

ALTERNATIVE TECHNOLOGIES AND ENERGY

Features of the unconventional gas deposits development

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This article generalizes the data on reserves and production of shale gas in different countries. It also analyzes the peculiarities of the geological structure and development of the shale gas and gas in dense rock deposits. As to the development of shale gas deposits with a net of horizontal wells with multi-stage hydraulic bed fracture, it presents the effect of the factor of the rock matrix permeability, half-length fracture and the distance between fractures on the gas recovery.

One of the directions of increase in production of natural hydrocarbons in Ukraine is to involve the unconventional gas deposits in the development. The current state of development of such deposits is characterized by a significant increase in gas production from shale and tight rocks in the United States, its production commencement in Canada, research of the issues of unconventional gas extraction in many countries (Australia, China, Germany, the United Kingdom, Sweden, Poland etc.).

Yet in the 19th century it became known that shales enriched with organic matter contain gas. The first well from which the industrial flow of gas from Devonian shale formations was obtained was drilled in 1821 in the Fredenia area, NY.

In the 20s' of 20th century, the large-scale development of shale gas (Big Sandy Field, Kentucky) was performed for the first time. On the verge of the 50s' and 60s' years of the last century the method of hydraulic stimulation of the layer in wells extracting the gas from shale was tested for the first time.

In the 70s' years of the 20th century in the United States the exploration work was carried out, during which four huge shale structures, Barnett, Haynesville, Fayetteville and Marcellus, occupying ten thousand square kilometers, were found. A new stage in the industrial extraction of shale gas began during the 80's and 90's of the last century. Several small companies, the largest and the most active of which was Chesapeake Energy, decided to return to the idea of extracting gas from shale beds. The main strategy has been drilling horizontal wells for shale gas extraction.

Today, in the U.S. the gas from shale is mined from more than 40,000 wells with more than 20 deposits, and the volume of its production in 2011 amounted to about 150 billion m³ [1, 2].

Shale gas is the gas found in fine-grained sedimentary rocks (usually of thermogenic origin), which are characterized by a relatively high content of organic matter, have low porosity and very low permeability. The slate rocks are characterized by layered structure and are penetrated with a grid of vertical and inclined cracks crossing the horizontal placement of the rock strata.

The required conditions for shale gas emergence are:

high content of organic matter;

relatively large thickness of the formation;

high thermal maturity of rocks and relatively small depth of their occurrence (up to 3000 to 4500 m).

Typically, the natural permeability of the shale rock matrix is in the range of $0.01 \cdot 10^{-6}$ mcm² to $0.01 \cdot 10^{-3}$ mcm².

The shale gas clusters are characterized by very large geological reserves with a low gas extraction coefficient. The shale gas consists mainly of methane and its homologues (ethane, propane, butane) mixed with hydrogen sulfide, carbon dioxide, nitrogen, hydrogen and helium, sometimes the increased radon content is observed [3].

Usually it is dry gas.

Another source of natural gas is the gas located in dense low-permeable sandstones, mudstones and other rocks. To extract this gas, it is required to use the agents to stimulate the reservoir. The permeability of these rocks is typically less than $0,1 \cdot 10^{-3}$ mcm². The pores in tight sandstones are distributed very unevenly, do not form a single pore space and are connected only by narrow capillaries, which leads to a very low permeability of the sandstone.

The main parameters of oil and gas systems are: a source of gas, parameters of traps, role of fluid stoppers, system physical characteristics (porosity, permeability) and temporal characteristics (time of accumulation and migration of gas). The gas deposits in tight sandstone are closer by its geological characteristics to traditional gas deposits than to the alternative ones. However, their physical and lithological characteristics are unconventional. Their feature is also the fact that thick sandstone is a reservoir rock, while the slate simultaneously serves as the rock collector, and parent rock. However, since the gas-containing tight sandstones and slates require artificial stimulation to extract gas, so they belong to unconventional sources.

The general comparison of the number of mining and reservoir characteristics of the shale gas, gas from tight reservoirs and conventional sources are given in Table 1 [2].

As can be seen from table 1, the shale gas is self-formed. It is not trapped and is dispersed all over the layer, the formation of which is continuous and unbroken. The tight rock gas and natural gas are peculiar of stratigraphic trap and lenticular/layered formation. Gas in shale rocks can be either in the free state, or be absorbed in the rock or dissolved in the fluid, and the actual rate of gas extraction does not exceed 35%, while the gas of tight rocks and natural gas is located in the pores and the coefficient of gas extraction for them is 45 and 95% respectively. It should be noted that the deposits of shale gas and tight rocks gas are characterized by low permeability. Therefore, for the commercial extraction of gas it is required to use the technology of hyperhydraulic layer fracturing (HLF).

