TECHNOLOGY OF MULTISTAGE HYDRAULIC FRACTURING IN HORIZONTAL WELLS: DEVELOPMENT EXPERIENCE OF SHALY CARBONATES IN THE US AND ITS OPTIMIZATION FOR THE FIELDS OF THE REPUBLIC OF TATARSTAN

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Abstract. The paper considers efficient development of Domanic reservoirs in Tatarstan using multistage fracturing technology in horizontal wells, based on the analysis of developing Shaly Carbonates in the United States, which are the closest in terms of geological and physical characteristics. Simulation in the software product GOHFER was carried out. Three types of multistage fracturing were considered: acid, proppant, and combined. Calculations show that practically all types of multistage fracturing with 5 stages are either not profitable, or are on the verge of profitability. Acid and combined multistage fracturing are the most effective at 10 stages; net discounted income for 5 years of operation is 90-100 million rubles. All three types of multistage fracturing are effective at 20 stages; acid and combined multistage fracturing are also characterized by the biggest net discounted income of 240-280 million rubles.

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1. Introduction

For a long time it was believed that production of hydrocarbons in tight and shale reservoirs is economically unprofitable. Significant improvements in horizontal drilling, completion and stimulation technologies have led to a change in this view.

In the last decade the interest of US oil companies in shale and tight reservoirs has intensified, production reached a maximum in 2014. After the crisis and the decline in oil prices in 2015, the volume of hydrocarbon production from such reservoirs has significantly decreased. Nevertheless, after that, the companies managed to reduce the cost of a well with multistage hydraulic fracturing twice, optimizing costs. In 2016-2017 at an oil price of about $50/bbl. US oil companies have resumed development of shale and tight reservoirs. The production from these sediments is currently growing, which is due to the relatively high economic efficiency of their development. It is expected that unconventional hydrocarbon resources, especially shale and tight, will provide the main growth in oil and gas production, and also attract significant investment in their development.

Studies conducted by Tatneft PJSC show that oil source reservoirs (shale and tight) are distributed throughout the territory of the Republic of Tatarstan, their reserves significantly exceed the reserves of conventional oil. Therefore, taking into account the positive experience of the USA, the issue of similar development of oil deposits in the Republic of Tatarstan, with the exception of previous mistakes made by national and foreign companies, is of great interest.

The purpose of this paper is to show how to efficiently develop oil source Domanic reservoirs in Tatarstan using multistage fracturing technology in horizontal wells, based on the analysis of developing Shaly Carbonates in the United States, which are the closest in terms of geological and physical characteristics.

2. Geological and physical characteristics of Domanic deposits and Shaly Carbonates

Fig. 1 shows the scheme of three main types of rocks – sandstone, limestone and shale. In nature, the ratio of these rocks in different proportions is more common. Characteristics analysis of different types of rocks shows that the Shaly Carbonate reservoir in the United States are fairly close to the carbonate Domanic deposits of Tatarstan. A comparison of the main geological and physical characteristics of these reservoirs is given in Table 1. The main difference is in two-fold lower reservoir temperature and two-fold higher viscosity of oil of the Domanic deposits, which undoubtedly influences the oil filtration, which lowers the rate of its withdrawal in comparison with the Shaly Carbonates.

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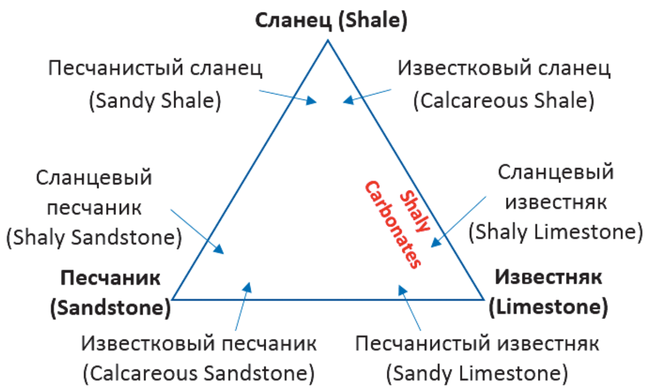

