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WELL PRODUCTION AFTER HYDRAULIC FRACTURING IN SANDSTONE ROCKS IN THE NORTH OF THE PERM REGION

Hydraulic fracturing is one of the most popular ways of increasing well production. The article investigates the results of hydraulic fracturing (HF) in sandstones of the northern Perm region territory (Tula–Bobrikovian oil reservoirs of the Visean stage). The oil of these sites has a high and medium gas content, and the rocks have a wide range of permeability values as well as natural cracking. Based on the value of the linear Spearman correlation coefficient, the most significant parameters affecting the efficiency of the HF are determined. A ranking of these parameters has been performed. The greatest influence on well productivity after HF is the bottomhole pressure and productivity indices before HF. The relationships between the geometrical dimensions of HF cracks and the volume of the injected proppant are shown. The dependencies of well parameters after HF on well parameters before HF are constructed. The permeability coefficients of the reservoir remote zone do not actually change much after HF and the permeability coefficients of the bottom-hole zone increase on average by 30%. The impact of the formation and bottomhole pressure values on productivity indices after HF has been noted. At the same time, the rate of oil production decrease after HF is also dependent on bottomhole pressures. Recommendations have been made on the selection of wells for HF at the site under study and similar production targets as well as their post-operation technology practices. Changes in well production after HF are forecasted depending on geological and technological parameters.

Keywords: *Oil reservoir, hydraulic fracturing, productivity index, bottom-hole pressure, deformations*

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Introduction

Currently, there has been an increase in the proportion of hard-to-recover oil reserves, including highly viscous oils, low permeability reservoirs, etc. To increase oil production, geological and technical measures are being actively implemented at such deposits: hydraulic fracturing, acid treatment, radial drilling, etc. Hydraulic fracturing is one of the most efficient and common methods of increasing well productivity. The use of HF improves the hydrodynamic connection of wells with the productive formation and contributes to the fuller development of oil reserves [1]. The selection of wells for the HF requires the analysis of information on the history of the well operation, past activities, the well technical state, and its bottom-hole zone, etc. [2]. The main factors affecting the hydraulic fracturing efficiency are [3–8]:

- geological parameters of the formation: effective oil-saturated thickness, permeability, porosity, pressure, etc.;
- fluid properties: viscosity and density;
- technological parameters of HF: opening and half-length of cracks, the mass of proppant, etc.

Researchers note the effectiveness of HF in different deposit conditions, including low permeability reservoirs [9–10]. In some fields, the energy state of the production targets has a significant impact on the well productivity incremental growth after HF [11, 12]. Formation conditions influence the choice of process fluids and materials [13–15], and injection technology conditions on the geometry of cracks [16]. The developed natural cracking [17, 18] and high perforation density [19] increase the HF efficiency. The reduction of reservoir pressures relative to the initial values may lead to irreversible deformations of the reservoir and a reduction in pore space permeability. In the design of the work, special attention should be paid to deposits with a high content of oil-soluble gas and bottomhole pressures lower than the saturation pressure.

Laboratory and field stress research, well geophysical research, fracture development monitoring, and research of fracture fluid rheological parameters are essential for successful HF design, as well as core filtration testing [20, 21].

Analysis of hydraulic fracturing results

The article studies sandstone of oil fields in the North of Perm region (Tula–Bobrikovian oil reservoirs of the Visean stage) (**Fig. 1**).

Ranges of physical and geological characteristics

Depth	1919–2340 m
Reservoir thickness	3.1–11.6 m
Porosity	0.12–0.18 unit fraction
Permeability	79–653 $\mu m^2 10^{-3}$
Reservoir oil density	730–839 kg/m^3
Dynamic viscosity of reservoir oil	1.22–3.19 mPa·s
Gas content	64.2–164.6 m^3/t
Saturation pressure	11.56–16.0 MPa
Initial reservoir pressure	20.3–24.4 MPa

The oil of the sites under study is characterized by low density, low viscosity, high and medium gas content, high values of saturation pressure. The sites are characterized by a wide variation in permeability, as well as natural cracking.

A synthesis of basic information on HF technologies and its results at the sites under consideration has been carried out. The article estimates the level of connection between a well productivity index after HF and permeability, porosity, oil-saturation thickness, a production index before HF, formation pressure, and a flow rate of proppant based on a Spearman linear correlation coefficient (**Fig. 2**).

