Nafta-Gaz 2019, no. 10, pp. 591–597, DOI: 10.18668/NG.2019.10.01

Hydraulic fracturing using liquefied hydrocarbon gases or light hydrocarbons. Technology prospects in the Russian Federation

Szczelinowanie hydrauliczne z wykorzystaniem skroplonych gazów węglowodorowych lub węglowodorów lekkich. Perspektywy technologiczne w Federacji Rosyjskiej

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ABSTRACT: One of the most effective methods of development of oil and gas fields with complicated hydrocarbon production conditions is hydraulic fracturing. However, utilization of the most commonly used water-based fracturing fluids is not always expedient, for instance, in unconventional formations, reservoirs with low formation pressure containing water-sensitive minerals, low-permeable or unconsolidated rocks. American and Canadian literature indicates that the most suitable and modern frac fluid is hydrocarbon one based on liquefied petroleum gas or light hydrocarbons. The use of such fluids in the fields of the Russian Federation is perspective. The main reason to face the new technology is the presence of one of the most promising production targets in Russia – the Bazhenov formation. It is nowadays one of the most desirable objects, and at the same time one of the most difficult to be developed. Enormous reserves of oil in this formation suggest its desirability. The government has for a long time stimulated exploitation of these deposits by introducing a tax credit. Today, there is no universal approach to the development of this target. A new advanced integrated approach will address this problem and pave the way for the development of this rich source of hydrocarbons containing million tons of oil. Another promising task for the implementation of this technology may be the use of associated petroleum gas, which according to the Russian regulations must be disposed of, but the technologies currently in use in Russia do not allow this to be done sufficiently. When developing the proposed technology, it is planned to start with the use of liquefied petroleum gas (propane-butane mixture) as the main hydraulic fracturing fluid and switch to petroleum gas as the technology develops.

Key words: hydraulic fracturing, fracking, liquefied petroleum gas (LPG), unconventional resources, Bazhenov formation.

STRESZCZENIE: Jedną z najbardziej efektywnych metod udostępniania złóż ropy naftowej i gazu o skomplikowanych warunkach produkcji węglowodorów jest szczelinowanie hydrauliczne. Wykorzystanie najczęściej stosowanych płynów szczelinujących na bazie wody nie zawsze jest jednak korzystne, np. w złożach niekonwencjonalnych, złożach o niskim ciśnieniu złożowym zawierających minerały wrażliwe na wodę, skałach słabo przepuszczalnych czy nieskonsolidowanych. Z literatury amerykańskiej i kanadyjskiej wynika, że najbardziej odpowiednim i nowoczesnym płynem szczelinującym jest płyn węglowodorowy oparty na skroplonym gazie lub lekkich węglowodorach. Wykorzystanie takich płynów na złożach Federacji Rosyjskiej jest perspektywiczne. Głównym powodem mierzenia się z nową technologią jest obecność w Rosji jednego z najbardziej obiecujących celów produkcyjnych – formacji Bazhenov. Aktualnie jest to jedna z najbardziej interesujących, ale równocześnie najtrudniejszych do udostępnienia formacji. Ogromne zasoby ropy naftowej oszacowane dla tej formacji wskazują na jej dużą perspektywiczność. Rząd przez długi czas stymulował eksploatację tych złóż, stosując ulgę podatkową. Dziś brak jest uniwersalnego podejścia do tego zagadnienia. Nowe, zaawansowane i zintegrowane podejście umożliwi rozwiązanie tego problemu i otworzy drogę do wykorzystania tego bogatego źródła węglowodorów, zawierającego miliony ton ropy naftowej. Kolejnym wyzwaniem wdrożenia tej technologii może być wykorzystanie gazu towarzyszącego ropie, który zgodnie z rosyjskimi przepisami musi być odseparowany od ropy, jednak obecne technologie stosowane w Rosji nie pozwalają na to w wystarczającym stopniu. Przy opracowywaniu proponowanej technologii planuje się rozpoczęcie od użycia skroplonego gazu węglowodorowego (mieszanina propan-butan) jako głównego płynu szczelinującego. W miarę rozwoju technologii planuje się przejście z gazu płynnego LPG na gaz pochodzący z ropy.