The conventional global shale gas resources constitute 704 trillion m³. Taking into consideration the relevant factors affecting the rate of the gas extraction, the technically extractable global shale gas resources are estimated at 181 trillion m³. The distribution of geological/technically extractable resources of shale gas by continent (trillion m³) is as follows: North America - 190.2/48.7; South America - 129.4/34.7, Europe - 73.3/17.7; Africa - 112.2/29.5; Asia - 160.3/39.8, Australia - 39.1/11.2.

The largest shale gas resources are concentrated in Asia (China), South America (Argentina, Brazil), Africa (South Africa), North America (USA, Canada and Mexico) and Australia. In Europe the greatest shale gas resources are located in France; however, the government of this state prohibited the development and production of shale gas for a number of the reasons.

So, we have very little information about the shale gas resources in Russia, which despite its global leadership in the export of natural gas today does not want to develop this area.

Table 1

Generalized comparative characteristics of conventional and nonconventional gas deposits

Parameters	Shale gas	Gas from compacted collectors	Conventional has
Origin	Self-formed	Migrated	Migrated
Trap	None	Stratigraphic	Structural/stratigraphic
Formation	Solid, continuous	Lenticular/layers	Lenticular/layers
Depth, m	610-4570	to 6100	from shallow to deep
Thickness, m	15-180	610-1370	30-300
Permeability	nano mcm ²	<0,1•10 ⁻³ mcm ² D	Up to 500•10 ⁻³ mcm ²
Porosity, %	6-12	7-15	14-25
Gas	free/adsorbed/dissolved	in pores	in pores
Actual gas extraction coefficient, %	25-35	25-40	to 95
Organic carbon content	Available	Unavailable	Unavailable
Seismicity	yes, 3D	yes, 3D	Yes
Well type	Horizontal	horizontal/vertical/S-shaped	horizontal/vertical
Layer hydraulic fracturing	Performed to allow commercial production	Performed to allow commercial production	Performed to increase the extraction/removal of complications
Fluid stoppers	grasped by absorption of rock matrix (traps and fluid stoppers are not required)	Available	Available
Time factor (formation and migration)	the time is not essential, it is important only in the context of aging and generation of gas due to organic matter	essential for generation and migration from source and localization in traps	essential for generation and migration from source and localization in traps
Method of extraction	Hydraulic fracturing	Hydraulic fracturing	first by the natural pressure in the deposit, then it is required to apply the methods of stimulation
Fluid (water)	No water	The water extraction is possible	The water extraction is possible
Condensate	Little/mainly dry gas	Little	Contained in gas in varying amounts

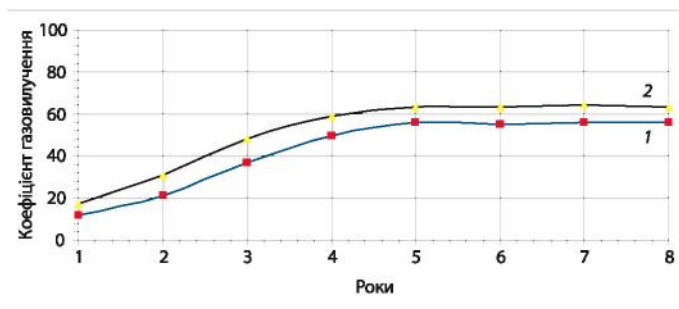


Figure 1. Dependence of gas extraction coefficient on the number of wells in the area of Marcellus deposit for varying lengths of its development

(basic version): 1 - 10; 2 - 60 years

The global gas reserves in dense rocks are 209.3 trillion m³ according to some estimates and about 850 trillion m³ according to the other [4].

The gas stock in dense rocks in the amount of 209.3 trillion m³ are distributed as follows (trillion m³): North America - 38.8; Central/Eastern Europe - 36.6; Sahara (Africa) - 9.9; Asia

Pacific – 2.2, South America - 25.5; countries of the former USSR - 23.3; central part of Asia/China - 22.2; South Asia - 9.9; Western Europe - 19.9; North Africa - 15.5; Pacific– 5.5. At present, there is almost no region in the world, which would not show interest in prospecting, exploration and increase of the resource base of natural gas in tight formations.

