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# APPROVAL OF THE TECHNOLOGY OF CARBON DIOXIDE INJECTION INTO THE V-16 WATER DRIVEN RESERVOIR OF THE HADIACH FIELD (UKRAINE) UNDER THE CONDITIONS OF THE WATER PRESSURE MODE

*The object of research is water-driven gas-condensate reservoirs. Using the main hydrodynamic modeling tools Eclipse and Petrel from Schlumberger (USA), the study was carried out to improve the existing technologies for the displacement of residual gas reserves by carbon dioxide from the water-driven gas-condensate reservoirs. The carbon dioxide injection technology was tested in the V-16 reservoir of the Hadiach oil and gas condensate field (Ukraine). According to the study results, it was found that due to the injection of non-hydrocarbon gas, the cumulative water production are reduced compared to the depletion. Based on the obtained modeling results, the calculation of the predicted hydrocarbon recovery factors at the moment of carbon dioxide breakthrough into the production well was carried out according to the cumulative formation water production. According to the calculations, it was found that the implementation of the enhanced gas recovery technology provides significantly higher ultimate hydrocarbon recovery compared to the depletion. The predicted gas recovery factor when injecting carbon dioxide into the V-16 reservoir increases by 2.95 % of the residual gas reserves, and the condensate recovery factor for these conditions by 1.24 %. Based on the study results, the technological efficiency of using carbon dioxide as an injection agent to increase the hydrocarbon recovery from water-driven reservoirs was established. According to the simulation results, the implementation of the technology of carbon dioxide injection into the V-16 reservoir of the Hadiach oil and gas condensate field can significantly increase the hydrocarbon recovery from the deposit, thereby increasing the production capacity of the field.*

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

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## 1. Introduction

The overwhelming majority of productive deposits of gas and gas condensate fields are depleted and are mainly influenced by water-pressure systems and are developed in conditions of the movement of formation water into gas-saturated horizons [1, 2].

The main difficulties that arise during the production of residual hydrocarbon reserves are associated with the peculiarities of the development of deposits at the final stage, which is characterized by low values of reservoir pressure, low production rate and water cut of producing wells [3].

Development of deposits under water-drive conditions is characterized by an uneven movement of the gas-water contact, depending on the nature of the distribution of reservoir properties, both in area and in thickness. The heterogeneity leads to selective flooding of productive deposits and entrapment of residual gas reserves by formation water. Significant reserves of micro- and macro-enclosed gas remain in the watered parts of the reservoir [4].

A significant number of experimental and theoretical studies are devoted to the design of the development of water-driven hydrocarbon deposits [5–7].

Based on the results of the studies, the mechanism of the behavior of the restrained gas by formation water in a porous medium was revealed and a significant number of technologies were developed, but most of them are ineffective and do not find practical implementation. According to the studies [8, 9], it has been established that it is the heterogeneity of productive deposits that introduces significant uncertainty in the process of justifying the recommended technology for further development of hydrocarbon deposits in an active water-drive mode.

In this work, the technology of injecting carbon dioxide into the reservoir of the V-16 horizon of the Hadiach oil and gas condensate field (Ukraine) was tested in order to displace the residual gas trapped by formation water.

## 2. The object of research and its technological audit

*The object of research* is water-driven gas condensate deposits. Based on the analysis of the current state of development of the V-16 horizon, significant residual natural gas reserves have been identified. According to the results of history matching of the simulation model of the reservoir of the V-16 horizon, it was established that part of the residual gas reserves is restrained by formation water.

Solving the problem of increasing the hydrocarbon recovery from the reservoir of the V-16 horizon and minimizing the harmful effect of aquifer waters on the gas recovery process led to the search for new approaches to the development of the reservoir in such conditions.

The need to improve the existing field development technologies under water-drive conditions has led to additional research using the current practice of using a simulation model of the Hadiach oil and gas condensate field.

## 3. The aim and objectives of research

*The aim of research* is to test the technology for displacing residual gas from the pore space with carbon dioxide and regulating the development process for the conditions of the V-16 horizon of the Hadiach oil and gas condensate field using hydrodynamic modeling.

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

1. To investigate the dynamics of the main technological indicators of the development of deposits of the V-16 horizon during the injection of carbon dioxide and during the development of deposits for depletion.

2. To establish the technological efficiency of the introduction of the injection technology of carbon dioxide for the conditions of the V-16 horizon of the Hadiach oil and gas condensate field.