Słowa kluczowe: szczelinowanie hydrauliczne, szczelinowanie, płynny gaz ropopochodny (LPG), źródła niekonwencjonalne, formacja Bazhenov.

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Article contributed to the Editor 17.05.2019. Approved for publication 23.09.2019

Introduction

The Bazhenov formation is nowadays one of the most desirable objects, and at the same time one of the most difficult to be developed. Enormous reserves of oil in this formation suggest its desirability. The government has for a long time stimulated exploitation of these deposits by introducing a tax credit (Klubkov, 2015). However, if the object was simple, everybody would rush to earn money by producing hydrocarbons from it.

To begin with, it is necessary to consider how this object looks like and what the main differences between this specific formation and traditional formations are. A brief description is given below (see Fig. 1 and Fig. 2).

Today there is no universal approach to the development of the Bazhenov formation and other formations of this kind. A new advanced integrated approach will address this problem and pave the way for the development of this rich source of hydrocarbons containing million tons of oil.

Such an approach cannot be created by one organization. This complicated, multidisciplinary work requires a large number of organizations having unique competences. Engineering center of Gubkin University of Oil and Gas is ready to become the initiator of this project, unite leading organizations of Russian oil and gas industry under its leadership.

The main aim of this prospective consortium is defined as follows:

- to improve the economic effectiveness of the development and exploitation of fields containing hydrocarbon reserves, which are difficult to recover;
- to implement an integrated approach to preparing and conducting fracturing with liquefied gases and their mixes as frac fluids.

A number of problems must be solved in order to achieve this aim. These are both challenges that oil and gas companies face every day and new research perspectives which are familiar to academic organizations. The novelty of these problems is that Russian companies have not used this technology so far and in the first stage of the project it has the form of a black box, which contains a lot of uncertainties, but has some huge prospects too.

The following stages are defined as the project objectives:

1. Creation of laboratory equipment for the development and testing of frac fluids based on liquefied petroleum/natural gases (LPG/LNG), light hydrocarbons and their mixtures. This equipment must be characterized by a high