Fig. 1. Oil and gas provinces of shale and tight reservoirs of US fields

The largest oil deposits in the Shaly Carbonates in the United States belong to the provinces of EagleFord, Utica, Haynesville (Fig. 2). The rocks consist mainly of limestone, dolomite, clays, partially carbonate siltstones, siliceous and calcareous mudstones, sometimes sandstone impurities

3. Multistage hydraulic fracturing in horizontal wells

There are two fundamental and critical properties of unconventional reservoirs – low permeability and extremely small pore sizes compared to conventional

Characteristic	Unit	Domanic deposits	Shaly Carbonates
Reservoir depth	m	1700-1800	1600-1700
Net oil thickness	m	7-35	9-21
Reservoir temperature	^{0}C	35	70
Permeability	mD	0.001-1	0.001-0.2
Viscosity of oil	mPa*s	20-35	1.3-10
Gradient pressure in depth	MPa/m	0.0094	0.0094-0.01
Initial reservoir pressure	MPa	16-17	15-16
Initial oil saturation	%	60-90	40-80
Porosity	%	6-15	6-10
T_{max}	^{0}C	420-433	427-440
TOC	%	2-20	4-12
Clay content	%	2-18	4-25
Kerogen type	-	I, II	I, II

Table 1. Basic geological and physical characteristics of Domanic deposits in Tatarstan and Shaly Carbonates in the USA

