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INCREASING NATURAL GAS PRODUCTION FROM TIGHT TERRIGENOUS RESERVOIRS

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Abstract

The paper presents a scientific substantiation of improving enhanced gas recovery technology and current gas production from fields with low-permeable terrigenous reservoirs. In the results of physical and hydrodynamic modeling the regularities of adsorption-desorption processes in tight gas reservoirs were established and the impact of different well placing with interval hydraulic fracturing on the production flow rate and gas recovery factor was estimated. On the basis of this research the existing technologies of enhanced gas recovery from tight reservoirs could be improved, their technological and economic impacts on field performance were established and recommendations for implementation were given.

Keywords:
Tight reservoirs;
Desorption;
Gas recovery factor;
Hydraulic fracturing.

Introduction

Natural gas fields that are being developed in Ukraine, mainly relate to reservoirs with high and medium permeability, most of which are at a stage of declining production. In this situation one of the main sources of additional gas production is unconventional natural gas fields development, which include deposits with low-permeability, low-porosity reservoirs. An additional point is that the number of tight reservoirs will increase with the drilling depth. Existing gas production technologies are characterized by relatively low initial gas flow rates which rapidly decrease during field development and the ultimate gas recovery factor is low. Therefore, the development of more efficient technologies for gas production from low permeable reservoirs is an extremely crucial task.

1. Research problems

The development and operation of unconventional natural hydrocarbon deposit at present are perhaps the most urgent issue for the petroleum industry in the world. In Ukraine a number of prospective areas which contain significant resources of unconventional hydrocarbons have been discovered so far, particularly Olesk and Yuzivsk areas. In all oil- and gas -bearing regions within conventional fields low-porous, low-permeable oil and gas reservoirs occur, which for various reasons have not been involved into development [1-4]. As the experience of unconventional field development proves gas production from low-permeable reservoirs by using vertical wells is economically unprofitable. Field data analysis shows that natural gas production from low-permeable reservoirs with economically effective production can be achieved only by drilling close horizontal wells spacing pattern with further gas flow stimulation [5-9].

As it was established by the results of Lane, Watson, Lancaster and according to the field data of unconventional natural gas deposits development the significant amount of gas is adsorbed on the pore surface. Consideration of adsorption processes in predicting development strategies will allow engineers to more accurately determine the reserves and predict the final gas recovery factor [10,11].

To investigate the adsorption-desorption processes occurring in low-permeability reservoirs a laboratory setup was developed. A schematic diagram and its general view are shown in Figure 1. The model is filled with the sand of selected fractions (0.125, 0.5, 1 and 2 mm). The porosity and absolute permeability, the volume of the model lines and additional cells are determined.

During experiments a model with the length of 0.45 m and the diameter of 0.04 m was used. The experiments were conducted at ranges of temperature from 40 °C to 60 °C, the model permeability was changed from 9.1 mD to 93 mD and the pressure from 1 MPa to 13 MPa.

Studies were conducted using experimental

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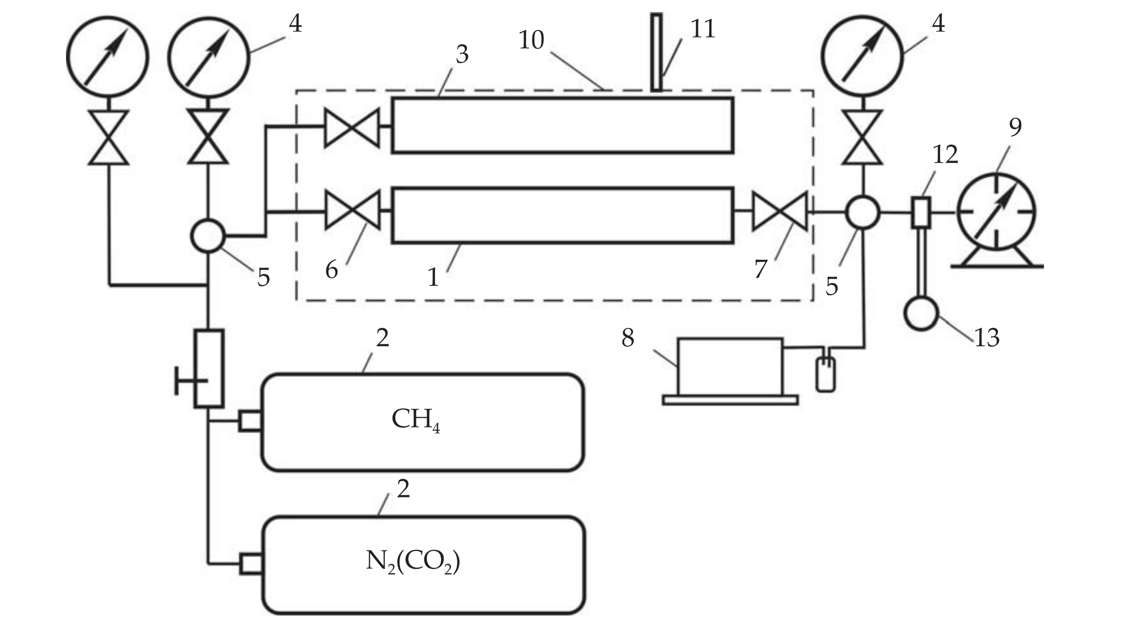

Fig.1. Scheme and general view of experimental setup
1 – model; 2 – gas source; 3 – measuring tank; 4 – pressure gauges; 5 – manifolds; 6 – input valve; 7 – output valve; 8 – vacuum pump; 9 – gas meter; 10 – thermostat; 11 – temperature sensor; 12- methane sensor (Dynament MSH-P/HC/NC/5/V/P/F); 13 – voltmeter

design theory. As a source of working agent methane gas was used. It allowed us to obtain reliable results in the research.