## 4. Research of existing solutions of the problem

There are known methods that are used to prevent and regulate the movement of formation waters and to combat flooding of production wells aimed at minimizing the negative impact of the water-drive mode on the development of deposits and increasing the hydrocarbon recovery factors under such conditions [8, 9].

Along with the problem of controlling and regulating the flow of aquifer waters into the gas-saturated part of the reservoir, an important problem is the production of restrained gas from the watered reservoirs. Today, the direction of increasing gas recovery from flooded gas-condensate fields by injecting non-hydrocarbon gases (nitrogen, carbon dioxide, flue and waste gases, mixtures of various gases) remains promising.

The high technological efficiency of displacement of restrained gas by non-hydrocarbon gases is evidenced by the results of laboratory studies [10, 11]. According to the results of the studies the highest gas recovery factor is achieved when gas is displaced from the flooded reservoir models with carbon dioxide. When using flue gas and nitrogen injection as agents to displace the residual gas from the pore space, the final values of the gas recovery factors are slightly lower.

Analyzing the physical and chemical properties of carbon dioxide, it should be noted that its density is 6 times higher than the density of natural gas in reservoir conditions. Numerous studies have confirmed that carbon dioxide dissolves well in water with increasing pressure, and much worse with increasing temperature and salinity of formation water. Despite the initial thermobaric conditions of occurrence of productive deposits, it can be argued that carbon dioxide will dissolve in the formation water, while slowing down the movement of marginal waters and their subsequent breakthrough to production wells. Due to the high solubility of carbon dioxide, effective displacement of the residual gas from flooded productive deposits is ensured [12].

Based on the results of theoretical studies of the process of injection of carbon dioxide into productive deposits, the effectiveness of its use as an injection agent has been confirmed. Due to the injection of non-hydrocarbon gas at the initial gas-water contact, a decrease in the activity of the water-pressure system is achieved due to the creation of a hydrodynamic barrier at the interface of the two phases and significantly higher ultimate hydrocarbon recovery factors are provided in comparison with depletion [13, 14].

The simulation results indicate that the introduction of the technology under study leads to a delay in the process of watering production wells and ensures their stable and waterless operation during a long period of development of productive deposits [15].

A huge number of studies using numerical modeling have been devoted to the improvement of existing technologies for the development of hydrocarbon deposits [16, 17]. The construction of digital three-dimensional models is an integral attribute of managing the process of developing hydrocarbon fields. Indeed, it is the constantly operating simulation model that is designed to solve the main problems of field development in order to maximize the hydrocarbon recovery reserves and achieve the maximum economic effect. However, the problem of increasing the hydrocarbon yield from hydrocarbon deposits, which are developed under the water-drive, has not been sufficiently studied so far [18].

To develop the optimal ways to recover the restrained gas, a numerical simulation of the development of the northeastern Hitchcock field, located in Texas, was carried out. Calculation of various options for field development made it possible to substantiate the optimal rates of hydrocarbon production and select a rational system for field development [19].

Also a study of the effectiveness of the displacement of residual gas by various injection agents and for a field that is located near the Sierra de Chiapas mountain range in Mexico. Dry gas, carbon dioxide, nitrogen and flue gases were used as injection agents. The results indicate that the most effective option is with the injection of carbon dioxide. Thanks to the introduction of this technology, part of the restrained 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 makes it difficult to move formation water into productive formations. The introduction of reservoir pressure maintenance technology leads to an increase in condensate production and provides significantly hydrocarbon recovery coefficients [20].

According to the results of studies of the injection process of non-hydrocarbon gases into the reservoir, it was found that the highest efficiency of the EOR technology is provided when the injection process is carried out upon reaching an economically viable period of reservoir development [21, 22].

Numerous studies have established that in most cases, in order to ensure a more complete coverage of the productive gas-saturated area of the deposit by development, it would be desirable to completely prevent the movement of aquifer waters into the productive deposits. However, today no practical solution to this problem has been found.

## 5. Methods of research

To test the technology of injecting carbon dioxide into the reservoir of the V-16 horizon of the Hadiach oil and gas condensate field in order to increase the hydrocarbon recovery factors, the main tools of hydrodynamic modeling Eclipse and Petrel from Schlumberger (USA) were used.

