через конструктивные элементы оборудования позволяют устанавливать закономерности взаимосвязи эффективности пенообразования от параметров и режимов работы пеногенерирующих устройств.

При этом:

- определена взаимосвязь между качеством пены и конструктивными особенностями отдельных элементов пеногенерирующего устройства;
- экспериментально обоснованы аналитические зависимости движения потоков жидкости, воздуха и пены и эффективности работы пеногенерирующих устройств от их конструктивных особенностей;
- научно обоснован метод выбора оптимальных конструктивных форм элементов пеногенерирующих устройств, влияющих на формирование потоков жидкости, воздуха и пены.

Практическая значимость. Определены оптимальные геометрические формы и параметры, установлены оптимальные режимы работы пеногенерирующих устройств, которые являются основой для создания новых высокоэффективных устройств. Предложен ряд методов и средств конструктивного и технологического характера для повышения эффективности промывки скважин пенистыми растворами. Результаты использованы при совершенствовании насосно-циркуляционной системы для промывки скважин пенистыми растворами.

Ключевые слова: *пятисопловое пеногенерирующее устройство, бурение пенами, газожидкостная смесь, аэрированные жидкости, пенные растворы*

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ENHANCED GAS RECOVERY FROM DEPLETED GAS FIELDS WITH RESIDUAL NATURAL GAS DISPLACEMENT BY NITROGEN

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ПІДВИЩЕННЯ СТУПЕНЯ ВИЛУЧЕННЯ ГАЗУ З ВИРОБЛЕНОГО ГАЗОВОГО РОДОВИЩА ВИТІСНЕННЯМ НЕВІДІБРАНОГО ПРИРОДНОГО ГАЗУ АЗОТОМ

Purpose. Evaluation of technological efficiency of a method for increasing final gas recovery from a depleted gas field with residual natural gas displacement by nitrogen.

Methodology. Computer research on the regularities of residual natural gas displacement by nitrogen from a circular shaped depleted gas field using licensed computer program CMG (Computer Modelling Group).

In the research is founded change in time of technological development indicators of gas production from the field for different values of a pressure of early nitrogen injection into the gas field and for duration of injection time.

Findings. According to the results of the computer research on the patterns of residual natural gas displacement by nitrogen from depleted gas field, there is received change of reservoir pressure by the years, flow rate of production well of gas and nitrogen, and gas recovery factor depending on the pressure of early nitrogen injection into the gas field and duration of injection period.

Originality. For the first time regularities of the process of residual natural gas displacement by nitrogen and optimal values of the pressure of early nitrogen injection into the gas field and duration of injection period are obtained for circular shaped depleted gas field.

Practical value. Injection of nitrogen into depleted gas field for the corresponding values of pressure of early nitrogen injection and duration of the period of its injection allows intensifying the process of further development of the field as well as increasing the current production of gas and gas recovery factor by 5–10 %.

Keywords: *field, well, gas, nitrogen, injection, gas recovery, pressure, flow rate*

Introduction. The most part of gas fields of Ukraine is largely exhausted. Some of them are at the final phase of gas production. There are still significant residual gas reserves in the depleted fields. According to actual data on fields, the development of which is completed, the final gas recovery factor is 85–90 % on average under gas mode. Due to limited gas reserves and insufficient volumes of its production, the involvement in the development of residual natural gas from depleted fields may become an additional source of hydrocarbons.

Effective ways to increase the final gas recovery factor from gas fields include: minimizing the values of the final reservoir pressure; creating conditions for the uniform production of productive fields according to square and gas-saturated section in the process of gas field development and the same (close) values of the final reservoir pressure in different parts of the reservoir; the displacement of residual gas from depleted gas field by nitrogen, carbon dioxide, flue gases [1]. The article presents the results of investigations of the regularities of residual natural gas displacement by nitrogen from circular shaped depleted gas field.