Model is evacuated for 8 hours maintaining a constant temperature, thereby releasing pore space of the model from previously adsorbed gas (including air). The temperature is maintained closes to 100 °C.

At the beginning of the experiment a constant temperature is set, which will be maintained throughout the whole period of its duration. The model is filled with methane at known pressure. The volume of methane in the model is determined by the Redlich–Kwong equation of state for a particular temperature and pressure conditions.

$$P = \frac{RT}{V-b} - \frac{a}{T^{0.5}V\left(V+b\right)}$$

Pressures at the inlet and outlet of the model were measured and have to be equal. The model withstands some period of time to stabilize the pressure in it with constant tempereture maintaining. This process can take to 8 hours. Throughout all period of time pressure is measured. Methane adsorption on the surface of the pore space is fixed as a result of the pressure drop in the model. Then the experiment is repeated for the other values of the initial pressure.

After the experiment is completed, the gas is discharged from the model through a gas meter. The correctness of the calculations was verified by the method of material balance.

2. Adsorption processes influence on gas fields development

Experimental results of the dependence of methane adsorption on porosity, permeability, pressure and temperature are shown in figures 2-3.

The maximum adsorbed gas content on the pore space surface increased with the temperature from 40 °C to 60 °C, decreased by 1.5 times (from 1.2 m^3/t to 0.75 m^3/t), for the model with permeability of 9.7 mD, by 1.2 times (from 0.43 to 0.35 m^3/t), for the model with permeability of 29 mD and by 1.5 times (from 0.25 to 0.15 m^3/t), for the model with permeability of 93 mD. Moreover, at constant temperature increasing the model permeability

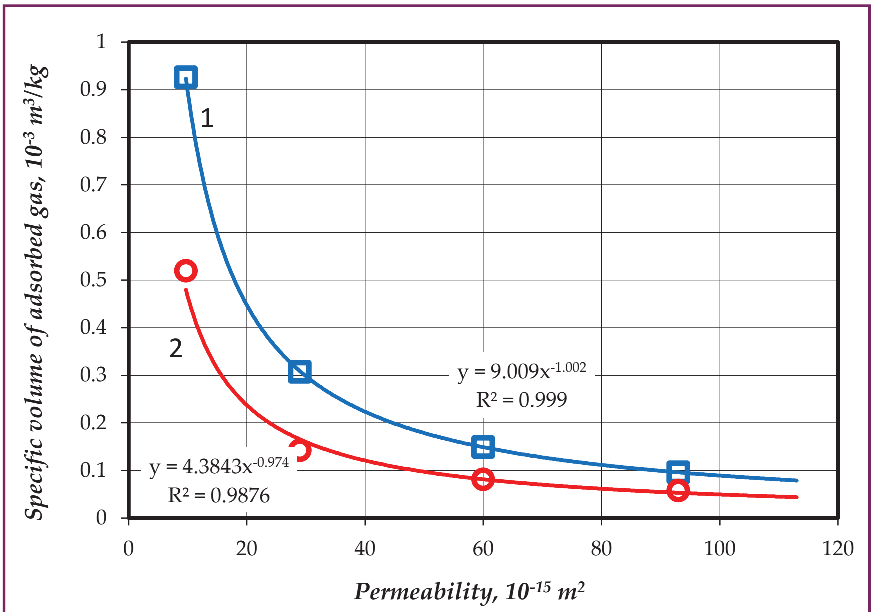

Fig.2. Dependences of specific volume of adsorbed gas on the model permeability for different values of temperature under the pressure of 3 MPa: 1 – 40 °C; 2 – 60 °C.

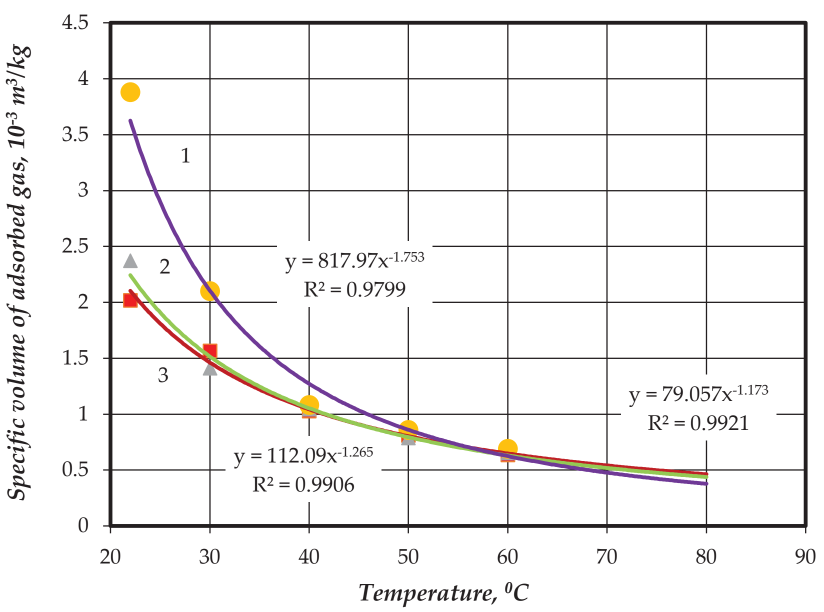

Fig.3. Graphical dependences of adsorbed gas content from temperature (adsorption isobar) for different pressures (model with permeability – 9.7mD): 1 – 20 MPa; 2 – 10 MPa; 3 – 8 MPa

reduced the amount of adsorbed gas by about 80% (from 1.2 m³/t for model with permeability of 9.7 mD to 0.22 m³/t for model with permeability of 93 mD) [12].