The study was carried out on the basis of a simulation model of the Hadiach field. To reproduce the physical processes that take place in the reservoir during the injection of carbon dioxide, a composite PVT model was created using the PVT module and the Eclipse software [23–25].

The gas condensate reservoir is being developed for depletion using 4 production wells (No. 56, 73, 74, 75). Injection of carbon dioxide is carried out using 4 injection wells (No. 52, 101, 201, 202) located around the perimeter of the current gas-water contact. The gas flow rate of the producing well is 50 thousand $m^3$/day. Injection of carbon dioxide is carried out at a rate of 50 thousand $m^3$/day per well. The development of the pay zone is carried out until the breakthrough of carbon dioxide into the last of the producing wells.

The layout of injection and production wells in the area of the V-16 horizon of the Hadiach oil and gas condensate field is shown in Fig. 1.

In the course of research, for the option with the injection of non-hydrocarbon gas into the productive deposits, 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 a productive reservoir for depletion, the production wells were stopped at the same time as in the development of a reservoir with injection of carbon dioxide.

Based on the studies, 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.

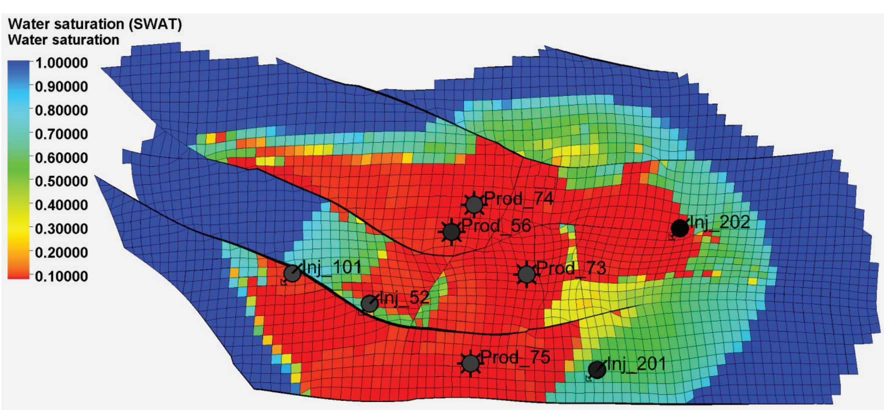


**Fig. 1.** Layout of injection and production wells in the area of the V-16 horizon of the Hadiach oil and gas condensate field

## 6. Research results

Using a simulation model of the Hadiach oil and gas condensate field, a study of the efficiency of the technology of injecting carbon dioxide into the productive reservoir of the V-16 horizon was carried out in order to increase the ultimate hydrocarbon recovery factor.

Analyzing the results of modeling the development of the reservoir of the V-16 horizon, it was found that when injecting carbon dioxide, the reservoir pressure is maintained at a higher level compared to the depletion.

The nature of the dynamics of reservoir pressure over time is due to the intensive movement of reservoir water into the reservoir and shutdown of production wells due to flooding or breakthrough of carbon dioxide. If the well is shut down for one of the above reasons, the production of natural gas from the reservoir decreases, which leads to a decrease in the rate of reservoir pressure drop.

The dynamics of reservoir pressure over time during the development of deposits of the V-16 horizon for depletion and injecting carbon dioxide is shown in Fig. 2.

Analyzing the dynamics of reservoir pressure, it should be noted that after the shutdown of the last production well, an intensive increase in reservoir pressure occurs. This character of the dependence is due to the further advancement of the aquifer waters into the gas-saturated intervals of the productive position and balancing of the hydrodynamic system.

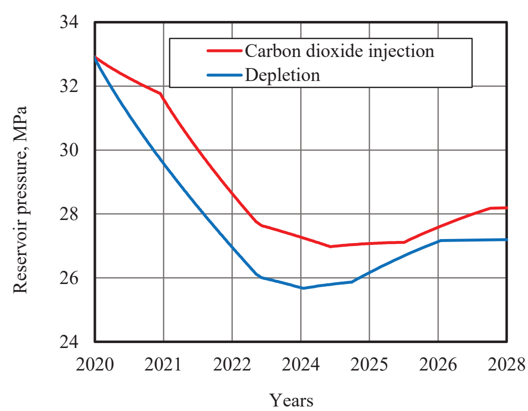


**Fig. 2.** Dynamics of reservoir pressure over time during the development of deposits of the V-16 horizon for depletion and injecting carbon dioxide

According to the simulation results, it was found that when injecting carbon dioxide, an additional hydrodynamic barrier is created, due to which there is a partial blocking of the movement of formation water through the most highly permeable interlayers in the V-16 horizon. Based on the calculations of the technological indicators of the development of the productive position, it can be argued that due to the introduction of the technology of injection of carbon dioxide, the activity of the water-pressure system decreases.