Table 2 shows the geological and physical features of selective formations of shale gas in Ukraine and world. The analysis of the data from table 2 shows that the prospective shale gas basins located in Ukraine have quite high geological and physical properties. The depth of shale in the Dnieper-Donetsk basin (PPD) account for 1,500 to 4,500 m, and in the Lublin Basin - from 1,500 to 2,800 m. As for the values of thermal maturity R_o the shale rocks of Lublin basin and DDB are approximately one-term with the European ones (0.8 to 1.5%), but still are inferior to the American ones by the content of carbon TOC (0.5 to 5.5%). However, the effective thickness does not differ from global indices and varies from 30 to 100 m. Given that the mining resources based on risks for the whole Ukraine are about 8.72 trillion m^3 , the aforesaid promising pools represent a huge potential whereby the volume of domestic gas production may increase due to the development of deposits of unconventional gas.

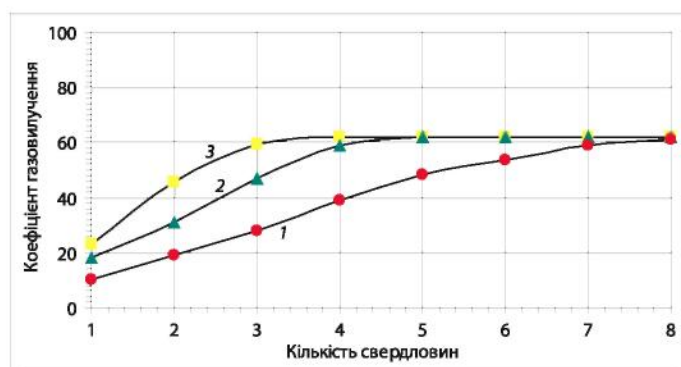


Figure 2. Dependence of the gas extraction coefficient on the number of wells on the area with cracks of varying half-length on the 60th year of operation: 1- 75; 2- 150 (base case); 3- 275 m

Table 2

Geological and physical characteristics of random formations of shale gas in Ukraine and worldwide

Continent	Region	Pool	Formation	Age	Promising area, km ²	Depth, m	R_o % (In brackets - mean)	TOC% (in brackets - mean)	Clay content	Depth (effective), m	Extractable gas resources, taking into account the risks, trillion m ³
N. America	USA	Barnett	Lower Carboniferous	C1	13000	2155-2833	1,3-1,7	4.5	Low	33,3-200	1.25
N. America	USA	Fayetteville	Lower Carboniferous	C1	23400	333-2333	1.2-1.8	4,0-9,8	Low	6,7-66,7	1.18
N. America	USA	Haynesville	Yura (upper)	J	23400	3500-4500	3,5-3,7	0,5-4,0	Low	66,7-100	7.12
N. America	USA	Marcellus	Middle Devonian	D2	247000	1333-2833	3,0-3,4	3-12	Low	16,7-66,7	7.42
N. America	USA	Woodford	Upper Devonian	D3	286000	2000-3666	2,7-3,3	1-14	Low	60-73,3	0.32
Europe	Poland	Baltic Basin	Silurian Shales	S1	22911.03	2499-4996	1-5 (1.75)	<10 (4)	Medium	96.32	3.65
Europe	Poland	Lublin Basin	Silurian Shales	Si	30199.26	1999-4099	1-2.5 (1.35)	1-1,7 (1,5)	Medium	69.49	1.25
Europe	Poland	Podlasie Depression	Silurian Shales	Si	3431.73	1749-3459	(1.25)	<20 (6)	Medium	90.53	0.40
Europe	Ukraine *	Dnieper-Donetsk Basin	Upper Devonian shales	D3	1311.00	2000 - 3000	0,8-1,55	2,5-5,5	Medium	40-90	1.15

Europe	Ukraine *	Dnieper-Donetsk Basin	Lower Carboniferous shales	Ci	3027.00	1500-4000	0,8-1,15	1,2-2,8	Medium	30-60	4.45
Europe	Ukraine *	Dnieper-Donetsk Basin	Mid-coal shale	C2	1714.00	2400-4500	0,8-1,1	1,1-2,7	Medium	40-70	2.39
Europe	Ukraine *	Lublin Basin (Volyn-Podillia)	Silurian shales	Si	2657.00	1500-2800	0.8-1.5	0,5-2,2	Medium	80-100	0.73

* - Initial promising areas of search for shale gas in Ukraine

There are the following statements about shale gas: "No two shales are the same," "There is no simulation model that would fit for all shale wells." Wells in shale and tight rocks, which were subjected to hydraulic layer fracturing (HLF) have quite non-standard nature of attrition. The initial gas flow rate is relatively small, from 60,000 to 280,000 m³/day (for horizontal wells). The rate of reduction of the gas flow rate is quite high. During the first year the gas flow rate may be reduced to 65-80% of the original, during the second - up to 35-45%, and during the third - 20-30%. Then the gas flow rate is reduced by about 5% per year. This low flow rate, or as it is called, the "tail" can be sustained for 25 to 30 years [2].