It is also worth noting that with increasing permeability the absolute dependence of the specific volume of adsorbed gas on temperature decreases. If for the model with permeability 9.7 mD by increasing temperature from 40 °C to 60 °C the specific volume of adsorbed gas is reduced from 0.95 to 0.5 m³/t (by 1.9 times), for the model with permeability of 93 mD the specific volume of adsorbed gas decreases from 0.1 to 0.065 m³/t (by 1.5 times). Thus, with increasing permeability by 10 times the specific volume of adsorbed gas is reduced by about 7-8 times. In this regard, it can be concluded that natural gas is adsorbed on the surface of the pore space even in conventional highly permeable layers, but its amount is much less than in unconventional low-porous low-permeable reservoirs.

It should be noted that the specific volume of adsorbed gas increases with rising pressure. However, at high pressure values the amount of adsorbed gas does not increase with pressure growth. This effect can be explained by the fact that all adsorption centers are occupied and further adsorption is not possible.

For the practical application of experimental studies the processing was conducted in order to get of empirical dependence for specific volume of adsorbed gas calculation from permeability, temperature and pressure.

$$V_a\,(k,P,T) = ATb_v\,(k,P,T)$$

where A – the vector of model parameters;

$b_v\,(k,P,T)$ - the basic functions vector of type $(1,k,P,T,kP,PT,kT,\ln k,\ln P,\ln T,k^2,P^2,T^2)^T$.

Class of models were formed from the linear section of basic functions with including their multiplication, logarithms, squares and it made up 82 models. Adequacy of accepted regressive models was estimated due to the results of checking total statistical hypothesis. In table 1 the assessment of parameters and dispersion of adequacy of obtained dependences for specific is given.

Table 1

The equation parameters of adsorbed gas specific volume

Basic functions b_v	Model parameters	Parameter value of the of model for specific volume of adsorbed gas					
		1	20	32	52	61	82
1	A1	2.017	3.68	32.196	31.711	3.176	15.144
k	A2	-0.11	-0.01	0.021	0.021	-0.517	-0.06
P	A3	0.037	0.046	0.022	0.03	$-8.029\cdot10^{-3}$	0.014
T	A4	-0.031	-0.104	0.507	0.491	0.063	0.045
kP	A5	—	—	—	—	$-4.785\cdot10^{-4}$	$-5.114\cdot10^{-3}$
kT	A6	—	—	—	—	—	$2.109\cdot10^{-3}$
PT	A7	—	—	—	—	—	$-1.836\cdot10^{-3}$
ln k	A8	—	—	-1.158	-1.158	6.059	-1.144
ln T	A9	—	—	-12.12	-11.842	-3.904	-3.741
ln P	A10	—	-0.151	—	-0.079	0.125	0.031
k^2	A11	—	—	—	—	$3.362\cdot10^{-3}$	—
P^2	A12	—	—	—	—	$1.221\cdot10^{-3}$	—
T^2	A13	—	$8.176\cdot10^{-4}$	$-2.77\cdot10^{-3}$	$-2.681\cdot10^{-3}$	—	—
Dispersion of model adequacy, m³/kg		0.136	0.108	0.057	0.058	0.165	0.027

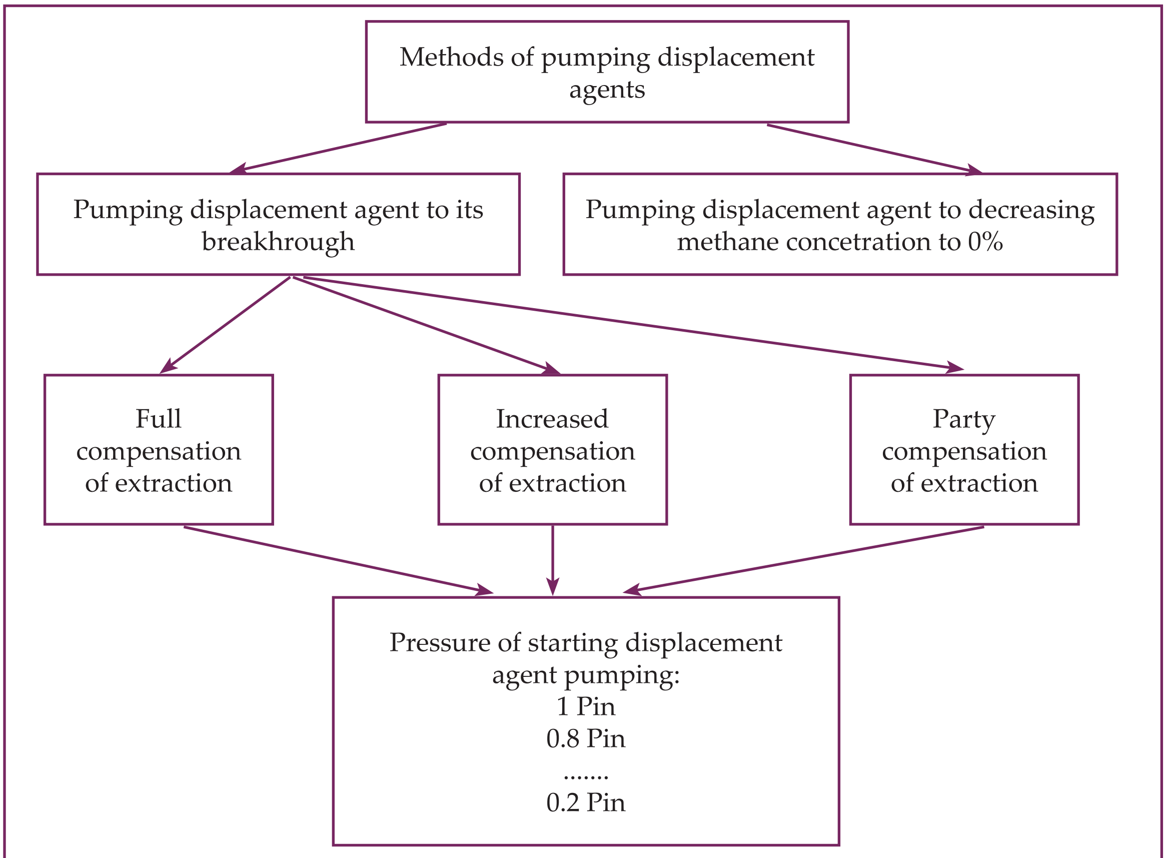

Fig.4. The scheme of conducting experimental researches

3. Grounding possible methods of experimental researches

Taking into account the fact that one of the methods of enhancing the factor of gas recovery (EGR) from shale formations, coal seams and tight sands is the stimulation of desorption of previously adsorbed gas, the research of the desorption stimulation methods was conducted. For example, in the world practice there are the following known methods of desorption stimulation [1]:

1. pressure reduction;
2. inert gas stripping;
3. thermal desorption;
4. displacement desorption.

According to the features of gas fields development with low-permeable, low-porous reservoirs the research into displacement desorption and inert gas stripping was conducted. These experimental studies were carried out by using methane (CH_4), nitrogen (N_2) and carbon dioxide (CO_2). According to the experimental results of relative adsorption capacity determination it can be concluded that the carbon dioxide usage as the displacement agent can lead to producing adsorbed gas by more than 30% than by using nitrogen.

With the aim of study the mechanism and specific features of natural gas desorption stimulation by inert gas stripping the experimental researches were performed in which the following groups of enhanced method of gas recovery were singled out (fig.4): pumping displacement agent to its breakthrough; pumping displacement agent to decreasing methane concentration to 0%.

4. Results analysis of nitrogen pumping

Analysis of experimental results shows that nitrogen injection method before its breakthrough is more efficient compared with the method of full methane displacement. Therefore, the rest of researches were conducted under the condition of nitrogen injection stoppage during his breakthrough to the model outlet [1].

For further researches the following methods of nitrogen injection were selected:

1. full voidage replacement (injection ratio) - maintaining constant pressure in the model, before nitrogen breakthrough, followed by a gradual depletion;
2. higher voidage replacement - with a gradual pressure increase in the model, but not higher than initial pressure, before nitrogen breakthrough, followed by a gradual depletion;
3. partial voidage replacement - with a gradual pressure reduction in the model, before nitrogen breakthrough, followed by a gradual depletion.

For grounding the EGR method, which provides the highest impact on technical, technological and economic indices it is necessary to minimize specific injection ratio and maximize gas recovery factor:

$$T = F\left(\min\left(\Delta V\right), \max\left(\beta_g\right)\right)$$

Specific injection ratio *(ΔV)* is the ratio of the volume of injected agent to additional methane production. In other words it is the amount of nitrogen (or carbon dioxide) that needs to be injected

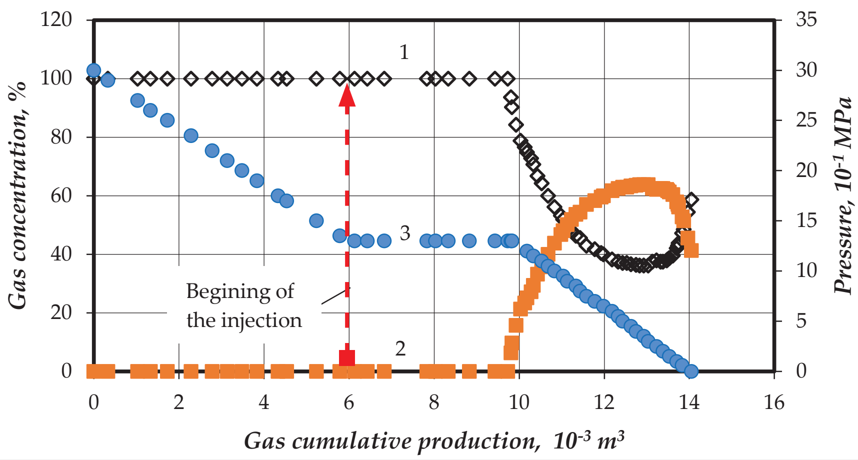

Fig.5. The dynamics of pressure and components concentration in produced gas during the implementation of the method of full voidage replacement at the pressure of 0.4 from initial pressure: 1 – methane concentration; 2 – nitrogen concentration; 3 – pressure in the model

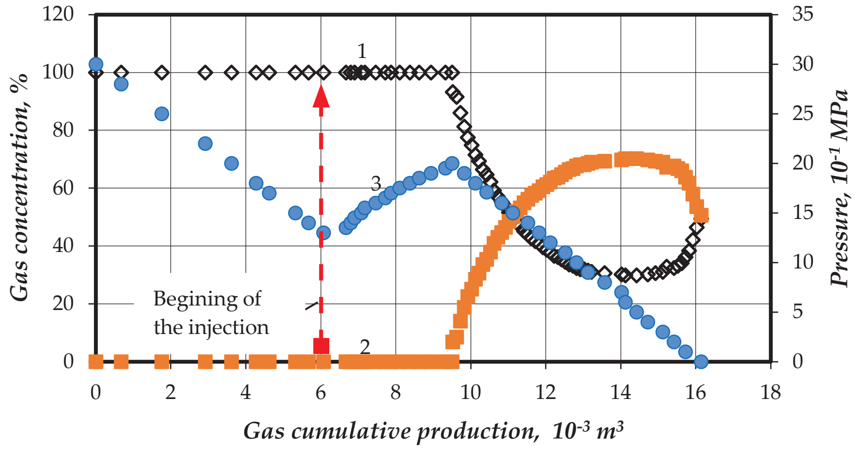

Fig.6. The dynamics of pressure and components concentration in produced gas during the implementation of the method of higher voidage replacement at the pressure of 0.4 from the initial pressure from initial pressure: 1 – methane concentration; 2 – nitrogen concentration; 3 – pressure in the model