According to the results of studies of the process of developing a productive reservoir, when injecting non-hydrocarbon gas, a decrease in the volume of produced water is provided in comparison with depletion.

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The dynamics of the cumulative production of formation water during the development of the reservoir of the V-16 horizon of the Hadiach oil and gas condensate field for depletion and with the injection of carbon dioxide is shown in Fig. 3.

Analyzing the dependences of the dynamics of the cumulative production of formation water, it should be noted that in the case of developing a reservoir of the V-16 horizon with the injection of carbon dioxide, the process of watering of production wells is delayed. Despite the difference in the densities of carbon dioxide and natural gas, as well as its solubility in formation water, it can be argued that an artificial barrier has been created at the interface between the two phases. Injection of carbon dioxide leads to blocking of the selective movement of formation water and thereby ensures stable waterless operation of production wells over a long period of reservoir development compared to depletion.

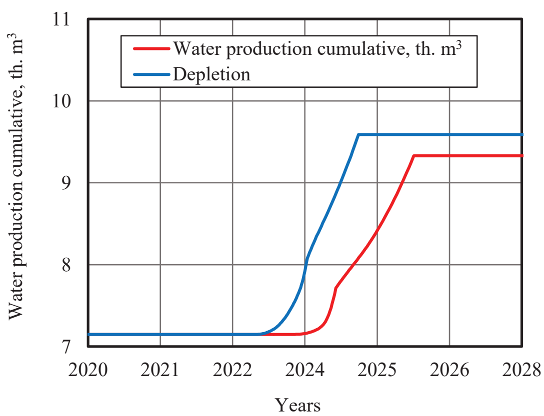



**Fig. 3.** Dynamics of the cumulative production of formation water during the development of the reservoir of the V-16 horizon of the Hadiach oil and gas condensate field for depletion and with the injection of carbon dioxide

The state of water cut in the productive well in the area of production well No. 73 and horizon V-16 is shown in Fig. 4.

Using the results of modeling the development process of the V-16 horizon, the calculation of the value of the hydrocarbon recovery factor by the value of the residual hydrocarbon reserves was carried out.

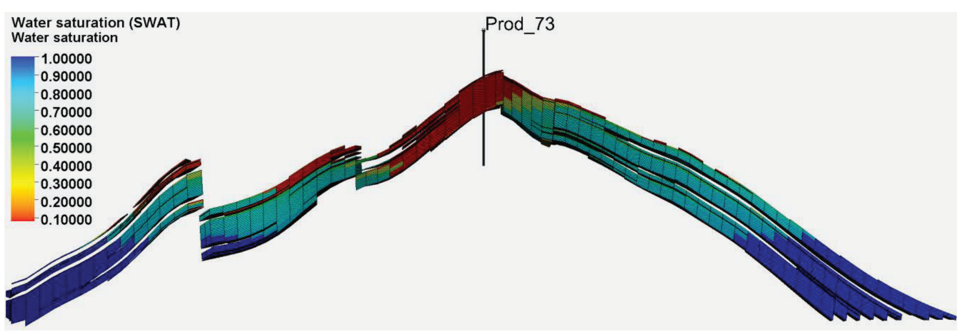
Based on the analysis of the calculated data, it has been established that due to the introduction of the technology for injecting carbon dioxide into the reservoir of the V-16 horizon, a significantly higher predicted gas recovery factor is provided compared to development for depletion.

The dynamics of the predicted gas recovery factor during the development of deposits of the V-16 horizon for depletion and during the injection of carbon dioxide are shown in Fig. 5.