The development of areas of unconventional gas is complex a process where the technical, commercial and environmental issues are closely related and play an important role in determination of the economic attractiveness of the project. The uncertainty of many variables, especially the geological data, wells productivity efficiency, and the cost of wells construction play a dominant role during the development of deposits. The requirements for infrastructure, especially in the early life cycle of the project, can provide a significant impact on the project economy.

The production data for major shale gas deposits of the USA imply that the total number of wells to develop the general extractable stocks should be provided by production of 30 billion m³ by 200-300 wells [2].

There are five life cycles of the shale gas and tight rocks deposits, i.e. exploration, evaluation, drilling, extraction and reclamation. According to the American scientists [4], at the phase of restoration it is worth applying the re-fracturing. It is known that the flow rate of gas from unconventional wells rapidly decreases, reaching the unacceptable levels after just a few years of extraction. The re-fracturing allows increasing the technological parameters of gas production.

Determination of the optimal number of wells at non-conventional deposits is an important task [5]. The peculiarity of development of such deposits is the consideration of both engineering and economic risks, including the permeability reduction due to compaction of rock and quality of completion of wells.

It is known that high performance is achieved upon tight placement of cracks. It is believed that when the distance between the cracks is about 15 m or less, they are less effective because of stress in the rock. The effectiveness of propan and conductivity of cracks are also important for wells productivity.

The distance between the cracks is defined as the distance between two adjacent flat hydraulically induced cracks along the borehole. Hence the term of the "stimulated deposit volume" (SDV). SDV is the total area covering all cracks, i.e. from the beginning to the end of the crack. EDV (external deposit volume) is the area outside SDV, which is defined for a particular well based on impermeable boundary of its reservoir.

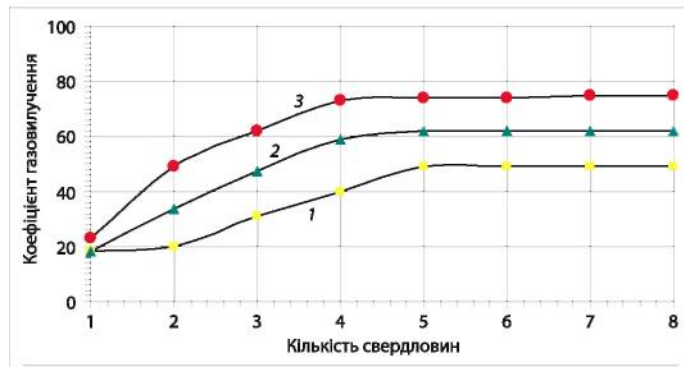


Figure 3. Dependence of the gas extraction coefficient on the number of wells for various values of the matrix permeability: 1- $5 \cdot 10^{-9}$; 2 - $50 \cdot 10^{-9}$; 3 - $500 \cdot 10^{-9} \text{ mcm}^2$

The data from Marcellus and Haynesville shale deposits were used to study the optimum distance between wells for various matrix permeability options ($5 \cdot 10^{-9}$, $50 \cdot 10^{-9}$ i $500 \cdot 10^{-9} \text{ mcm}^2$), half-length of the crack (75, 150 and 275 m), the distance between the cracks (12, 18, 24, 36 and 48 m). [5] The studies used the following mean values of Marcellus and Haynesville deposits: the depth of the layer roof – 3,627 and 2,095.5 m, the thickness of the reservoir - 61 and 71.6 m, porosity - 8 and 4.8%, initial reservoir pressure - 69 and 28.3 MPa, and relative density of the gas - 0.593 and 0.57. The properties of Haynesville deposit were determined using an average of 100 different wells along the area. The properties of Marcellus deposit were taken on the basis of mean values of 160 wells of Tioha county, Pennsylvania. The length of the horizontal section of wells was the same for all options, i.e. 1,170 m. The lateral trunk is placed in the middle of the deposit thickness. The basic option for Marcellus and Haynesville deposits was the matrix with permeability of $50 \cdot 10^{-9} \text{ mcm}^2$, the distance between the cracks is 25 m, which corresponds to 48 cracks, and the crack half-length is 150 m. The following maximum gas flow rates were investigated: for Marcellus deposit - 85 thousand m^3/day and for Haynesville deposit 170 thousand m^3/day .