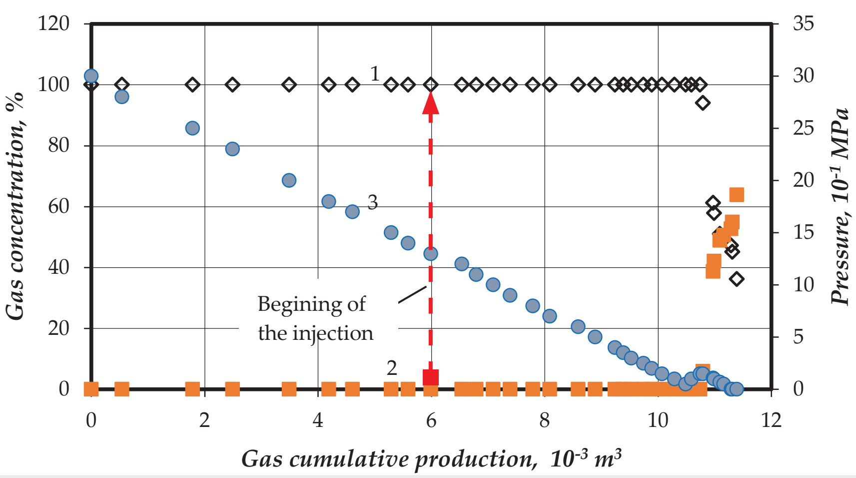

Fig.7. The dynamics of pressure and components concentration in produced gas during the implementation of the method of partial voidage replacement at the pressure of 0.4 from the initial pressure: 1 – methane concentration; 2 – nitrogen concentration; 3 – pressure in the model

into the reservoir for producing additional unit of methane volume.

The analysis of obtained data shows that the maximum increase of the gas recovery factor is achieved in nitrogen injection with 0.8 Pinitial (fig.8). Thus additional production is 23% of methane. With decreasing the injection pressure the gas recovery factor lowers.

The result of performed investigations testifies that most of methane at the moment of nitrogen break through is produced by using the method of partial compensation of extraction (with the formation pressure decrease).

For this variant the minimization of specific amount of injected displacement agent as also achieved, but at the same time we can monitor the lowest final recovery factor.

The data analysis of conducted experiments testifies that given condition is achieved by injected nitrogen under the pressure which is equal to 0.8 from the initial formation pressure under full compensation of extraction (with maintaining formation pressure). This variant allows us to provide maximizing the gas recovery factor in minimizing the amount of injected displacement agent.

5. Results analysis by using carbon dioxide

Using the same algorithm the laboratory experiments of methane displacement desorption by using carbon dioxide were conducted. The results analysis shows that the method of full and higher voidage replacement leads to obtaining higher gas recovery factor compared with partial voidage replacement method. Therefore, further studies were carried out for these two methods in order to determine the pressure of carbon dioxide injection at which optimal gas recovery factor will be achieved.

As it was established, with CO_2 injection the pressure increases and the gas recovery factor grows, which is not observed by using nitrogen. This is because CO_2 displacement properties improve at high pressure. Also at higher pressure the amount of adsorbed CO_2 increases, and hence the greater amount of methane is released in

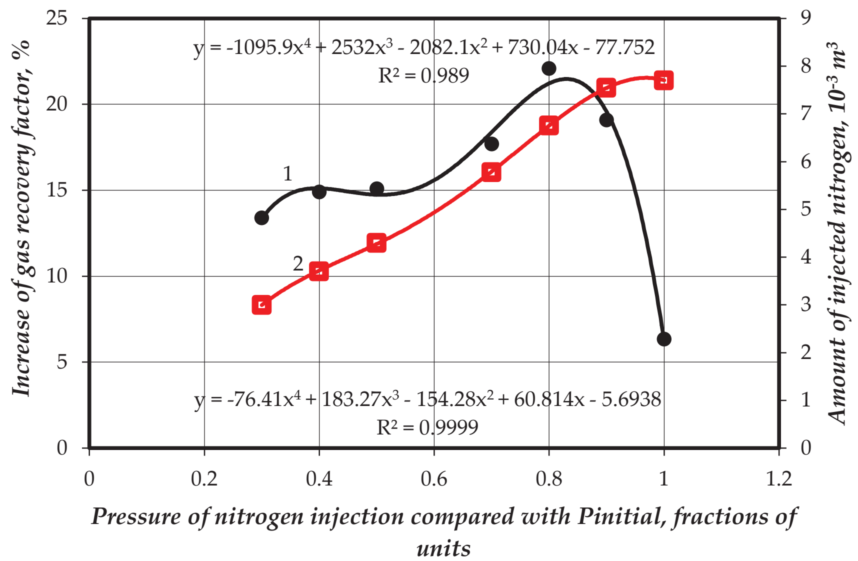

Fig.8. Graphic interpretation of experimental data on methane displacement by nitrogen 1 – increase of methane production compared with basic variant; 2 – amount of injected nitrogen

the pore space.

The analyses of research data show that with increasing the pressure of CO_2 injection the volume of additionally produced methane increases, which was not observed in using nitrogen (fig.9). Maximum gas recovery factor is achieved in using the method of enhanced compensation of extraction by injecting carbon dioxide at the pressure of 80% from the initial formation pressure.

But the method of full compensation of extraction at the pressure of 60% from the initial formation pressure meets the condition of minimizing the volume of injected carbon dioxide. That's why it is recommended for implementation.

Nitrogen application in oil and gas production industry is simpler and more common. In this case near the field or integrated gas processing unit one of nitrogen plants is built which according to its characteristics is the most suitable for the specific conditions.