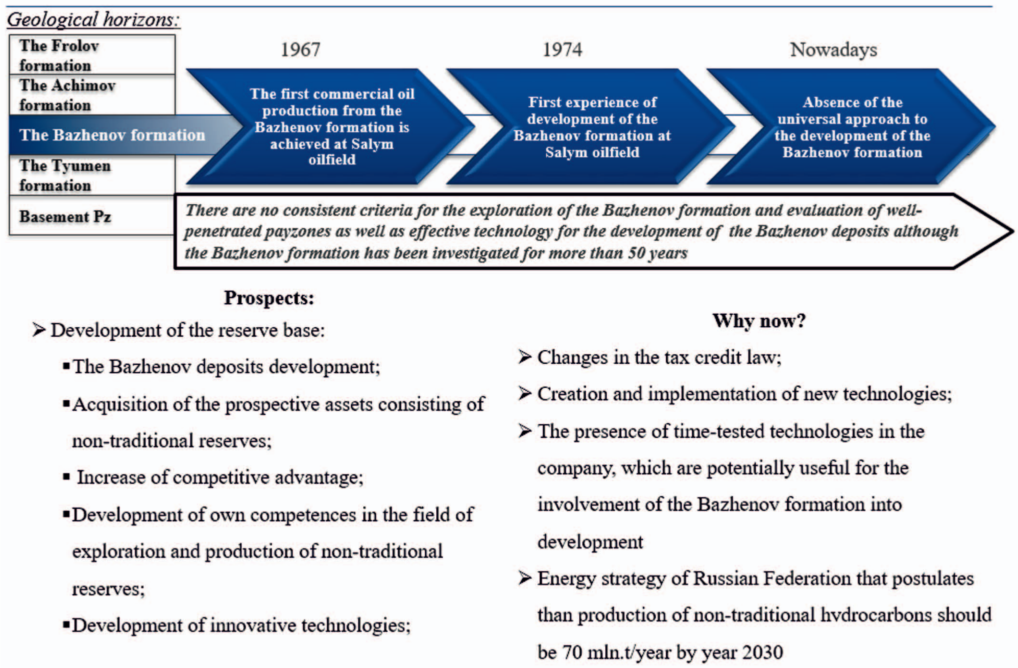

Fig. 1. Prospects of the development of non-conventional reserves

Rys. 1. Perspektywy rozwoju złóż niekonwencjonalnych

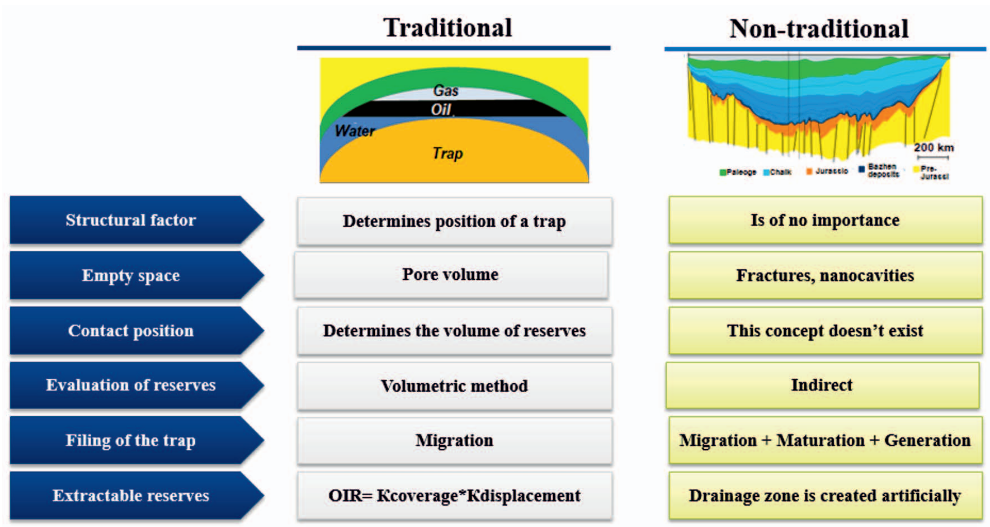

Fig. 2. Key features of non-traditional reserves

Rys. 2. Kluczowe cechy złóż niekonwencjonalnych level of functionality. It will be used to test LPG frac fluids, determine viscosity changes of these fluids, analyze their rheological properties and the rate of the proppant settling at the bottomhole in conditions close to formation ones. In addition, it will allow to determine hydraulic properties of frac fluids including measurement of the friction pressure losses during fluid pumping through the tubing pipes.

2. Development of LPG-based and light hydrocarbon-based fracturing fluids with unique properties. These properties allow to achieve fracture performance obtained by using this type of treatment. This is very important when developing unconventional reservoirs and hard-to-recover hydrocarbon reserves. Non-traditional hydrocarbon-based frac fluids dramatically increase the flow of hydrocarbons into the well due to the maximum cleaning-out of hydraulic fracture from the breakdown products of the technological fluid. In addition, the effective length of the fracture is very close to its created propped length. Thermal stability of the fluids falls within a wide temperature range from 20°C to up to 120°C.
3. Development of specific software for the well test analysis, particularly post LPG fracturing production from unconventional reservoirs. This software will help to increase the amount of useful information obtained without raising the cost of field surveys. The proposed software can be used to assess peculiarities of the reservoir, in particularly, the quality of pre and post frac well performance. The following data is automatically calculated from pressure-time curves:
   - Filtration parameters of the formation (mobility and transmissibility of formation fluid);
   - Radius of the damaged zone, permeability of critical matrix and formation;
   - Filtration parameters of the porous-fractured formation and the response time of transition processes;
   - Filtration parameter of the formation with impermeable boundaries: half-infinite formations, wedge-shaped formations; lens-shaped and shoestring formations.