In studies assumed that all wells are placed evenly over the area, draining the homogeneous reservoir area of 2.6 km^2 , are put into operation simultaneously and are operated with a constant gas flow rate until the pressure at the wellhead is reduced to a pressure in industrial pipeline. Thereafter the wells are operated at a constant working pressure at the mouth (1.7 MPa).

According to the calculations (Fig. 1), the rate of gas extraction, as well as a combined net profit reaches the maximum value on five wells. Upon further increase in the number of wells the gas extraction ratio increased only slightly, and the cumulative net income is reduced.

The basic option provides for cracks with the half-length of 150 m. The SDV of each well extends to 304.8 m (152.4 m in each direction). Five wells form a total SDV length of 1,524 m of the possible 1,609 m, like at the area of 2.6 km^2 . The optimum distance between wells is well correlated with SDV length.

For comparison with the basic option, the other options changed the value of the matrix permeability, crack half-length and the distance between the cracks.

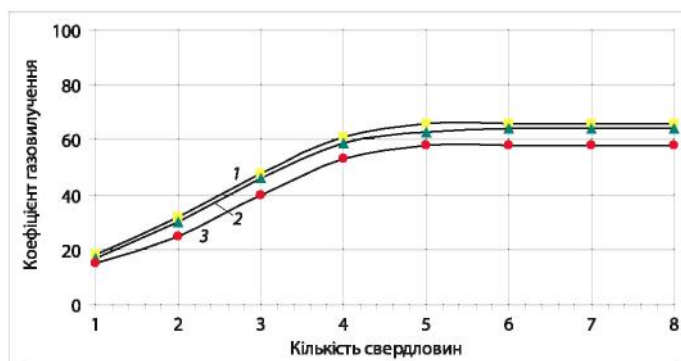


Figure 4. Dependence of the gas extraction ratio on the number of wells for different distances between the cracks: 1- 12; 2- 24; 3- 48 m

Fig. 2 shows the dependence of the gas extraction coefficient on the number of wells for half-length crack of 75, 150 (basic option) and 275 meters. For half-length cracks 75 m the maximum gas extraction coefficient is achieved only on eight wells in the area, but still is less than the other values of the half-length crack. For half-length crack 275 m the maximum gas extraction coefficient is achieved in three wells. The same gas extraction coefficient is the case for half-length crack of 150 m in the presence of five or more wells. The results indicate the importance of the SDV and EDV ratios. To maximize the gas extraction SDVs of each well should contact with each other.

The permeability effect on the gas extraction coefficient is shown in fig. 3. For $5 \cdot 10^{-9} \text{ mcm}^2$ permeability the gas extraction coefficient on five wells reaches only 50%. For all models with $5 \cdot 10^{-9} \text{ mcm}^2$ permeability the net cumulative income was negative or below the minimum 10%, indicating a lack of economic feasibility of the development of the area with rocks permeability of $5 \cdot 10^{-9} \text{ mcm}^2$. The option with $500 \cdot 10^{-9} \text{ mcm}^2$ permeability has the highest value of the net cumulative income. As shown in Fig. 3, the optimum number of wells in this case will be four (for the basic penetrability of $50 \cdot 10^{-9} \text{ mcm}^2$ the number of wells shall be five). Thus, the external flow from this matrix can be significant for permeability values of $500 \cdot 10^{-9} \text{ mcm}^2$ and more.

In experiments with various distances between the cracks it was assumed that the hydraulic cracks are distributed evenly along the perforated horizontal site so that 96 cracks have a 12-meter distance between the cracks and 24 cracks have a 48-meter distance.

The dependence of gas extraction coefficient on the smallest and biggest distances between the cracks is shown in Fig. 4. For a distance of 48 m the gas extraction coefficient reaches 58% with five wells in the area. For a distance of 12 m the gas extraction coefficient is 66%, also with five wells in the area. The smallest spacing between the cracks provided the maximum values of the net cumulative income and gas extraction coefficient. For the distances less than 24 m, the gas extraction coefficient is increased by less than 5%. The analysis of the research findings shows that the optimal interval between cracks ranges from 24 to 30 m, if the half-length crack is 150 m (basic option).