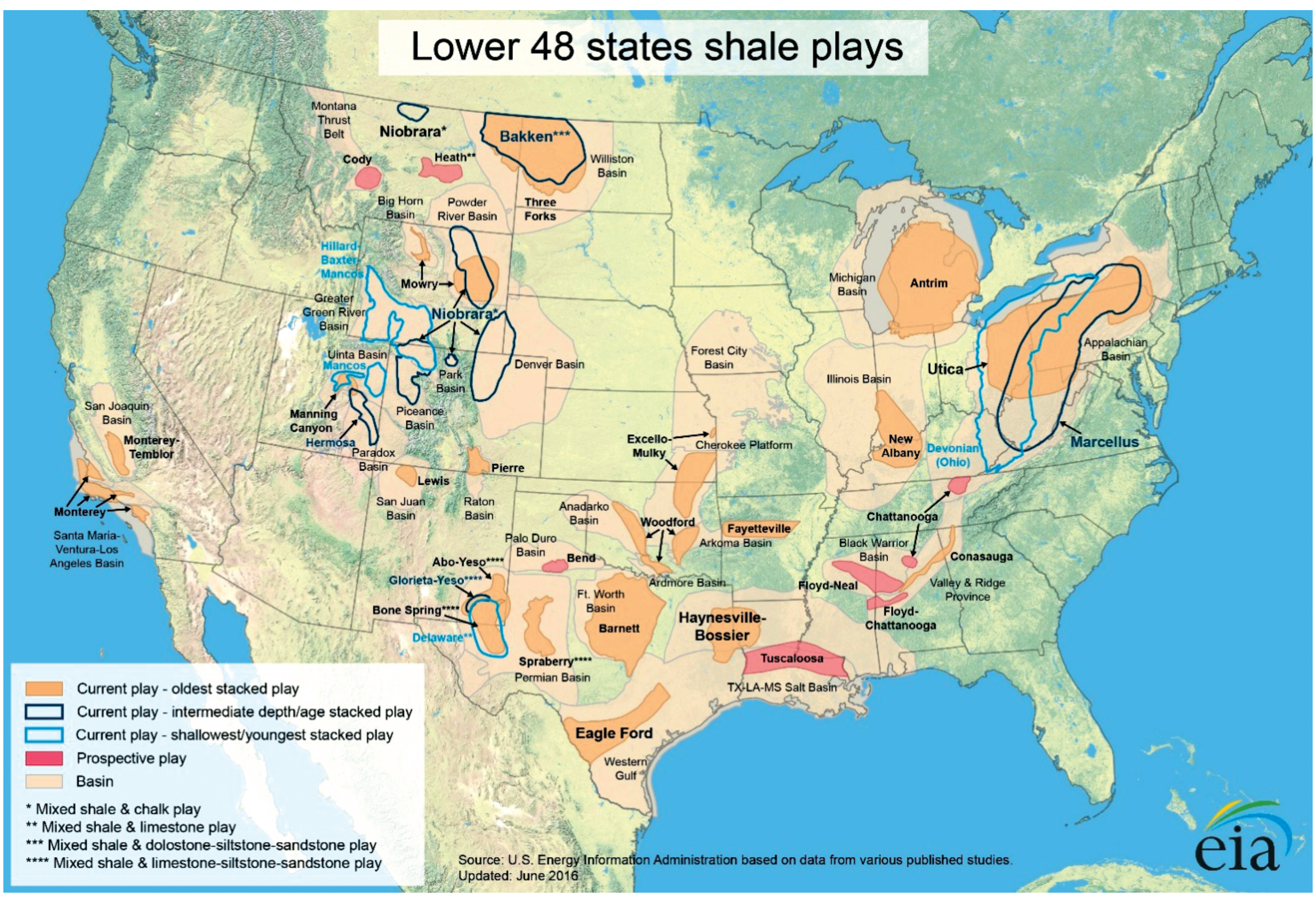

Fig. 2. Oil and gas provinces of shale and tight reservoirs in the US (according to Energy Information Administration – Agency for the collection, analysis and distribution of information on energy and energetics)

reservoirs. Very low permeability significantly hinders the filtration of hydrocarbons within the reservoirs. This means that hydrocarbons can be extracted only by natural or artificial fracturing of the formation. The main method for this is hydraulic fracturing.

An analysis of the works that are carried out in the USA before the modeling and design of the multistage fracturing showed that the standard set of studies includes:

1. SEM-Scanning Electron Microscopy. It determines the composition and structure of the rock at the pore level. Particular attention is paid to clay inclusions.

2. Thin section petrography. It describe in detail texture, rock skeleton, pore systems and minerals.

3. X-Ray Powder Diffraction. It determines the composition and structure of the rocks and inclusions.

4. Test for the content of TOC – Total Organic Carbon.

5. Test for determining VRo – Vitrine Reflectance. It determines the maturity of kerogen.

6. RCA – Routine Core Analysis. The properties of core samples are measured and used to construct petrophysical models.

7. Test for proppant embedment into the rock (Proppant Embedment Test). It determines the most effective fraction and proppant material. For rocks with high clay content, a larger fraction of the propane is used.

8. A complex of studies on migration of clay particles and determination of the critical salinity of working agents (Critical Salinity Test, Capillary Suction Time Test, Roller Oven Shale Stability Test, Erosion Test). It is necessary to select the optimal working agents for completion of the well and hydraulic fracturing, to prevent a significant decrease in the permeability of the reservoir.

9. Determination of capillary pressures.

10. Determination of the Young's triaxial modulus, Poisson's ratio, vertical and horizontal stresses of the formations.

In addition, it is possible to conduct special or additional studies.

In general, the complex of these studies, modeling, design of the multistage hydraulic fracturing, selection of working fluids and equipment allows to significantly reduce technical and technological risks, increase the economic efficiency of the project. The results of the works carried out in the USA on Shaly Carbonates are impressive. With a horizontal trunk length of 1600-3200 m, 20-40 stages of multistage fracturing, an initial oil production rate of about 130-200 t/d is obtained. The bulk of oil is extracted in the first 1.5 years. During this time, the reservoir pressure and, accordingly, the oil production rate drop rapidly. After 2.5-3 years, a second multistage fracturing is carried out, which allows extending the economically viable life of the well by another 2-2.5 years. All this allows, with an average drilling cost of $ 4 million (about 240 million rubles), to recoup capital costs for 6-12 months. In this case, after 3-5 years after putting the well into operation, the profitability index is 2.0-2.5 currency units.

A comparison of these indicators with the multistage fracturing conducted in 2015 in well 2917G for the Domanic deposits (Dankovo-Lebedyanian horizon) of the Bavlinsky oil field is given in Table 2. With a horizontal trunk length of 300 m, 4 stages of the multistage fracturing, an initial oil production rate of 12 tons/day was obtained. Capital costs for drilling, completion of wells and conducting acid multistage fracturing amounted to approximately $1.5 million (about 90 million rubles), the expected payback period is 5-10 years.

Thus, if we calculate the oil production rate of one well in Shaly Carbonates for a length of 270 m and 4 stages of the multistage fracturing, we will get 20-25 tons/day, which can be taken as potential production rate of well 2917G for Domanic deposits. To achieve this rate, it may be necessary to use large amounts of acid, as well as proppant, additional research and careful selection of working fluids. However, this issue requires additional study.