Analysis of the recent research and publications. The laboratory and theoretical research studies are completed to the effectiveness of displacement of residual gas from depleted gas field on non-hydrocarbon gases. Results of the experiments with displacement of methane by non-hydrocarbon gases from models of reservoir indicate high technological efficiency of this method for raising the gas recovery factor. Among the studied non-hydrocarbon gases carbon dioxide features the most displacing capacity [2]. Displacement ratio of methane with carbon dioxide in experiments reached 81–97.4 %. Flue gases and nitrogen have less displacing abilities.

According to the simulation results it is defined that high rates and early stages of injection have a higher gas recovery, but economically this will contaminate the production due to early breakthrough of carbon dioxide [3].

According to the results of theoretical studies of displacement of residual gas from depleted gas field by carbon dioxide gas recovery factor increases with the decrease in the pressure of early carbon dioxide gas injection into the layer [4]. However, the displacement of residual gas from depleted gas field with non-hydrocarbon gas at the minimum pressure “backing up” may be uneconomical due to low flow rates of wells.

The paper [5] presents the results of theoretical studies on displacement of natural gas by nitrogen from a hypothetical gas field in the form of a square with four production wells in the corners of the square and a central injection well for different values of pressure of early nitrogen injection into the gas field and for duration of injection time. The results of the performed studies indicate that the degree of gas recovery from depleted gas field can be regulated by the choice of pressure of early nitrogen injection into the gas field and for duration of injection time. However, because of the hypothetical (square) form of the field, which differs from real fields, the results of the performed research cannot be fully used in practice. Therefore, in order to assess the effect of pressure of early nitrogen injection into depleted gas field and the duration of injection time on the degree of gas recovery factor, a complex of theoretical studies.

Unsolved aspects of the problem. In known publications of the considered problem no data is present about the impact of the pressure of early nitrogen injection and duration of injection period into the circular shaped depleted gas field on gas recovery factor. This served as the basis for surveying the fields of circular form.

Objectives of article are as follows: according to the results of computer research studies on residual natural gas displacement by nitrogen from the circular shaped depleted gas field to obtain patterns in change of reservoir pressure, flow rate of production well of gas and nitrogen, nitrogen content in extracting production and gas recovery factor by years for different values of the pressure of early nitrogen injection and duration of injection period, and to find optimal values for parameters of the process of nitrogen injection into the depleted gas field.

Presentation of the main research. Non-hydrocarbon gases are increasingly used in oil and gas industry. They are used on an industrial scale to maintain reservoir pressure in oil fields in order to increase the oil recovery factor and as a substitute cushion gas in underground storage facilities. Among the non-hydrocarbon gases (carbon dioxide, flue gases, nitrogen) the highest displacement capacity as for oil, gas condensate and natural gas is featured by carbon dioxide. The main amount of carbon dioxide is contained in flue gases. In most cases, enterprises producing flue gases are located at a considerable distance from the produced gas fields. Therefore, considerable expenses are required for transporting flue gases from their place of receipt to gas fields. Use of nitrogen as a non-hydrocarbon gas is more rational. There are known simple and worked out technologies for obtaining nitrogen from the air and industry plants for their implementation, which can be constructed directly on the field. Therefore, nitrogen is used in the research in the role of a working agent to displace residual natural gas from depleted gas field.

Research methodology and output. To assess the impact of characteristics of the process of injection of nitrogen to circular shaped depleted gas field, computer research was conducted using licensed computer software CMG (Computer Modelling Group). The research was performed using a circular hypothetical gas field with the following parameters: the radius of gas content contour – 3000 m, an area of the field – $28.26 \cdot 10^6$ m^2, the thickness of the reservoir – 12 meters, open porosity ratio – 0.14, the rate of initial gas saturation – 0.78, the coefficient of permeability of the reservoir – 0.2 mkm^2, the depth of the reservoir (average depth of wells) – 3200 m, initial reservoir pressure – 33 MPa, reservoir temperature – 340 K, the relative density of the gas – 0.6, compressibility factor at initial reservoir pressure and temperature – 0.979 initial gas reserves calculated by CMG program – 11.713 billion m^3.