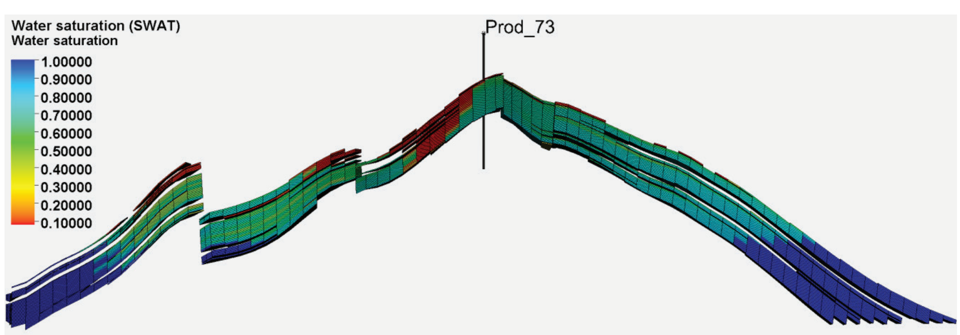
The final gas recovery factor from residual gas reserves during injection of carbon dioxide at the time of its breakthrough into the last production well is 32.56 %. When developing the V-16 gas condensate bed for depletion, the ultimate natural gas recovery factor is 29.61 %. Taking into account the obtained research results, it should be noted that due to the introduction of the injection technology of non-hydrocarbon gases in order to displace micro- and macro-entrained gas, it is possible to increase the ultimate gas recovery factor by 2.95 %.

According to the analysis of the calculation results of the development of the gas condensate bed of the V-16 horizon, an increase in the value of the condensate recovery factor is observed when injecting carbon dioxide as compared to the development of a deposit for depletion.

The dynamics of the predicted condensate recovery factor during the development of deposits of the V-16 horizon for depletion and during the injection of carbon dioxide is shown in Fig. 6.




*a*




*b*

**Fig. 4.** The state of water cut in the productive well in the area of production well No. 73 and the horizon V-16 of the Hadiach oil and gas condensate field: *a* – the beginning of carbon dioxide injection; *b* – at the time of carbon dioxide breakthrough

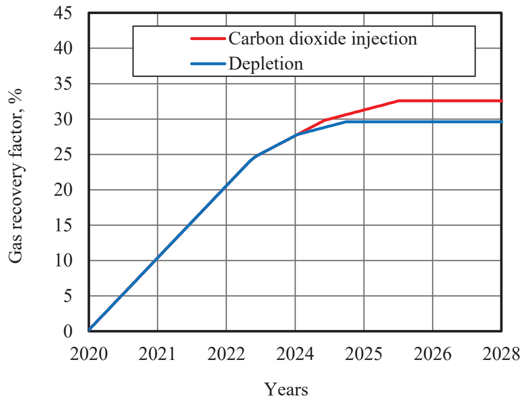



**Fig. 5.** Dynamics of the predicted gas recovery factor during the development of deposits of the V-16 horizon for depletion and injecting carbon dioxide

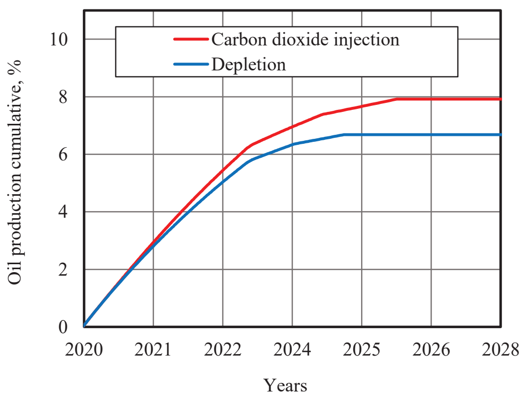



**Fig. 6.** Dynamics of the predicted condensate recovery factor during the development of the V-16 horizon for depletion and during the carbon dioxide injection

The gas condensate reservoir of the V-16 horizon is characterized by a high potential content of liquid hydrocarbons $C_{5+}$, which is more than 300 g/m$^3$. Despite the fact that due to the carbon dioxide injection into the reservoir of the V-16 horizon, the reservoir pressure is maintained at a higher level compared to depletion development, additional condensate production is provided.

The predicted condensate recovery factor from residual condensate reserves when injecting carbon dioxide at the time of its breakthrough into the last of the producing wells is 7.92 %, and when developing a V-16 horizon for depletion is 6.68 %. According to the results of the calculations, due to the implementation of carbon dioxide injection technology, the ultimate condensate recovery factor increases by 1.24 % in terms of the residual condensate reserves.

The results of the studies indicate the technological efficiency of injecting carbon dioxide into productive deposits to regulate the advancement of marginal waters and displacement of micro- and macro-entrained gas in order to increase the ultimate hydrocarbon recovery factor for the conditions of a particular field.