It should be noted that in spite of the vast experience of the USA in the field of multistage hydraulic fracturing

Parameter	Unit	Domanic deposits (well 2917G)	Shaly Carbonates (mean values)
Trunk length of the horizontal well	m	270	1600-3200
Stage numbers of multistage hydraulic fracturing	pcs.	4	20-40
The initial oil production rate	t/day	12	130-200
The main oil production period	years	-	1.5
Time through which multistage hydraulic fracturing is repeated	years	-	2.5-3
Period of well operation after repeated multistage hydraulic fracturing	years	-	2-2.5
The total life of the well	years	-	3-5
Capital costs per 1 well (drilling + completion + multistage hydraulic fracturing)	$ mln	1.5	4
Payback period	month	60-120	6-12
Cost-benefit index	cur.un	-	2-2.5

Table 2. Indicators comparison of multistage hydraulic fracturing conducted in well 2917G in the Republic of Tatarstan and on an average of Shaly Carbonates in the USA

in oil source deposits, Russia is also carrying out pilot commercial development. However, a review of the literature shows that most of the works relate to conventional low-permeability reservoirs (0.1-5 mD). The largest oil companies, such as Rosneft PJSC NK, Gazpromneft PJSC, Lukoil PJSC, Surgutneftegaz JSC, as well as their divisions, have been carrying out since 2013 in tight reservoirs both acid and proppant multistage fracturing in average of 4-8 stages per well. Comparison with vertical unstimulated wells shows that the oil production rate of horizontal wells with multistage fracturing is 4 times higher on average.

4. Computational simulation of multistage hydraulic fracturing in the Domanic deposits of the Republic of Tatarstan

Simulation in the software product GOHFER was carried out to assess the potential of the multistage hydraulic fracturing in the Domanic deposits of Tatarstan. The basis was a well Stoler-21-3N (North Dakota, USA) that penetrated Shaly Carbonates reservoir. The reservoir has similar mineralogy, depth of occurrence, and also petrophysical parameters, contains 30-45% limestone, 15% anhydrides, 35% dolomite, 1-10% clay. The average geological and physical characteristics correspond to the Domanic deposits in Tatarstan, the values are given in Table 1.

Three types of multistage fracturing were considered: acid, proppant, and also combined that includes cracks fixation by proppant after acid multistage fracturing. In each of the three types of multistage fracturing, three options are calculated, differing in the number of fracturing stages and, respectively, in the length of the horizontal well trunk. The length of the horizontal trunk for 5 stages is 300 m, for 10 stages – 550 m, for 20 stages – 1050 m. SlickWater (a fluid with additives for reducing friction) and Guar- 20 (guar-based resin fluid) were used as fracturing fluids. Ceramic proppant of low density was used, of CARBOECONOPROP and CARBOLITE grades, 20/40 mesh fraction, concentration 0.0275 kg/m^2. The acids were applied with 15% HCl and 2% KCl. The results of the calculations are given in Table 3.

Calculations show that practically all types of multistage fracturing with 5 stages are either not profitable, or are on the verge of profitability. Acid and combined multistage fracturing are the most effective at 10 stages; net discounted income for 5 years of operation is 90-100 million rubles. All three types of multistage fracturing are effective at 20 stages; acid and combined multistage fracturing are also characterized by the biggest net discounted income of 240-280 million rubles.

5. Conclusion

Taking into account the existing amendments to the tax legislation of the Russian Federation, which have exempted the Bazhenov, Abalak, Khadum and Domanic formations from taxation of mineral extraction tax for 15 years, it is necessary to accelerate the process of studying oil reservoirs and conduct pilot commercial development by the technology of horizontal wells with multistage hydraulic fracturing. The experience of foreign experts in this can significantly reduce the risks of developing such reservoirs. Nevertheless, it is unlikely that all the works