Depleted field is developed by 12 production wells located at a distance of 1500 meters from the centre of the circular layer. The distance between the wells is 785 meters. Exploitation of wells is done in a mode of constant depression on layer – 0.02 MPa. The initial flow rate of one gas well at the beginning of the development of the field amounted to 125 m^3/day.

After reducing the reservoir pressure on a certain amount from the initial pressure, injection of nitrogen into the reservoir is started through 12 injection wells, which are located on the contour of gas content layer with the distance of 1570 meters between the wells.

During the injection of nitrogen into the reservoir through injection wells operation of production wells was continued. The rate of injection of nitrogen in the field is assumed to be equal to the rate of sampling gas from the reservoir, taking into account the gas compressibility factor. As a result, the continuity of reservoir pressure during the period of the nitrogen injection into the layer is maintained.

The research was conducted for variants of injection of nitrogen in the field after reduction of reservoir pressure to 0.5; 0.4; 0.3; 0.2; 0.1 from the initial pressure. In each variant, the injection of nitrogen into the reservoir was carried out at different time periods: 6, 12, 18, 24, 30 and 36 months.

Research results. The gas field is put into development on the 1st of January, 2016. The technological parameters of the field development were calculated after 1 year. For each time point there was found reservoir pressure, flow rate of gas and nitrogen production well, nitrogen content in downhole production and gas recovery factor. The calculations of field development indices of attrition without nitrogen injection into the reservoir were performed for additional comparison. Graphical dependencies of changes during the years in technical indicators of developed gas field depending on the pressure of early nitrogen injection into the layer and duration of injection period were built according to calculation results. In the work, graphical dependencies are presented for individual process parameters only for the period from 2021 for better visibility. In the version with a decrease in reservoir pressure to 0.5 from the initial pressure the injection of nitrogen in the field was initiated on 01.12.2023 and in other versions – later.

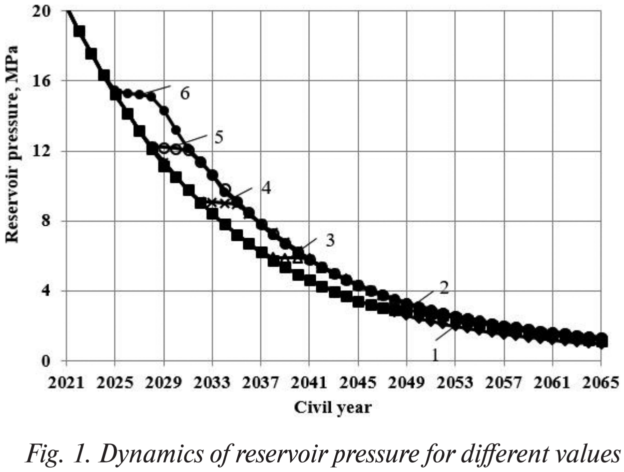


Fig. 1. Dynamics of reservoir pressure for different values of early nitrogen injection pressure into field for the duration of the period of injection equal to 36 months: 1 – depletion; 2 – 0.1 P_{init}; 3 – 0.2 P_{init}; 4 – 0.3 P_{init}; 5 – 0.4 P_{init}; 6 – 0.5 P_{init}

Fig. 1 shows dependencies of changes in time of reservoir pressure in the gas field for different values of the pressure of early nitrogen injection into the reservoir for the duration of injection period equal to 36 months. These graphic dependencies have horizontal platforms for each pressure of early nitrogen injection into the field throughout the period of the injection. Earlier injection of nitrogen into the field and the increase in the duration of the injection period allows maintaining the bigger reservoir pressure in the future development of gas field. Dependencies of reservoir pressure presented in Fig. 1 do not overlap each other and the difference between reservoir pressure values decreases over time.

During the injection of nitrogen into gas field production rate is maintained constant and is higher than in the development of attrition, and then decreases. Fig. 2, for example, shows the corresponding dependencies for the duration period of nitrogen injection into gas field equal to 36 months. After nitrogen break into gas production wells, flow rate decreases sharply and becomes smaller than in the development of attrition, and the nitrogen flow rate increases. Fig. 2 shows the intersection between the respective dependencies.

