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Prediction of the Efficiency of Hydraulic Fracturing Based on Reservoir Parameters

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ABSTRACT

According to experts, the use of hydraulic fracturing can increase the oil and gas recovery factor by 10-15%. The Perm Territory belongs to the old oil-producing region of the Russian Federation. To date, more than 60% of the remaining recoverable oil reserves of the fields of the Perm region are concentrated in carbonate deposits. Most of the fields are currently in the late stages of development. These fields, as a rule, are characterized by the presence of undrained zones with residual reserves and low well flow rates. Most of the remaining reserves of the fields are concentrated in low-permeability reservoirs with a high degree of heterogeneity and difficult fluid filtration. Unfortunately, the results obtained in practice do not always correspond to preliminary calculations and do not reach the planned oil production rates. In connection with the above, the problem arises of predicting the effectiveness of hydraulic fracturing operations using mathematical methods of analysis. The effectiveness of hydraulic fracturing is undoubtedly influenced by both geological and technological parameters. In this paper, for the carbonate Kashirsky (K) and Podolsky (Pd) productive deposits of one of the oil fields in the Perm region, using step-by-step regression analysis based on geological and technological parameters, a forecast of the initial oil production rate after hydraulic fracturing was made. There was good agreement between model and experimental results obtained.

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NOMENCLATURE

m	Porosity, %	q_p	Specific proppant consumption, t/m
q_o	Actual oil flow rate, t/day	C_r	Reservoir compartmentalization
S_o	Oil saturation, %	P_b	Bottom hole pressure, atm
K	Permeability, $10^{-3}\mu m^2$	q_l	Liquid flow rate pre-frac, m^3/day
h	Gross pay thickness, m	q_o^{Cal}	Oil production post-frac
S_X	Standard deviations of variables X	$a_0, a_1, \ldots, a_8$	Regression coefficients
S_Y	Standard deviations of variables Y	p	Levels of statistical significance
r	Correlation coefficients		

1. INTRODUCTION

During the development of oil and gas fields, there is a requirement to increase production efficiency. This goal, in particular is achieved by set of enhanced oil recovery measures, including a variety of technological method and special techniques. Existing technologies can be divided into 2 types: those that affect the entire oil reservoir and local reservoir stimulation methods that are directed to the area next to the well. Local methods refer to the methods of intensification, which cover only a certain well with the specified condition [1, 2].

The development of oil fields with hard-to-recover oil reserves is a very important problem in the nearest future. The assessment of the prospects for using geological and technical measure is related to the creation of unconventional methods; the essence of which differs not only in high technological effectiveness, but also is energy consumption with a substantial improvement in geological criteria for their applicability [3]. Even after achieving the latest techniques, in primary and secondary recovery, only

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one-third of the oil in the reservoir can be recovered. One of the most common local methods of stimulation is hydraulic fracturing. Recently, hydraulic fracturing has found wide application in wells, the effectiveness of which in most cases has been proven theoretically and practically, and it is difficult to find appropriate solutions [4-6].

Hydraulic fracturing is an effective method to enhance oil recovery. With the help of hydraulic fracturing technology, high well production rates are achieved by significantly expanding the drainage zone and the beginning of fluid filtration in tight areas of the reservoir [7, 8].

Hydraulic fracturing is a common method for producing oil or gas. Hydraulic fracturing technology consists of several steps: the first step is to pump the fracturing fluid at a high rate to create burst pressure and initiate a fracture in the formation. Next, proppant is pumped in to fix the crack and, at the third stage, the well is kept until the pressure at the wellhead is reduced. It is very important to choose the composition of the hydraulic fracturing fluid. The effect of many different chemicals on oil production must be determined in advance in the laboratory [9, 10].

In the absence of complete data, it is necessary to use integrated models to evaluate and improve the efficiency of hydraulic fracturing or reduce sand production of various operations and fluid modifications. For example, it is possible to use the Appach D model to simulate hydraulic fracturing and determine the duration of the effect, the change in sand and water content [11, 12].

Lolon et al. [13] used fracture modelling and multi-well simulation to evaluate down-spacing potential for horizontal well sand also examines the effectiveness oil permeability affect production profiles and oil recovery in the middle Bakken formation (North Dakota), proppant type, treatment volume. The study showed a significant infill drilling potential because of the low estimated effective oil permeability located between 0.002 and 0.04 mD.