Characteristic			Acid multistage fracturing		Proppant multistage fracturing		Combined multistage fracturing	
			1 year	5 years	1 year	5 years	1 year	5 years
Volume of injected fluids per 1 stage of multistage fracturing, tons	SlickWater		114		127		132	
	Guar-20		-		170		-	
	15%HCl		132		-		132	
	2%KCl		19		-		-	
	CMHPG#35		57		-		106	
Mass of injected proppant per 1 stage of multistage fracturing, tons	CARBOLITE		-		59		-	
	CARBOECONOPROP		-		-		21	
Initial oil production rate, t/d		5 stages	34.0		33.5		56.3	
		10 stages	71.6		73.7		112.6	
		20 stages	143.2		147.4		225.2	
Accumulated oil production, thousand tons		5 stages	1.7	4.1	1.2	2.1	1.8	4.9
		10 stages	3.5	8.5	2.5	4.4	6.2	9.7
		20 stages	7.0	17.1	5.1	8.8	8.9	19.4
Total capital costs, mln rub.		5 stages	151.6	151.6	135.2	135.2	163.7	163.7
		10 stages	177.8	177.8	162.3	162.3	203.5	203.5
		20 stages	255.0	255.0	217.8	217.8	283.6	283.6
Net discounted income, mln rub.		5 stages	-41.8	-10.2	-40.9	-25.8	-49.0	16.1
		10 stages	-10.2	91.4	-21.0	14.6	-2.4	104.1
		20 stages	32.2	239.0	13.9	88.7	63.4	280.1

Table 3. Indicators comparison of multistage hydraulic fracturing conducted in well 2917G in the Republic of Tatarstan and on an average by Shaly Carbonates in the USA

and operations of the horizontal wells with multistage fracturing will be copied completely due to the presence of some distinctive features of the Domanic deposits in Tatarstan and Shaly Carbonates in the USA. First of all, this is the lower reservoir temperature and higher oil viscosity. Therefore, it is necessary to create our own modification of the multistage hydraulic fracturing technology for the development of Domanic deposits.

The main recommendations that can be learned from the development of Shaly Carbonates in the US and which can be recommended for Domanic deposits in the Republic of Tatarstan:

1. Use of proppant. In the USA, multistage fracturing is rarely used with acid injection, even in purely carbonate rocks. Many studies by US scientists show the closure of the multistage fracturing cracks in a short time. If an acid is used, the proppant is injected into the formed “wormholes”.

2. Shank cementing. Statistics on the wells completion in oil source deposits in the United States shows that the number of wells with an open trunk is decreasing annually and now most of the new wells are completed with cementing and perforation.

3. Large length of horizontal trunk. A number of studies conducted for horizontal wells in Tatarstan shows that the effective length of the horizontal trunk is much less than the actual one and drilling horizontal trunks longer than 300-400 m can be economically not profitable. However, firstly, the research data include mainly open-hole wells, and secondly, do not include wells in tight reservoirs. Therefore, it is necessary to carry out additional studies for the drilling of wells above 1 km.

4. More stages of the multistage fracturing. The oil production rate is directly proportional to the number of fracturing stages, which in turn depend on the length of horizontal trunk. Therefore, in the US, less than 20 stages are rarely used. For the Domanic deposits, the main obstacle to increasing the stages is the technical side – the need for more expensive equipment.

Application of chemicals and temperature. The viscosity of oil in reservoir conditions of 20-35 mPa*s for conventional reservoirs is not a problem. However, filtration is greatly complicated for Domanic deposits with ultra low permeability. Therefore, it is recommended to carry out research and pilot commercial development on the use of chemicals during the multistage fracturing, or the use of heated working fluids.

Maintenance of the reservoir pressure. In the US, water injection is used in a reservoir with a permeability of up to 1 mD. For permeability with lower values, research is currently conducted on injecting CO_2.

Thus, for the successful development of Domanic deposits in the Republic of Tatarstan with the use of multistage hydraulic fracturing in the horizontal well, it is necessary to conduct full-scale research, starting with the study of the formation and structure specifics of these reservoirs, geochemistry, geophysics, geomechanics, etc., the collection and analysis of all geological and geophysical information, creation of geological, hydrodynamic, geomechanical and other models, horizontal well designing and its completion, design of the multistage hydraulic fracturing, and finishing with the selection of working fluids and equipment for drilling, opening and multistage hydraulic fracturing. All this, according to the experience of the United States, allows minimizing all risks and, accordingly, obtaining economically efficient oil production from oil source deposits.

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