In the case of using carbon dioxide the field should be located not far from big industrial enterprises which provide it with the necessary amount of nitrogen for injecting into formation. When such enterprise is not available there is the necessity of constructing the system of compressor stations and pipelines for its transportation to wells. Also the use of CO_2 is complicated by its toxic and corrosive properties.

Due to the results of performed researches two possible methods of enhanced gas recovery are suggested: with the use of nitrogen or carbon dioxide.

6. Improved technologies of enhanced gas recovery

The technology of increasing the gas recovery factor in gas field development with low permeable reservoirs by using nitrogen.

This technology envisages the construction of nitrogen plant near the field. Its type is chosen dependently on the necessary production efficiency but at the initial stage it is recommended building membrane plants as they are the most reliable and durable. Production of natural gas is realized through producing wells till there will not be achieved formation pressure decrease to 0.8 from the initial formation pressure. After that part of wells which are located on the periphery are transformed for nitrogen injection. Thus constant formation pressure at the level of 0.8 from the initial formation pressure is maintained. The volume of injected nitrogen is chosen to be equal to the volume of produced gas during the definite period with the aim of full compensation of extraction by injecting with maintaining constant formation pressure. Nitrogen injection continue till there will not be its breakthrough to producing wells. After nitrogen breakthrough its injection stops, but their operation of producing wells continues.

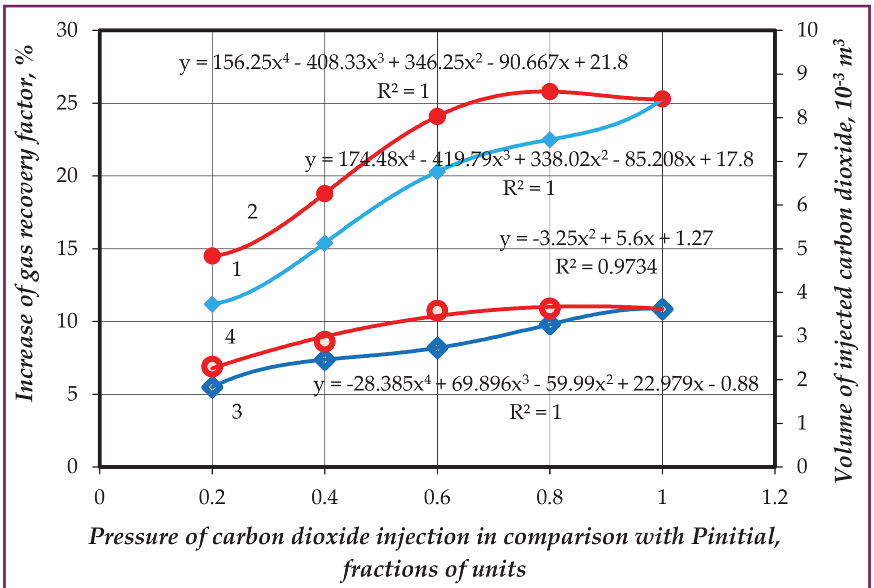

Fig.9. Graphic interpretation of experiment results in methane displacement by using carbon dioxide 1 – increase of gas recovery factor for the method of full compensation of extraction; 2 - increase of gas recovery factor for the method of enhanced compensation of extraction; 3 – volume of injected CO_2 for the method of full compensation of extraction; 4 - volume of injected CO_2 for the method of enhanced compensation of extraction

The technology of increasing the gas recovery factor in gas field development with low permeable reservoirs by using carbon dioxide.

This technology anticipates the construction of pipeline systems for CO_2 transportation from industrial enterprises to the field. The production of natural gas is taking place through producing wells till the decrease of the formation pressure is not achieved to 0.6 from the initial formation pressure. After that, those wells which are located on the periphery are transformed for carbon dioxide injection. At the same time constant formation pressure is maintained at the level of 0.6 from the initial formation pressure. The volume of injected carbon dioxide is chosen to be equal to the volume of produced gas during the certain period with the purpose of full compensation of extraction by injecting with maintaining constant formation pressure. Injection of CO_2 continues until there is not its break through towards producing wells. After CO_2 breakthrough its injection is stopped but producing wells continue to be operated.

Analyzing experimental research data and considering the ways of obtaining nitrogen and carbon dioxide the use of nitrogen for stimulation of methane desorption from the surface of porous space is supposed to be more efficient.

7. Hydraulic fracturing optimization

The main parameters that affect the well performance using this technology are the length of the horizontal wellbore, the number and size of perforation intervals, the number of hydraulic fractures, their length, density and permeability [13, 14]. As a tool to assess the optimal parameters of horizontal wells with transverse hydraulic fractures hydrodynamic simulator ECLIPSE 300 was used in combination with geological simulator PETREL which was donated and licensed to IFNTUOG by Schlumberger. The study was conducted in three stages. At the first stage the horizontal well length was estimated, at the second stage - the impact of the fracture length in horizontal wells on technical and economic parameters was determined, and the third stage included the determination of the optimal fractures density. More details about the research was presented in [12].

The technological efficiency was evaluated being based on the analysis of cumulative gas production and the recovery factor for different variants. The economic analysis was based on the determination of net present (discounted) value (*NPV*) and was conducted on the basis of national legal regulation acts and international publications [12]. *NPV* was determined by the equation:

$$NPV = \sum_{i=1}^{n} \frac{CF_t}{\left(1+r\right)^t} - \sum_{i=1}^{n} \frac{I_t}{\left(1+r\right)^t}$$

where CF_t - cash inflow over the year t, mln. hrn;

I_t - investments over the year t, mln. hrn;

r - discount rate, unit fractions.

Figure 11 shows the results of the hydrodynamic modeling in order to determine optimal parameters of hydraulic fractures.