   In addition, this software will allow to:
   - Increase the interpretation quality of hydrodynamic survey of the wells with unconventional reservoirs, in particular the Bazhenov formation, low-permeable oil and gas formations as well as conventional reservoirs;
   - Analyze the effectiveness of data frac and main frac operations and update the parameters of the achieved fracture by applying the processing of pressure decline curves; increase the accuracy of post frac production evaluation capabilities;
   - Perform a reasonable and faster interpretation of the data compared to the classical approach.
   - One of the advantages of this software is taking into account non-linear laws describing filtration of liquid in porous media. The existing analogues are not capable to fulfil this task.
4. Creation and implementation of software for oilfields and well LPG frac candidate selection (screening). Such adviser will reduce the risk of mistakes during the screening of fields and wells. Since the new technology is to be implemented at oilfields containing unconventional resources, the analysis of both technological and economic constituents is essential, with the latter being the most significant. The software will also consist of modules of expert analysis, economical evaluation and detailed technological assessment of parameters;
5. The last and the most technologically difficult part of the whole project is the creation of the unique frac fleet. Its originality lies in two points: first – there is no existing "culture" of creating frac fleets in Russia; second – the equipment to be designed will not be similar to all those units and equipment which are used during normal fracturing job. Every piece of equipment of the unique frac fleet operates under high pressure.

The essence of the LPG frac technology

The technology in question is widely used throughout the USA and Canada. More than 1500 operations have been conducted on fields with shale gas and oil so far (Tudor et al., 2009; Leblanc et al., 2011). However, its implementation decreases over time due to the increasing costs of the technique. The economic peculiarity of the mentioned countries shows that the cheapest alternative is to drill horizontal wells and conduct less efficient but less expensive, fracturing with water-based frac fluids. This method is more profitable than fracturing with more effective hydrocarbon-based frac fluid.

This technology was launched due to both common sense and environmental restrictions. According to American and Canadian statistics, shale formations treatment requires an average of 800–1500 m^3 of water per well (Leblanc et al., 2011). First, one has to find such amount of water, treat it with chemical reagents and pump it into a formation. The problem of fracture clean-up and well start often occurs after treatment. More than 50% of pumped water remains trapped in a formation after treatment due to the low permeability of shale formations, presence of swelling minerals, quite high residual viscosity. Part of that trapped water will be produced for the next several years. Moreover, it does not stop there: one faces the problem of utilization of such huge amounts of water produced. It should be noted that there is a risk of

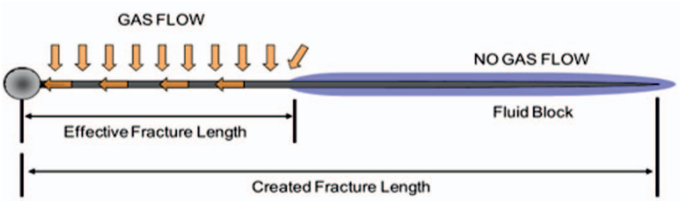

Fig. 3. Characteristics of the fracture obtained with water gel

Rys. 3. Charakterystyka szczeliny otrzymanej przy użyciu żelu na bazie wody

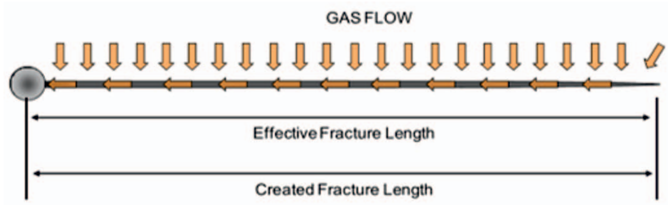

Fig. 4. Characteristics of the fracture obtained with hydrocarbon gel

Rys. 4. Charakterystyka szczeliny otrzymanej przy użyciu żelu na bazie węglowodorów

the wellbore collapse during a flow stimulation. Generally, to stimulate flow it is necessary to reduce a pressure to the atmospheric level, which may result in a wellbore collapse (Leblanc et al., 2011).

If you imagine a graphical comparison of normal fracturing with LPG fracturing (Figs. 3, 4), you will realize the reason for the beneficial effect at once. It can be seen that the effective length of the fracture is 2 times larger and hydrocarbons flow rate is correspondingly greater than in the case of water-based fracturing. In addition, if you take into consideration the fact that the final conductivity of a fracture obtained with hydrocarbons is more than 90% whereas the conductivity of a normal fracture does not exceed 40%, the positive effect will be evident (Leblanc et al., 2011).

The existence of the fluid block can be proved by recent research carried out at Gubkin University, the results of which are given in Fig. 5. They show that most of rocks swell when in contact with water-based frac fluids.