The greatest correlation is observed between the bottomhole pressure values, the productivity indices before HF and after HF. For these parameters the correlation coefficient is above 0.7. The porosity coefficient is more closely correlated with the productivity index after HF than the permeability and effective oil-saturated thickness. The minimal correlation density for the productivity index after HF is observed with the flow rate of proppant. In [22], it is noted that the clay content of the rock skeleton also has a major impact on the efficiency of HF, as it increases, the pore permeability of the reservoir space decreases.

After HF, the permeability of the remote area is practically unchanged (**Fig. 3**). The permeability of the bottomhole formation area increases on average by 30%. These facts may indicate the creation of cracks with a wing length no larger than the bottom-hole zone.

The values of the well production indices after HF are substantially dependent on the energy state of the formation, wherein the dependence of the production index on the bottomhole pressure has a correlation coefficient $R^2 = 0.5951$ (**Fig. 4**) and on the formation pressure $R^2 = 0.04$. This might indirectly confirm the position of the fracture wing within the bottomhole.

The effective voltage increases substantially as the bottomhole pressure decreases in the well bottom zones. At initial reservoir pressures of 20.3÷24.4 MPa, the effective pressure in the bottom-hole zones varied between 27.1÷31.2 MPa. At bottomhole pressures of 8÷12 MPa, the effective pressure in the bottom-hole zones shifted into the 39÷43 MPa range. When the pressure is reduced by more than 6÷7 MPa, there is no change in the porosity and permeability of the reservoir as the reservoir is completely compacted. Consequently, the decline in productivity indices in bottom-hole zones is mainly due to the release of gas from oil into the free phase. The most significant reduction in productivity indices, for this reason, occurs in the range of 10÷16 MPa.

Forecasting of well productivity after HF

There is some possibility of using probability-statistical models to predict the effectiveness of HF technology noted in specialist literature [23]. A multi-dimensional model has been made to determine wells productivity index in the fields under study based on porosity, effective oil-saturated thickness, dismemberment, productivity index before HF, and the planned bottomhole pressure after the operation:

$$PI = 1.41m + 1.35H - 4.6D + 0.52PI + 4.1P_{bot} - 33.1, \quad R = 0.79, \qquad (1)$$

The equation is obtained for the following parameter intervals:

m – 13÷22; H – 2.2÷24; D – 1÷10; PI – 0.2÷120; P_{bot} – 3÷17.4,

where PI is the productivity index; m is the porosity, fractions of units; H is the oil-filled thickness, m; D is the dismemberment, fractions of units; P_{bot} is the bottomhole pressures, MPa.

The dependency analysis (1) allows us to note that increasing the split of the reservoir reduces the efficiency of the operation. As the porosity, productivity index, and bottomhole pressure increase, the productivity index after HF increases significantly.

The rate of decline in well productivity after HF also depends on the bottomhole pressure values (**Fig. 5**). At a ratio of bottomhole pressure and saturation pressure (P_{bot}/P_{sat}) of 0.18, well production fell by 80%

Fig. 1. The study area

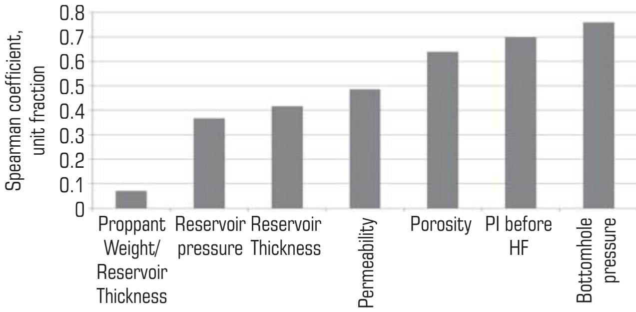

Fig. 2. Values of the Spearman linear correlation coefficient between PI of wells after hydraulic fracturing and the initial parameters of the reservoir and hydraulic fracturing technology