The primary technology for developing tight gas is hydraulic fracturing of horizontal wells. After fracturing, the gas well exhibits the traits of a significant variation in production energy and a variety of parameters influencing production capacity [14, 15]. By using 10 fractured wells in a gas fields, Liu et al. [16] were able to fully count for the influence of geological and engineering factors. They were chosen 17 geological and engineering parameters then based on the statistical analysis of gas well productivity and used the gray correlation method. The findings demonstrate that tight gas fracturing horizontal wells can achieve high production which is influenced by both engineering and geological factors.

Predicting hydraulic fracturing efficiency, assessing the factors to one degree or another influencing the event, as detailed and justified selection of design wells for impacts are fundamental processes that need to be carried out and coordinated at the early stages of oil fields development. An early assessment of possible risks prior to the event and identification of the various factors influencing the potential for the projected event to be effective will minimize the probability of an unfavorable outcome [17, 18].

Identification of parameters that have a prevailing effect on the efficiency, and the subsequent formalization of the process based on statistical modelling, allow implementing a scientifically grounded choice of wells and selecting the optimal stimulation technology in order to increase hydraulic fracturing efficiency [19, 20].

2. METHODOLOGY

The research methodology consisted of several successive stages. The first step was to create a database of wells that were hydraulically fractured. Information was obtained on well productivity, reservoir permeability, bottom-hole and reservoir pressures before and after hydraulic fracturing. Information was also obtained on water saturation and oil saturation, reservoir thickness, porosity.

To create a model that would allow to quickly predicting the well flow rate after hydraulic fracturing, a regression analysis was performed on the parameters available in the database. During regression analysis, a correlation matrix was created.

A correlation matrix is a special type of covariance matrix. A correlation matrix is a covariance matrix that calculated on variables that have a mean of zero and standard deviation of one. The general formula for a correlation coefficient between variables X and Y is:

$$corr\ (X\ Y = \frac{COV(X\ Y)}{S_X S_Y} \quad (1)$$

Because a correlation is a specific form of a covariance, it has the same two properties magnitude and sign as a covariance. The sign indicates the direction of the relationship. Positive correlations imply a direct relationship, and negative correlation imply an inverse relationship. Similarly, correlation close to zero denote to statistical associations or predictability between the two variables. Correlations that deviates from 0in either direction (positive or negative) indicate stronger statistical associations and predictability.

The correlation coefficient has one important property that distinguishes it from other types of covariance. The correlation coefficient has a mathematical lower boundary of -1.0 and an upper bound 1.0. This property permits correlation coefficient to be compared, while ordinary covariance usually cannot be compared.

A linear statistical model for predicting oil production has been obtained, which has been verified against the original database. The use of the model will allow the engineer to predict the results of hydraulic fracturing with a minimal set of data.

3. RESULTS OF HYDRAULIC FRACTURING

Analysis of the hydraulic fracturing operation was carried out on the operating well stock of the investigated field in order to study the influence of geological and technological parameters on the success of hydraulic fracturing in the conditions of one of the oil fields in Perm region.

The regression model was built in order to identify the mathematical dependence of technological and geological parameters. Twenty wells, belonging to the K and Pd carbonate reservoir were identified on the basis of the production data on hydraulic fracturing treatment of the reservoir in the considered field.

The main geological and technological parameters were considered by wells for affecting the hydraulic fracturing efficiency of the actual rate oil production post-frac: geological- porosity, permeability, oil saturation and the pay thickness, technological- specific proppant consumption, reservoir compartmentalization, bottom-hole pressure and liquid production rate pre-frac (see Table 1).

The influence of various factors on the event success was defined by means of regression analysis.

The correlation matrix is presented in Table 2. The correlation coefficients and levels of statistical significance were determined for paired dependencies.

The correlation matrix demonstrated that the actual oil production rate post-frac (q_o), porosity and oil saturation correlate well with all others parameters. At the same time, there are statistically significant relationships between:

- Bottom-hole pressure with specific proppant consumption and reservoir compartmentalization;
- reservoir compartmentalization and specific proppant consumption;
- specific proppant consumption and the gross pay thickness

Correlation fields were built for the initial sample parameters with high correlation coefficients and low levels of statistical significance: according to geological factors - Figure 1, according to technological factors - Figure 2.

The initial oil production rate increases with increasing porosity and oil saturation of the formation.