As a result of 3D computer modeling it was established that the optimal horizontal wellbore length is quite dependent on the reservoir permeability. For low-permeable reservoirs the optimal horizontal wellbore length can be determined exclusively on the basis of the specific field conditions and technical and economic indices of the company. For reservoirs with relatively high permeability (about 1 mD) the optimal horizontal wellbore length is about 1000m, and its further increase does not give significant

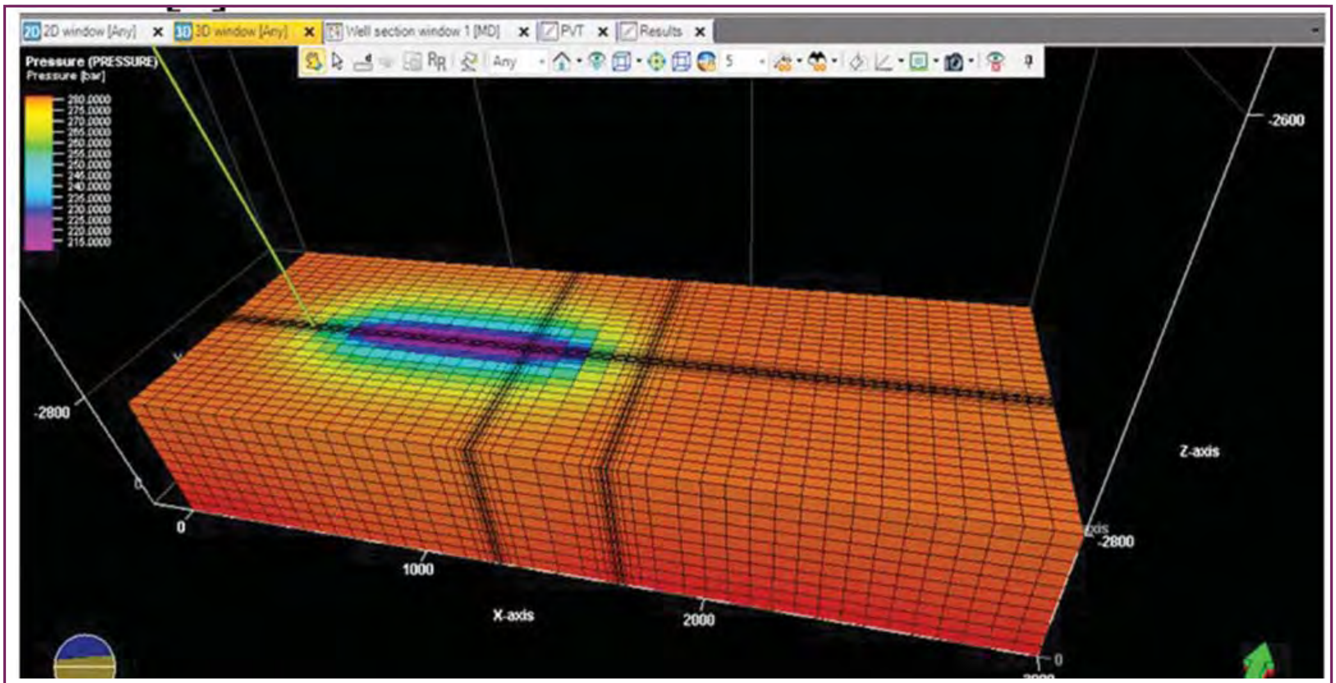

Fig.10. General view of the hydrodynamic model sector

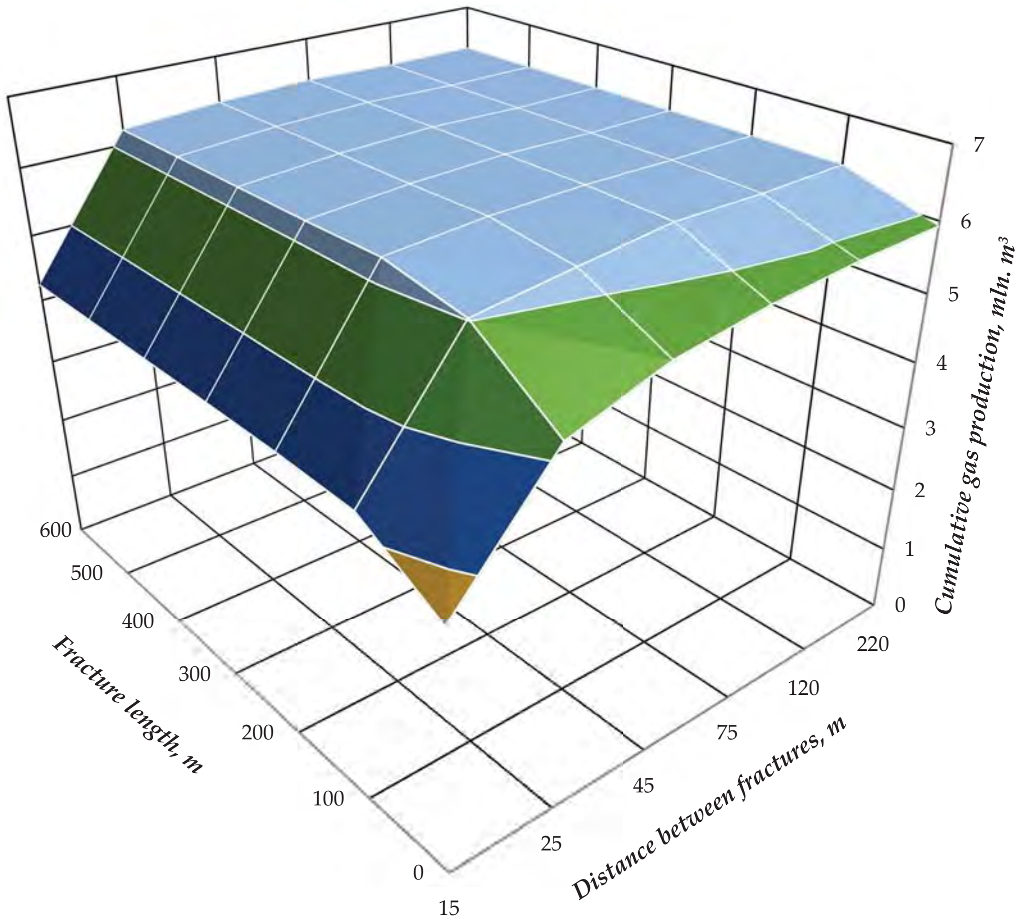

Fig.11. The dependences of hydraulic fracture length and the distance between them on cumulative gas production for horizontal well