## 7. SWOT analysis of research results

*Strengths*. Using the results of calculations obtained on the basis of studies of digital models of gas condensate reservoirs, the technology of injecting carbon dioxide into the reservoir of the V-16 horizon of the Hadiach field was tested. According to the results of approbation, the technological efficiency of using carbon dioxide to control and regulate the advancement of marginal waters for the conditions of the V-16 horizon was established. Based on the results of the studies, it was found that when carbon dioxide is injected into the reservoir of the V-16 horizon of the Hadiach oil and gas condensate field, an increase in the gas recovery factor is achieved by 2.95 % compared to the development of the reservoir for depletion. The ultimate condensate recovery factor is increased by 1.24 %.

*Weaknesses*. The research results make it possible to improve the existing development technology of the V-16 horizon of the Hadiach oil and gas condensate field in the conditions of the water-driven development mode. According to the simulation results, carbon dioxide injection provides significantly higher final hydrocarbon recovery rates compared to depletion development. However, the final decision on the implementation of the technology under study should be made on the basis of a comprehensive technical and economic analysis. Since it is the economic assessment that plays a decisive role in making the final decision. Usually, according to the research results, some effective technologies are recommended, but completely different ones are recommended for implementation based on the results of calculations of economic indicators.

*Opportunities*. The technology of injecting carbon dioxide to the conditions of the productive state of the V-16 horizon was tested using a simulation model of the Hadiach oil and gas condensate field. Considering the significant influence of the heterogeneity of hydrocarbon deposits, both in area and in thickness, on the process of choosing the optimal technology for the development of hydrocarbon deposits, it is advisable to conduct additional research in order to ensure maximum hydrocarbon yield. To inject carbon dioxide into the reservoir of the V-16 horizon of the Hadiach field, drilled wells were used at the field. Considering the above, the main task of subsequent studies should be to substantiate the optimal number of production and injection wells, as well as their spatial location in the gas-bearing area. The results of the above studies can be used in the world practice of oil and gas recovery.

*Threats*. If the technology of injecting carbon dioxide into the productive reservoir of the V-16 horizon of the Hadiach oil and gas condensate field is introduced in order to displace the residual gas from the pore space, it is necessary to provide sources of supply of non-hydrocarbon gas to the field. On an industrial scale, carbon dioxide is emitted from flue gases. Air separation technology is also an alternative source of carbon dioxide production. The construction of the air handling unit produces nitrogen, carbon dioxide and argon.

## 8. Conclusions

1. Using the simulation model of the Hadiach oil and gas condensate field, the technology of injecting carbon dioxide to the conditions of the V-16 gas condensate horizon was tested. Based on the research results, the calculation of the main technological indicators of the development of the productive state was carried out. According to the calculations, it was found that due to the carbon dioxide injection, the formation pressure is maintained at a higher level compared to the development of the reservoir for depletion. Thanks to this, an increase in the cumulative production of hydrocarbons is achieved. Based on the analysis of the technological indicators of the development of the V-16 horizon,

it has been established that in the case of the introduction of the technology of carbon dioxide injection, an increase in gas recovery and a sharp decrease in the production of produced water are provided. Considering the above, it can be argued about the high technological efficiency of using carbon dioxide injecting as an agent in order to block the movement of produced water into the productive reservoir of the V-16 horizon and prevent watering of production wells.

2. Using the research results of the development process of the V-16 horizon of the Hadiach oil and gas condensate field, the calculation of the predictive factors in the hydrocarbon yield was carried out according to the considered modeling options. The ultimate gas recovery factor for the carbon dioxide injection at the time of its breakthrough into the last production well is 32.56 %, and the condensate recovery factor is 7.92 %. When developing a productive capacity for depletion, the predicted gas recovery factor is 29.61 %, and the condensate recovery factor is 6.68 %.

According to the simulation results, it is found that thanks to the implementation of the carbon dioxide injection technology, it is possible to increase the ultimate gas and condensate recovery rates by 2.95 % and 1.24 %, respectively.

The research results indicate the technological efficiency of injecting carbon dioxide into the reservoir of the V-16 horizon in order to displace micro- and macro-entrained gas and increase the ultimate hydrocarbon recovery factor. The further feasibility of introducing this technology at gas condensate fields in Ukraine should be determined based on the results of a comprehensive technical and economic analysis.

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