TABLE 1. Results of hydraulic fracturing

q_o, t/day	m, %	S_o, %	K, 10^{-3}μm^2	h, m	q_p, t/m	C_r	P_b, atm	q_l, m^3/day
5.4	14.05	59.40	3.50	3.0	9.40	2	203.0	0.9
4.9	15.60	63.65	3.20	4.2	8.79	3	165.0	1.2
5.5	15.85	63.75	5.80	3.8	8.64	2	178.0	1.1
5.7	16.75	64.60	6.00	3.8	7.54	4	168.0	1.2
5.8	15.75	63.45	5.80	3.0	9.87	3	157.7	1.4
5.6	15.70	68.80	14.50	3.1	7.58	3	176.5	1.6
6.2	15.50	62.80	5.40	3.8	6.89	3	179.0	4.0
7.5	26.60	72.30	91.41	2.6	10.43	3	138.8	3.7
6.1	17.70	67.70	9.59	3.0	10.17	2	161.1	3.0
5.5	16.10	64.30	6.23	3.6	5.31	1	245.0	1.4
6.0	14.00	69.20	31.00	4.4	7.20	1	191.0	2.4
6.7	26.60	72.30	91.41	2.6	10.43	3	138.8	3.7
6.1	17.70	67.70	9.59	3.0	10.17	2	161.1	3.0
4.4	16.10	59.00	6.23	3.6	5.31	1	245.0	0.5
5.5	14.50	63.10	14.20	3.8	6.45	2	161.0	1.0
6.0	22.75	69.95	33.00	2.6	10.19	4	156.0	1.7
4.9	17.05	66.20	4.50	4.2	7.26	2	163.4	1.9
5.6	15.00	61.00	4.40	3.2	8.59	2	166.0	0.5
6.0	21.20	71.00	15.00	4.0	8.90	4	155.5	2.3
5.6	17.20	60.00	7.00	3.8	6.08	2	186.0	1.8
7.0	25.20	74.00	79.00	2.4	8.11	4	120.7	1.9
5.0	12.30	59.00	5.00	3.8	8.03	1	173.3	1.3

High reservoir permeability before hydraulic fracturing leads to a significant increase in initial production.

The greater the well flow rate before hydraulic fracturing, the greater it becomes after hydraulic fracturing. With an increase in the mass of injected proppant, the well flow rate after hydraulic fracturing increases.

4. REGRESSION ANALYSIS

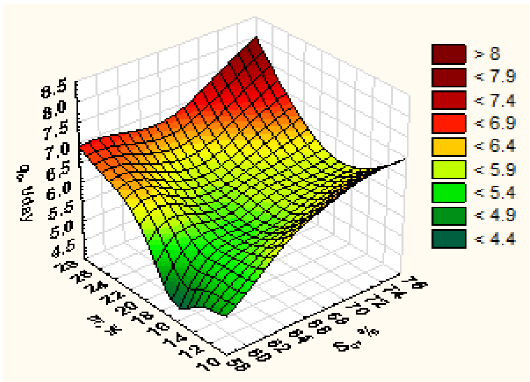
According to the values of the correlation coefficients r of the dependences of the actual rate of the oil production q_o on geological and technological factors and the level of statistical significance p, the degree of influence of these factors on the calculated oil production rate post-frac is determined.

Further, the regression model is built by the method of multiple linear regression. The general of the regression equation and the equation obtained after calculations in statistical software (Statistics), in which