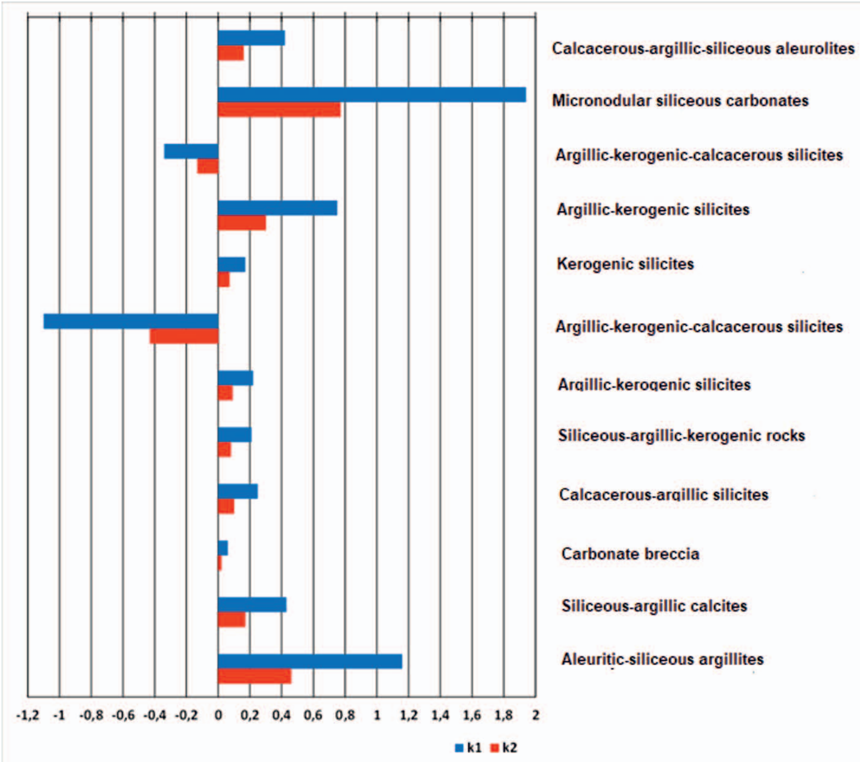

Fig. 5. The Bazhenov formation rocks compatibility with water-based frac fluids. Swelling coefficient K_1 is equal to the ratio of volumes of liquid and rock, while swelling coefficient K_2 is equal to the ratio of liquid volume to rocks weight

Rys. 5. Kompatybilność skał formacji Bazhenov z płynami szczelinującymi na bazie wody. Współczynnik pęcznienia K_1 jest równy stosunkowi objętości płynu i skały, współczynnik pęcznienia K_2 jest równy stosunkowi objętości płynu i masy skały

Simplicity of the flow stimulation after treatment can be easily estimated by comparing the characteristics of base liquids for both types of fracturing (Table 1) (Gaurav and Kashikar, 2015).

According to Table 1, the density of liquefied gases is 2 times lower than the density of water, which results in the reduced hydrostatic pressure, hence it will be much easier to start a well into production. The viscosity of propane/butane is 6 times lower than the viscosity of water, so less differential pressure will be needed for movement of liquid in the fracture during the flow stimulation. The interfacial tension of liquefied gases is 6 times lower than the interfacial tension of water; it means that capillary pressure during movement of liquid

Table 1. Liquid's characteristics affecting flow stimulation after fracturing

Tabela 1. Charakterystyka płynu wpływająca na stymulację przepływu po hydraulicznym szczelinowaniu

Liquid	Density at 20°C	Viscosity at 40°C	Interfacial tension with CH_4 at 20°C
	[g/cm^3]	[cP]	[dyne/cm]
Water	1	0.66	72.8
Oil	0.78–0.85	1–10	21.8
Liquefied gases (propane/butane)	0.51–0.58	0.08–0.14	7.6–12.4

through porous media will be smaller (in other words, liquid will be exposed to smaller capillary end effect at the interface with rocks and reservoir fluids). Finally, it should be noted that 1 m^3 of liquefied gas can be converted into 272 m^3 of normal gas, therefore liquid will gas itself during the well stimulation.

