSN 2664-9969

Based on the obtained modeling results, the calculation of the value of the natural gas recovery factors at the time of the breakthrough of carbon dioxide in the producing wells was carried out according to the value of the comulative water production. Analyzing the dependence of the gas recovery factor depending on the pattern arrangement of injection wells at the time of the breakthrough of carbon dioxide into production wells, it was found that with an increase in the number of injection wells from 4 to 8, the maximum value of the gas recovery factor is 44.87 %. A further increase in the number of injection wells leads to a sharp decrease in hydrocarbon production due to the rapid breakthrough of carbon dioxide into production wells. The dependences of the gas recovery factor on the number of injection wells at the time of the breakthrough of carbon dioxide into the production wells are shown in Fig. 5.

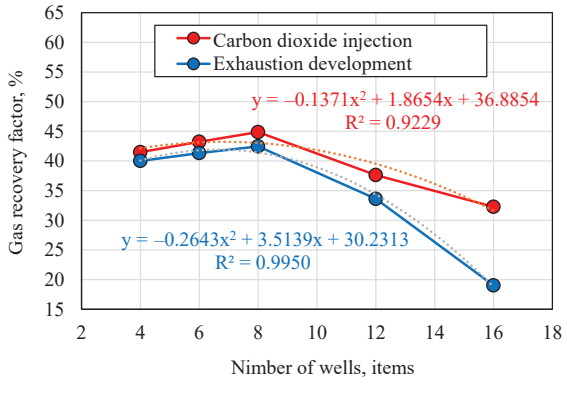


Fig. 5. Dependence of the gas recovery factor on the number of injection wells at the time of the breakthrough of carbon dioxide in the production wells

The gas recovery factor for the variant with the injection of dioxide, depending on the number of injection wells, 4 wells – 41.48 %; 6 wells – 43.24 %; 8 wells – 44.87 %; 12 wells – 37.63 %; 16 wells – 32.27 %.

For the option of developing productive reservoirs for depletion, the gas recovery factor, depending on the number of injection wells, 4 wells – 40.01 %; 6 wells – 41.33 %; 8 wells – 42.46 %; 12 wells – 33.61 %; 16 wells – 19.03 %.

Based on the results of statistical processing of the calculated data, the optimal and maximum values of the number of injection wells were determined when injecting carbon dioxide into the reservoir. The optimal value of the number of injection wells at the time of the breakthrough of carbon dioxide into the first production well is 7.86 (8) wells. The maximum value of the number of injection wells according to the results of statistical processing is 6.8 (7) wells. The optimal ratio of the distance between the production and injection wells is 1.53:1 (612:400 m), and the maximum ratio is 1.8:1 (720:400 m).

The final gas recovery ratio for the given optimal ratio of the distance between injection and production wells is 62.07 %, for the maximum – 63.52 %. When developing productive reservoirs for depletion, the final gas recovery factors for the optimal and maximum ratio of the distance between injection and production wells are 50.67 % and 51.72 %, respectively.

7. SWOT analysis of research results

Strengths. On the basis of the studies carried out according to the results of statistical processing of the calculated data, the optimal and maximum values of the number of injection wells for injecting carbon dioxide into the reservoir were determined. According to the analysis of the results of the studies carried out, the technological efficiency of using non-hydrocarbon gases, namely carbon dioxide, to control and regulate the movement of produced water was established. Thanks to the introduction of this technology, at the initial stages of the development of natural gas fields, gas entrapment by formation water is prevented and the final coefficients of hydrocarbon production are provided significantly higher. According to the research results, for the optimal number of injection wells, an increase in the gas recovery factor of 11.4 % is achieved, compared to the development of a reservoir for depletion. The increase in the recovery factor for the maximum number of injection wells is 11.8 %.

Weaknesses. The study of the influence of the pattern arrangement of injection wells on the natural gas recovery factor was carried out on a homogeneous model of a gas condensate reservoir. Taking into account the significant heterogeneity of hydrocarbon reservoirs both in area and in thickness, the dependences obtained based on the results of the studies carried out for a real field may be of a different nature. To confirm the effectiveness of the introduction of technologies for injecting carbon dioxide in production, it is advisable to conduct additional hydrodynamic studies using permanent geological and technological models of hydrocarbon deposits.

Opportunities. The introduction of the technology for injecting carbon dioxide into a productive reservoir on the border of gas-water contact in production with the aim of slowing down the advancement of the reservoir will provide significantly higher final of hydrocarbon recovery factors. The increase in hydrocarbon production from depleted and watered hydrocarbon fields necessitates the use of the results of this kind of research in order to improve the existing development technologies not only at Ukrainian fields, but also in world practice.

Threats. To implement the technology of injecting carbon dioxide into productive reservoirs to reduce the negative impact of edge waters on the natural gas production process, it is necessary to determine the source of its supply to the field. On an industrial scale, carbon dioxide is emitted from flue gases. Air can be an alternative source of carbon dioxide production. The construction of an air separation unit produces nitrogen, carbon dioxide and argon.

8. Conclusions

1. Using a digital three-dimensional model of a gas-condensate position, the influence of the pattern arrangement of injection wells on the coefficient of gas recovery factor during the injection of carbon dioxide at the gas-water contact boundary has been investigated in order to slow down the movement of formation water into the productive reservoir. According to the results of the studies, it was found that an increase in the pattern arrangement of injection wells leads to a decrease in the volume of produced water production. Thanks to the introduction of the technology of injecting carbon dioxide into productive reservoirs on the border of gas-water contact, a slowdown in the advance of formation water into gas-saturated horizons is achieved and the process of watering the field and subsequent production of natural gas becomes more controllable.

Analyzing the concentration of carbon dioxide at the time of its breakthrough into production wells for different numbers of injection wells, it was found that an increase in the pattern arrangement of injection wells leads to a more complete coverage of the perimeter of gas content with carbon dioxide. This creates an artificial barrier, which leads to more efficient blocking of produced water.

2. On the basis of the studies carried out according to the results of statistical processing of the calculated data, the optimal and maximum value of the number of injection wells was established. The optimal value of the number of injection wells at the time of carbon dioxide breakthrough is 7.86 (8) wells. The maximum value of the number of injection wells, according to the results of statistical processing, is 6.8 (7) wells.

3. Using the results of the studies carried out on the basis of a three-dimensional digital model of gas condensate, the prediction of the value of the final gas recovery factors was carried out according to the considered modeling options. The final gas recovery factor when injecting carbon dioxide into productive reservoirs for the optimal ratio of the distance between the injection and production wells is 62.07 %, for the maximum – 63.52 %. When developing productive reservoirs for depletion, the final gas recovery factors for the optimal ratio of the distance between injection and production wells are 50.67 %. For the maximum ratio, the recovery factor is 51.72 %. The results of the studies carried out indicate the technological efficiency of injecting carbon dioxide into productive reservoirs at the boundary of the gas-water contact in order to slow down the movement of formation water into productive reservoirs and increase the final coefficient of hydrocarbon production for the conditions of a particular field.

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