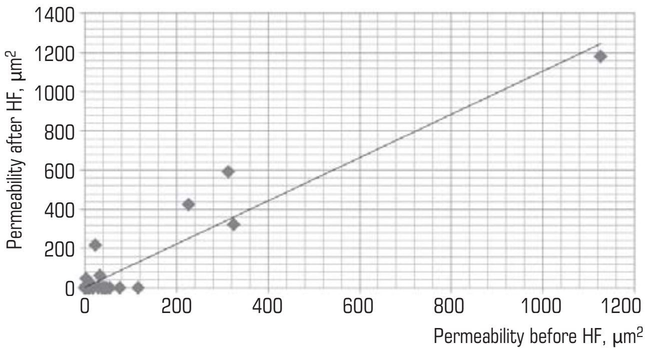

Fig. 3. Permeability before and after hydraulic fracturing

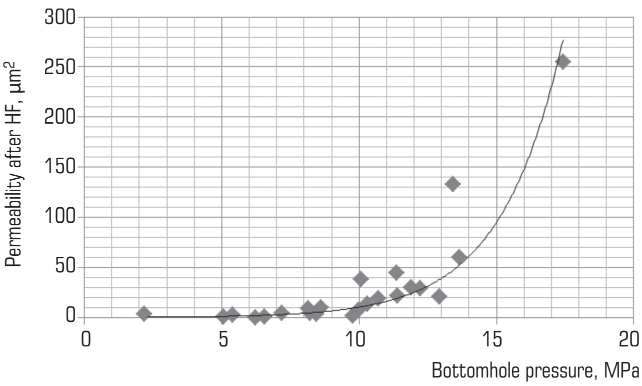

Fig. 4. Dependence of the productivity index after hydraulic fracturing on the bottomhole pressure

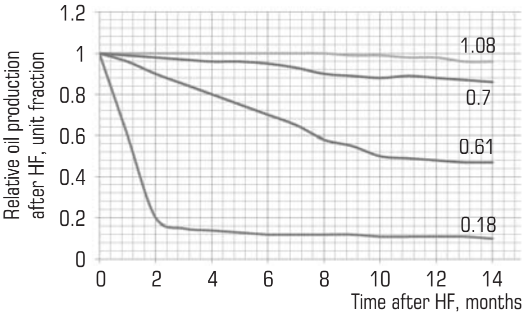

Fig. 5. Dependence of the relative well production after hydraulic fracturing on time

(0.18; 0.61; 0.7; 1.08—ratio of bottomhole pressure and saturation pressure)

in two months and was 11% of the initial value 14 months after HF. With P_{bot} / P_{sat} equal to 0.61, well production fell by 50% in 15 months. For a well with a bottomhole pressure higher than the saturation pressure, the production of the well after HF has remained almost unchanged during the period under review.

An approximate estimate of the relative well productivity after HF with bottomhole pressures higher than $0.5P_{sat}$ depending on time is possible by the equation:

$$Q/Q_0 = 1 - 2e^{-6.7P_{bot}/P_{sat}}T, \quad (2)$$

where Q is the flow rate, m^3/day; Q_0 is the well flow rate before hydraulic fracturing, m^3/day; T is time after fracturing.

The equation to determine rational bottomhole pressures [24], which are in the range 0.75÷0.89 from gas saturation pressure has been earlier obtained for the targets under study. To extend the time for increasing well production after HF, it is recommended to maintain the bottomhole pressure above values obtained in [24].

With a well drainage zone of 250 m and the average reservoir parameters, the production time of 1 ton of oil increases by 1.35 years with the reduction of the bottomhole pressure from P_{sat} to $0.85P_{sat}$.

Conclusions

At the Tula–Bobrikovian oil reservoirs of the Visean stage in the north of the Perm region, the main factors influencing well productivity index after HF are porosity, effective oil-saturation thickness, dismemberment, index of productivity before HF, and planned bottomhole pressure after HF. Under the conditions considered, it is not advisable to operate wells with bottomhole pressures below $0.75P_{sat}$, as this would result in a significant reduction in the technological impact of the operation and an increase in the production time of oil reserves.

Based on static processing, a dependency is proposed for estimating well productivity index after HF. An equation has been developed to estimate the change in the relative current well productivity from the bottomhole pressure and time after HF.

There has been a significant decline in the relative productivity of wells after HF, with lower bottomhole pressure and longer oil production time.

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