Potential application of LPG fracturing in the Russian fields

The results of the research should be implemented in the proposed fields containing hard-to-recover reserves.
Such objects include:

- Shales of the Bazhenov, Abalak, Domanik formations;
- Low- and ultra low-permeable oil- and gas-bearing formations;
- Formations containing water-sensitive rocks (for example, the Turonian deposits, the deposits of Novoportovskoye and Messoyakhskoe oilfields);
- Productive formations where high risk of the breakthrough into overlying/underlying water/gas zones exists (large effective length of fracture will allow pumping large volumes of liquid and proppant to achieve desired productivity of a well);
- Productive formations with a low formation pressure;
- Unconsolidated reservoirs, which have some differential pressure limitations during well clean-out, start and production period.

Prospects of new technology in Russia

One of the most important conditions for the implementation of any technology in oilfields with hard-to-recover reserves is economic effectiveness, estimated on the ground of the well-known economic indicators (ROR, ROI, and NPV) as well as various risk levels such as technological or technical ones. Because the technology which we present is unique for Russia, the level of uncertainty about all possible risks is relatively high and huge attention should be paid to this fact.

Technological effect

The evaluation of the technological effect for ultralow-permeable formations, the permeability of which is measured in nano and micro scales, is a non-trivial task because traditional ways of calculating the inflow of fluid to a well do not obey the Darcy's law. This feature was considered in papers published by Gurevich et al. (1996), Inson et al. (2004), Gringarten et al. (2005), Kholodovskii (2009a, 2009b), Belyadi et al. (2010), Zolotukhin and Shulev (2018), Zolotukhin and Zhou (2018). The results obtained by various calculation methods (multivariate analysis, approximation methods, computer modeling) indicate a 1.2–2-fold increase in the production rate of a well stimulated with hydrocarbon-based frac fluids compared to the well where normal water-based fracturing was performed. According to the sources, this indicator ranges from 1.3 to 3-fold increase.

As for the creation of the so-called artificial reservoir (stimulated reservoir volume, SRV), its importance increases minimum up to 25% (for the planar hydraulic fracture). This indicator is higher for branched fractures. Such results can be calculated if geometrical dimensions of the fracture are taken into consideration.

According to the article (Gaurav and Kashikar, 2015), SRV has strong correlation with oil recovery index (OIR). The increase of SRV by 25% results in a 1.6-fold increase of OIR.

Economic evaluation

The data from Table 2 was used for the economic evaluation of the project. The results of the evaluation are shown in Fig. 6.

The production data was based on mathematical modeling. The statistical data of the well opened in the Bazhenov deposits as well as information given in the literature were taken into account during the process of modeling.

The value of the discounting rate is determined by a variety of factors, particularly, the degree of existing project risks. The cost of construction of the horizontal well was based on literature data (Kumar et al., 2017); the prices on the Russian market were taken into account.

Horizontal wells were taken for calculations. The average length of the horizontal part was 1000 meters, the total length of the borehole was 4000 meters. 50 tons of proppant and 200 m^3 of frac fluid were needed to conduct one treatment.

Figure 6 shows that economic indicators are the lowest for the case without fracturing. NPV increases after 3 years of exploitation for the hypothetic horizontal well with 10 multi-fracturing operations (water-based frac fluid) compared to the hypothetic non-fractured horizontal well. However, no positive effect is observed, which means that this way is unprofitable and unpromising. Wells fractured with LPG-based fluids show positive dynamics. In the case of a 1.2-fold increase in the production rate compared to water-based fracturing, the technology reaches the level of zero profitability. In the optimistic case, which is characterized by a twofold increase in the production rate, NPV is 2 times higher and the payback period is only 1 year. These results show that the optimization of the

Table 2. Input data for comparison of different ways of fracturing process implementation for hard-to-recover reserves of non-conventional formations

Tabela 2. Dane wejściowe do celów porównania różnych sposobów zastosowania procesu szczelinowania dla trudnych do pozyskania zasobów złóż niekonwencjonalnych

Indicator		Well without fracturing	Water-based fracturing	Hydrocarbon-based fracturing (1st)	Hydrocarbon-based fracturing (2nd)
Cumulative production per year [m^3]	0 year	0	0	0	0
	1st year	239	12404	14850	24859
	2nd year	106	5488	6570	10998
	3rd year	18	915	1095	1833
Cost of construction of one horizontal well [mln. USD]		4	4	4	4
Cost of carrying out 10 fracturing operations. [mln. USD]		–	0.6	1.2	1.2
Operating costs for the production of additional volume of oil [% of the annual crude oil revenue]		15	15	15	15
Oil prices [\$/m^3]		315	315	315	315
Discounting rate [%]		15	15	15	15