Thus, the findings of study of the optimal distance between wells during shale gas extraction in the case of Marcellus and Haynesville deposits show that the net cumulative income for the basic option of the matrix permeability of $5 \cdot 10^{-9} \text{ mcm}^2$ begins to decline after 10 years of gas extraction if there are more than five wells. So the best option for the area of 2.6 km^2 is five wells. The maximum gas extraction coefficient can be achieved when the SDVs and EDVs of each well contact. In the case of matrix permeability of $500 \cdot 10^{-9} \text{ mcm}^2$, which is ten times more than the basic option, the optimal number of wells in the area of gas content is four. The influence of matrix permeability on

the gas extraction coefficient showed that the outer flow from the rock matrix can become significant when the value of the permeability is $500 \cdot 10^{-9}$ mcm² and more. It was found that the optimal spacing between the cracks –s 24 to 30 m.

The findings of the presented researches describe the impact of natural and technological factors on the shale gas extraction coefficient. Method [5] can be used to select the optimal option for the design and development of shale gas deposits in Ukraine.

Analyzing the data from current and future formations of shale gas in the world and in Ukraine, it can be assumed that all the criteria of the prospective areas for shale gas in Ukraine generally meet the European ones (by the content of clay, geological age, R_0 values, TOC, effective thickness). The shale gas deposits in North America have better geological and physical characteristics.

Mastering of the unconventional gas spaces is a complex process where the technical, commercial and environmental issues are very interrelated to determine the economic attractiveness for the project. The uncertainty of many variables, especially the geological data, wells productivity, and the cost of well construction is dominant throughout the period of development of deposits.

To mitigate the risks, it is recommended using a series of the life cycle phases of the shale gas with clear criteria for deciding on the subsequent of the project for investigation and subsequent development of the promising areas, i.e. exploration, evaluation, drilling, extraction and reclamation.

The key factors for successful development of unconventional gas reserves remain for many years (and will remain) are the drilling of operational horizontal wells and performance of a multi-grade hydraulic layer fracturing therein.

These two factors reflect the fundamental differences between the development of unconventional and traditional gases. The natural gas deposit is the uniform hydrodynamic system. Therefore, its design provides for control and management of the process of fluid movement in the reservoir to the extraction wells, determination of the key averaged development indicators (average single well production rate, average reservoir pressure, etc.). The development of unconventional gas deposits is discrete and actually connected to the control and management of each well operation processes. Since the unstimulated gas-containing rocks of unconventional gas (matrix) have very low permeability, the fluid filtration to the downhole almost does not occur. By drilling horizontal shafts and performance of multiple hydraulic layer fracturing the simulated deposit volume is formed in the well, which is the main source of gas during the entire period of operation of an economically viable well. Thus, when drilling a grid of wells in the unconventional gas deposit the wells should be placed so that their SDVs contacted with each other or at least overlapped to prevent the well interference phenomenon.

The above difference between the conventional and unconventional gas deposits explains the inability to use the existing analytical approaches for calculation of development performance and evaluation of the layer hydrodynamic properties. To do this, it is required to apply the different techniques, including the decline analysis method according to Arps, Argaval-Gardner, Fetkovich's curves and plotting of the gas flow rate dependence and accumulated gas collection on the time in bilogarithmic scale subject to determination of various modes of gas filtration, i.e. non-linear, pseudolinear, radial, pseudo-pseudostationary and pseudostationary flows. These methods make it possible to predict the gas production over time, to evaluate various well parameters, such as half-length of the crack, crack conductivity, skin effect, SDV limits, potentially recoverable well reserves etc. In addition to the aforesaid techniques it is required to apply the numerical modeling of the process for extraction of unconventional gas from wells, including the principle of dual porosity and Voronoi's grid, using the special software (e.g. Eslipse, CMG, etc.)

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NEWS

Jordan and Iraq Will Build the Pipeline

Jordan and Iraq agreed to build a pipeline to supply oil to Jordan. The pipeline will transport oil to a refinery in Zarha to meet Jordan needs and to the only Jordanian port of Aqaba for its export. The total capacity of the pipeline is estimated at 160 thousand m³ per day. Jordan and Iraq also agreed to increase the volume of oil to be delivered to Jordan from 1.6 to 2.4 thousand m³ per day.

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