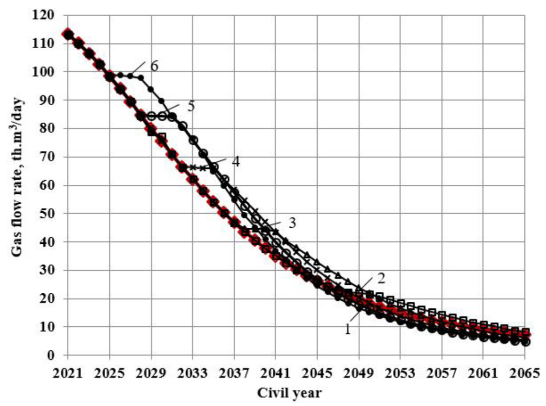


Fig. 2. Dynamics of gas flow rate for different values ofearly nitrogen injection pressure into field for the duration of the period of injection equal to 36 months: 1 – depletion; 2 – 0.1 P_{init}; 3 – 0.2 P_{init}; 4 – 0.3 P_{init}; 5 – 0.4 P_{init}; 6 – 0.5 P_{init}

During injection of nitrogen in gas field reservoir pressure is maintained greater than in the development. As a result, the gas flow rate pressure at the wellhead increases, which allows intensifying gas production and reducing the costs of gas preparation and transportation.

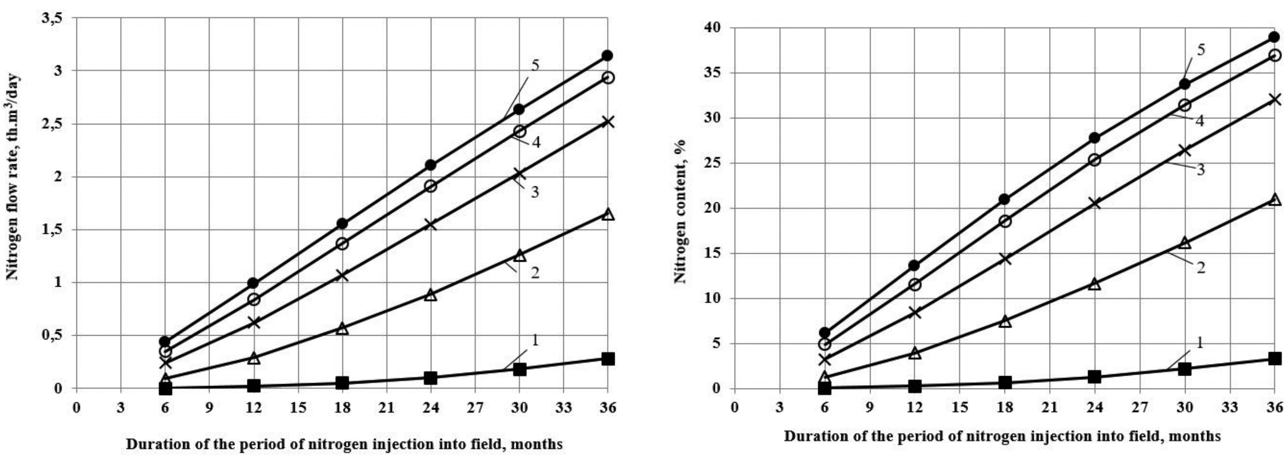
The time of nitrogen breakthrough in production wells depends on the pressure of early injection in the field and duration of the injection period. The earlier start of nitrogen injection in the field and the greater duration of its injection period lead to faster breakthrough in production wells (Table). During changes in pressure of early nitrogen injection in the field from 0.3 to 0.5 P_{init} duration of nitrogen breakthrough in production wells for individual values of duration of injection period is constant. For values of 0.3, 0.4 and 0.5 P_{init} of pressure of early nitrogen injection in the field and duration of injection period equal 24 months or more, nitrogen breakthrough in production wells for the same time is 3.33 years.