technical and economic effect. For reservoirs with lower permeability the dependence of the recovery factor and NPV on the horizontal wellbore length is almost straight-line and horizontal wellbore increase leads to the growth of the recovery factor. These results are confirmed by the field experience of horizontal wells drilling in the unconventional natural gas fields of the United States, where oil and gas companies choose the length of the horizontal well not being based on technologically reasonable parameters, but on the basis of financial resources of the company and mutual spatial arrangement of the wells and field boundaries.

In assessing the optimal transverse fracture length during hydraulic fracturing it should be noted that it practically does not depend on the reservoir permeability and ranges within 100-200 m, and on average is 100-150 m. High permeable reservoirs (~ 10 mD) can be only the exception for which hydraulic fracturing with the formation of transverse fractures with the length of up to 50 m is reasonable.

Further researches showed that the optimum distance between hydraulic fractures is 25 m. At this value of distance between fractures the maximum NPV and cumulative gas production are observed. At shorter or greater distance between the fractures the technical and economic indices are lower compared to the previous ones.

Evaluation of technical and economic efficiency of the proposed solutions was made being based on the assumptions that bottomhole formation zone is not polluted, and the reservoir is isotropic (porosity and permeability in all directions are the same).

To sum up it should be noted that for reservoirs with permeability of 1-0.01 mD it is recommended drilling horizontal section of the wells up to 1000 m long, and then conducting multistage hydraulic fracturing with fractures length up to 150 m at a distance between them of 25 m.

The results do not contradict the international experience of horizontal wells drilling and hydraulic fracturing, and in some cases confirm the results of known researches. However, in order to obtain the best results in the real Ukrainian fields the selection of these parameters should be held on the basis of specific geological, technological and economic conditions.

Conclusions

The paper experimentally studied the effect of temperature, pressure and permeability of sandstone reservoirs on their ability to adsorb methane and appropriate empirical relationship was obtained. The relative adsorption of methane, nitrogen and carbon dioxide on the surface of a sand packed model was experimentally determined and the directions for enhancing gas recovery factor by gas desorption intensification using the injection of non-hydrocarbon displacement agents were established. The influence of pressure and the method of injection of non-hydrocarbon displacement agents on ultimate gas recovery factor was determined.

The influence of injection pressure of the displacement agent on the gas recovery factor was experimentally proved. The physical sense of the processes that occur during natural gas desorption stimulation using non-hydrocarbon gases was established.

According to the research results it was found that in the case of nitrogen the most effective method is full voidage replacement at the injection pressure of 80% from the initial reservoir pressure, and in case of carbon dioxide usage - full voidage replacement method at the pressure of 60% from the initial reservoir pressure. Taking into account the results of this researche the injection of N_2 and CO_2 is recommended for further study in tight terrigenous reservoirs.

As a result of hydrodynamic computer simulation using Eclipse 300 software the optimal parameters of well profiles and hydraulic fractures were evaluated on the basis of technological and economic criteria.

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Увеличение добычи газа из месторождений с низкопроницаемыми терригенными коллекторами

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Реферат

В работе предлагается научное обоснование технологии повышения газоотдачи и текущей добычи газа из месторождений с низкопроницаемыми терригенными коллекторами. По результатам физического и гидродинамического моделирования установлены закономерности адсорбционно-десорбционных процессов в низкопроницаемых коллекторах и оценено влияние размещения разнопрофильных скважин с поинтервальными гидроразрывами пласта на дебит скважин и коэффициент газоотдачи. На основе полученных результатов представлены усовершенствованные технологии повышения добычи газа с месторождений с низкопроницаемыми коллекторами, оценено их влияние и технологические и экономические показатели разработки месторождений и даны рекомендации для их дальнейшего внедрения.

Ключевые слова: низкопроницаемые коллектора; десорбция, газоотдача; гидравлический разрыв пласта.

Aşağı keçiricilikli terrigen kollektorları olan yataqlardan qaz hasilatının artırılması

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Xülasə

Məqalədə aşağı keçiricilikli terrigen kollektorı olan yataqların qazveriminin və cari qaz hasilatının artırılması texnologiyasının elmi əsaslandırması təklif edilir. Fiziki və hidrodinamiki modelləşdirmənin nəticələrinə əsasən aşağı keçiricilikli yataqlarda adsorbsiya-desorbsiya proseslərinin qanunauyğunluqları təyin edilmiş və müxtəif profilli quyuların layın intervallı hidroyarılması vasitəsilə yerləşdirilməsinin quyuların debitinə və qazveriminə təsiri qiymətləndirilmişdir. Alınmış nəticələr əsasında aşağı keçiricilikli kollektorları olan yataqlardan qaz hasilatının artırılmasının təkmilləşdirilmiş texnologiyaları təqdim edilmiş, onların yataqların işlənməsinin texnoloji və iqtisadi göstəricilərinə təsiri qiymətləndirilmiş və gələcək tətbiqinə dair tövsiyələr verilmişdir.

Açar sözlər: aşağı keçiricilikli kollektorlar; desorbsiya; qazverimi; layın hidravlik yarılması.