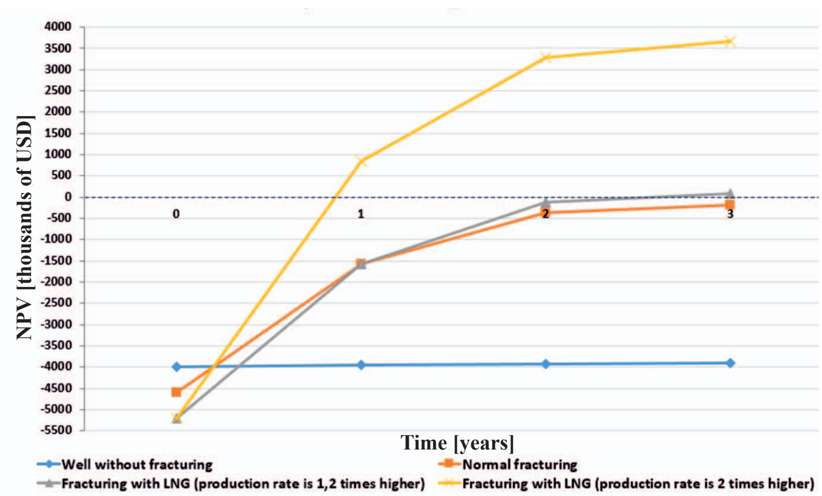

Fig. 6. Change in cash flow with time for different scenarios

Rys. 6. Zmiana przepływu pieniędzy z uwzględnieniem czasu dla różnych scenariuszy

proposed technology with its subsequent cheapening can turn it into a cost-effective one.

An assumption was made to calculate economic effects according to which all fracturing treatments were successful. The calculated profitability index for the projects ranges from 1.19 to 1.9.

There is not enough information now to unambiguously conclude whether LPG-based fracturing is economically effective. The value of capital investments as well as production dynamics data must be clarified.

Risks and uncertainties of the project

The problem of risks and uncertainties has not yet been solved. Currently, they are defined as follows:

1. There is no set of special standards and rules that ensure safe execution of LPG-based fracturing treatment. Therefore one must either follow existing regulatory documents, which are used in oil and gas industry, or develop new rationale for typical technological operations of hydrocarbon-based fracturing treatment.
2. High risk of fire and explosion requires additional protection rules. Western companies have some experience in implementing safety measures, in particular in developing and applying standard and rules for carrying out such work, specialized personal protective equipment, fire-extinguishing appliances, etc.
3. Traditional laboratory equipment for testing regular frac fluids is not suitable for the analysis of modern ones. However, sufficient potential for the solution of this problem has been accumulated in our country.
4. As to the development and production of chemical reagents for obtaining hydrocarbon-based gel, there are sufficient production capacities and experience in manufacturing of such systems existing in Russia. Sufficient experience has been accumulated in Oil and Gas Gubkin University to viscosify individual hydrocarbons of different molecular weights, their mixtures and natural hydrocarbons (oil, gas condensate) as well as hydrocarbon cuts.
5. The technology of storage, operational treatment and pumping of liquefied gas requires the presence of specific equipment at field: storage tanks, blenders, proppant silos, modified sealing joints, equipment for the regeneration of the frac fluid, etc. The cost of such equipment is relatively high. In most cases high capital investments and high degree

of uncertainty of obtaining desired results constitute serious obstacles for the project investments.

6. Huge amounts of liquefied gases are necessary for the realization of the project. The availability of this gas is not a problem. The required fractions are produced in sufficient volumes in gas processing factories in the Russian Federation. In particular, in Western Siberia more than 4.5 million of tons of liquefied gas are produced annually. Condensate stabilization factories should be taken into consideration, too.
7. The lack of qualified specialists in Russia requires the involvement of a sufficient number of experts from various fields of industry at the initial stage of the project. However, one should think about the establishment of Russian fracturing school as well as the creation of "culture" of carrying out of sophisticated hi-tech projects.

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