Table

Duration of the period from the beginning of nitrogen injection into field to its breakthrough in production wells

The duration of nitrogen injection in the field, months	Duration of the period from the beginning of nitrogen injection into field to its breakthrough in production wells for various pressures of early nitrogen injection, years				
	0.1 P_{init}	0.2 P_{init}	0.3 P_{init}	0.4 P_{init}	0.5 P_{init}
6	5.67	4.59	4.25	4.25	4.25
12	4.84	3.92	3.67	3.67	3.67
18	4.42	3.67	3.42	3.42	3.42
24	4.25	3.59	3.33	3.33	3.33
30	4.25	3.59	3.33	3.33	3.33
36	4.25	3.59	3.33	3.33	3.33

With increasing pressure of early nitrogen injection in the field and the duration of the period of its injection, the flow rate of nitrogen and its quantity in production gas increase. Fig. 3 shows the corresponding graphic dependencies at the end of the settlement period (01.01.2065). According to the calculation results increasing pressure of early nitrogen injection in the field leads to decrease of its impact on nitrogen flow rate and its quantity in downhole products.



a *b*

Fig. 3. Dependence of nitrogen flow rate (a) and nitrogen content in extracting gas (b) on the duration of the nitrogen injection period into the field for different pressures of early nitrogen injection (01.01.2065):
1 – 0.1 P_{init}; 2 – 0.2 P_{init}; 3 – 0.3 P_{init}; 4 – 0.4 P_{init}; 5 – 0.5 P_{init}

With pressure of early nitrogen injection in the fields equal 0.1 P_{init}, nitrogen flow rate and its contents in the well products for different duration of nitrogen injection period into the reservoir are equal to: under 6 months – 0 th. m^3/day and 0.04 %; 12 months – 0.02 thousand m^3/day and 0.23 %; 18 months – 0.05 thousand m^3/day and 0.64 %; 24 months – 0.1 thousand m^3/day and 1.26 %; 30 months – 0.18 thousand m^3/day and 2.16 %; 36 months – 0.28 thousand m^3/day and 3.25 %.

With pressure of early nitrogen injection in the fields equal to 0.3 P_{init} nitrogen flow rate and its contents in the well products for different duration of nitrogen injection period into the reservoir are equal to: under 6 months – 0.24 thousand m^3/day and 3.24 %; 12 months – 0.62 thousand m^3/day and 8.4 %; 18 months – 1.07 thousand m^3/day and 14.36 %; 24 months – 1.55 thousand m^3/day and 20.54 %; 30 months – 2.03 thousand m^3/day and 26.44 %; 36 months – 2.52 thousand m^3/day and 32 %.

According to calculation results volume of 5 % of nitrogen in the well products is achieved with such values of pressure of early nitrogen injection and the duration of the injection period: 0.2 P_{init} – 13.866 months; 0.3 P_{init} – 8.047 months; 0.4 P_{init} – 6.117 months; 0.5 P_{init} – 4.918 months. For 20 % volume of nitrogen in the well products the following values were received: 0.2 P_{init} – 34.833 months; 0.3 P_{init} – 23.476 months; 0.4 P_{init} – 19.253 months; 0.5 P_{init} – 17.267 months.

In order to reduce the amount of nitrogen extracted, it is expedient to stop the production wells earlier, for example, by volume content of nitrogen in well products of 5 %. As results of the calculations show, the gas recovery factor does not increase at higher nitrogen content in well products. You can also use special equipment to separate nitrogen from well products, and then throw it into the air or return to the layer through the injection wells.

Gas recovery factor increases with raising pressure of early nitrogen injection in the field and its duration of the injection period (Figs. 4 and 5). On 01.01.2065 for values of the period duration of the nitrogen injection in field from 6 to 36 months and different pressure values for beginning its pumping, the gas recovery factor changes in the following ranges: 0.1 P_{init} – 91.86–93.09 %; 0.2 P_{init} – 92.24–94.54 %; 0.3 P_{init} – 92.47–94.96 %; 0.4 P_{init} – 92.59–95.07 %; 0.5 P_{init} – 92.65–95.18 %.

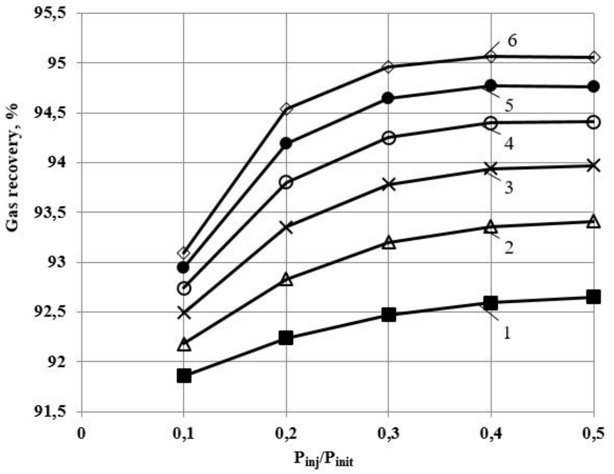


Fig. 4. Dependence of gas recovery factor from the pressure of early nitrogen injection in the field for various values of the duration of nitrogen injection period (on 01.01.2065 year):
1 – 6 months; 2 – 12 months; 3 – 18 months; 4 – 24 months; 5 – 30 months; 6 – 36 months

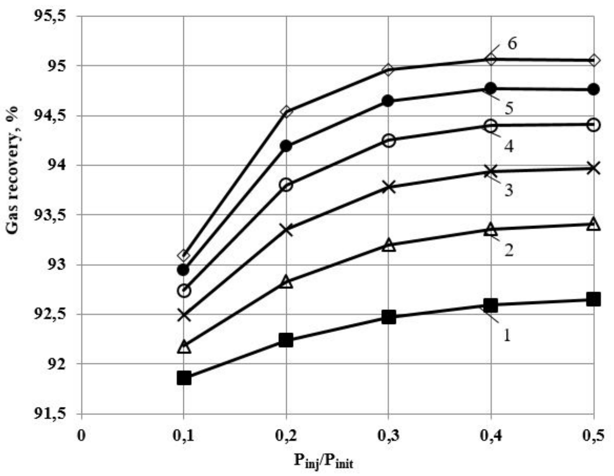


Fig. 5. Dependence of the gas recovery factor on the duration of the period of nitrogen injection in field for different values of the pressure of early nitrogen injection (01.01.2065):
1 – 0.1 P_{init}; 2 – 0.2 P_{init}; 3 – 0.3 P_{init}; 4 – 0.4 P_{init}; 5 – 0.5 P_{init}

The rate of growth of the gas recovery factor decreases with increasing of the pressure of early nitrogen injection in the field and the duration of its injection period, influence on the gas recovery factor gradually decreases and related graphics dependencies in Figs. 4 and 5 became aligned. As a result of statistical processing of numerical data determined "critical" (optimal) values of the studied parameters above which gas recovery factor is changed little.

Critical value of the pressure of early nitrogen injection in the field for different duration period of its injection is: 6 months – 0.293 P_{init}; 12 months – 0.292 P_{init}; 18 months – 0.29 P_{init}; 24 months – 0.28 P_{init}; 30 months – 0.286 P_{init}; 36 months – 0.284 P_{init}; average value for 6–36 months – 0.29 P_{init}.

Critical value for the duration of the period of nitrogen injection in the field at different pressure of early nitrogen injection is: 0.1 P_{init} – 20.826 months; 0.2 P_{init} – 20.323 months; 0.3 P_{init} – 20.04 months; 0.4 P_{init} – 19.737 months; 0.5 P_{init} – 19.596 months. Average value within changes from 0.1 to 0.5 P_{init} of the pressure of early nitrogen injection in the field is about 20 months.

For pressure of early nitrogen injection in the field equal to 0.29 P_{init} and duration of injection period equal to 20 months the gas recovery factor is 94.02 % on 01.01.2065.

While developing a gas field on depletion with reservoir pressure reduced to 0.1 P_{init}, which is often taken researches as an economic limit of profitable field development, gas recovery factor amounted to 81.79 %. During development of the fields using nitrogen injection with critical parameters gas recovery factor for the current reservoir pressure of 0.1 P_{init} is 85.95 %, which is 4.16 % more than in the developing field on attrition without nitrogen injection.

Conclusion. According to the results of the computer research on residual natural gas displacement by nitrogen from depleted gas field for the first time there are established patterns of change in time (by years) of technological indicators of development (reservoir pressure, flow rate of producing wells for gas and nitrogen, and gas recovery factor) for different values of the pressure of early nitrogen injection and the duration of its injection period. Optimal values of the pressure of early nitrogen injection (0.29 from initial pressure) and the duration of injection period (20 months) are defined. With these critical parameters values, higher values of gas recovery factor are achieved compared to the development on depletion. As a result of maintaining on the higher level of current reservoir pressure during the injection of nitrogen into the field, gas flow rate and pressure at the wellhead increase. This allows increasing current gas production and efficiency of the system of gas collection and preparation.

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Мета. Оцінка технологічної ефективності методу підвищення ступеня вилучення газу з виробленого газового родовища шляхом витіснення невідібраного природного газу азотом.

Методика. Комп'ютерне дослідження закономірностей витіснення невідібраного природного газу азотом з виробленого газового родовища кругової форми за допомогою ліцензованої комп'ютерної програми CMG (Computer Modelling Group). У дослідженнях знаходили зміну в часі технологічних показників видобування газу з родовища для різних величин тиску початку нагнітання азоту в родовище й тривалості періоду нагнітання.

Результати. За результатами комп'ютерного дослідження закономірностей витіснення невідібраного природного газу азотом з виробленого газового родовища отримано зміну за роками пластового тиску, дебіту видобувної свердловини по газу та азоту, і коефіцієнта вилучення газу залежно від тиску початку нагнітання азоту в родовище й тривалості періоду нагнітання.

Наукова новизна. Уперше для виробленого газового родовища кругової форми отримані закономірності витіснення невідібраного природного газу азотом та оптимальні величини тиску початку нагнітання азоту в родовище й тривалості періоду нагнітання.

Практична значимість. Нагнітання азоту у вироблене родовище газу за відповідних величин тиску початку нагнітання азоту й тривалості періоду нагнітання дозволяє інтенсифікувати процес дорозробки родовища, підвищити поточний видобуток газу й ступінь вилучення газу на 5–10 %.

Ключові слова: *родовище, свердловина, газ, азот, нагнітання, вилучення газу, тиск, дебіт*

Цель. Оценка технологической эффективности метода повышения степени извлечения газа из выработанного газового месторождения путем вытеснения неотобранного природного газа азотом.

Методика. Компьютерное исследование закономерностей вытеснения неотобранного природного газа азотом из выработанного газового месторождения круговой формы с помощью лицензированной компьютерной программы CMG (Computer Modelling Group). В исследованиях находили изменение во времени технологических показателей добычи газа месторождения для различных величин давления начала нагнетания азота в месторождение и продолжительности периода нагнетания.

Результаты. По результатам компьютерного исследования закономерностей вытеснения неотобранного природного газа азотом из выработанного газового месторождения получено изменение по годам пластового давления, дебита добывающей скважины по газу и азота, и коэффициента извлечения газа в зависимости от давления начала нагнетания азота в месторождение и продолжительности периода нагнетания.

Научная новизна. Впервые для выработанного газового месторождения круговой формы получены закономерности вытеснения неотобранного природного газа азотом и оптимальные величины давления начала нагнетания азота в месторождение и продолжительности периода нагнетания.

Практическая значимость. Нагнетание азота в выработанное месторождение газа при соответствующих значениях давления начала нагнетания азота и продолжительности периода нагнетания позволяет интенсифицировать процесс доразработки месторождения, повысить текущую добычу газа и степень извлечения газа на 5–10 %.

Ключевые слова: *месторождение, скважина, газ, азот, нагнетания, извлечения газа, давление, дебит*

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