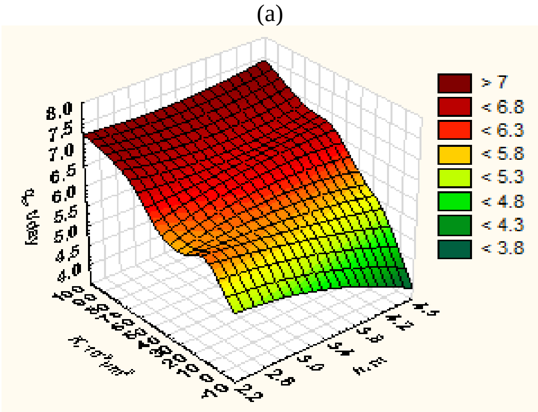
TABLE 2. Correlation matrix

	q_o	m	S_o	K	h	q_p	C_r	P_b	q_l
q_o	1	r= 0.759 p= 0.000	r= 0.760 p= 0.000	r= 0.799 p= 0.000	r= -0.617 p= 0.002	r= 0.521 p= 0.013	r= 0.501 p= 0.018	r= -0.638 p=0.001	r= 0.719 p= 0.000
m		1	r= 0.795 p= 0.000	r= 0.872 p= 0.000	r= -0.637 p= 0.001	r= 0.475 p= 0.025	r= 0.599 p= 0.003	r= -0.580 p= 0.005	r= 0.541 p= 0.009
S_o			1	r= 0.751 p= 0.000	r= -0.435 p= 0.043	r= 0.465 p= 0.029	r= 0.560 p= 0.007	r= -0.623 p= 0.002	r= 0.593 p= 0.004
K				1	r= -0.603 p=.003	r= 0.395 p= 0.069	r= 0.372 p=0.088	r= -0.552 p=0.008	r= 0.534 p= 0.010
h					1	r= -0.59 p= 0.004	r= -0.376 p= 0.084	r= 0.408 p=0.059	r= -0.253 p= 0.256
q_p						1	r= 0.440 p= 0.041	r= -0.665 p= 0.001	r= 0.391 p= 0.072
C_r							1	r= -0.670 p= 0.001	r= 0.245 p= 0.271
P_b								1	r= -0.420 p=0.052
q_l									1

Note: the cells in the numerator indicate the value of the correlation coefficient, in the denominator - the level of statistical significance (p); red highlighted statistically significant correlation coefficients, for which p <0.05.

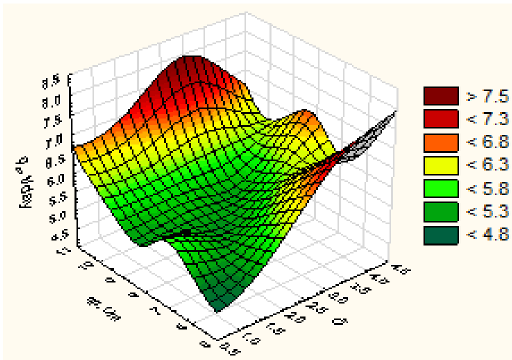


(a)



(b)

Figure 1. Dependences of the actual oil production rate after hydraulic fracturing with geological factors: a) porosity, oil saturation; b) permeability, gross pay thickness



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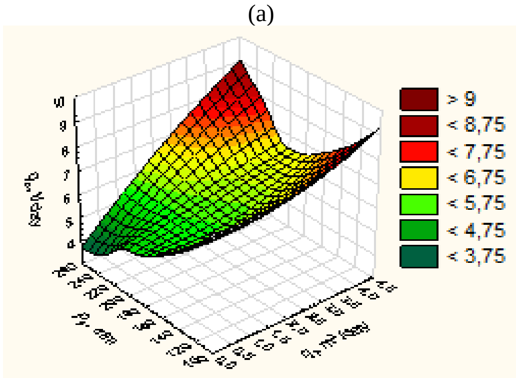

(b)

Figure 2. Dependences of the actual oil production rate after hydraulic fracturing with technological factors: a) specific proppant consumption, reservoir compartmentalization; b) bottom-hole pressure, liquid flow rate before hydraulic fracturing

the dependent variable is the calculated rate of the oil production post-frac q_o^{Cal}, and the independent variables are the sampling factors for which the level of statistical significance $p < 0.05$.

In general, the equation is written as follows:

$$q_o^{Cal} = a_o + a_1 m + a_2 So + a_3 K + a_4 h + a_5 q_p + a_6 C_r + a_7 P_b + a_8 q_l \quad (2)$$

General view identifying the coefficients of the regression equation and the obtained equation after simulation in software are presented in Table 3.

The future productivity of a well can be predicted using an exponential type well curve. The performance of wells with a very short production history can be modeled using aggregated analysis results as informative values.

Comparison of the calculated and actual rate of oil production increase after hydraulic fracturing is shown in Figure 3.

The absolute deviation of the calculated values of the oil production rate from its actual values in the field is in the range from 0.006 to 0.511 t/day, with an average of 0.219 t/day. The relative deviation is in the range of 0.11 to 10.90% with an average of 3.97%.

TABLE 3. Results of hydraulic fracturing

a_o	**5.857**
a_1	-0.054
a_2	0.025
a_3	0.011
a_4	-0.356
a_5	-0.028
a_6	0.126
a_7	-0.002
a_8	0.286

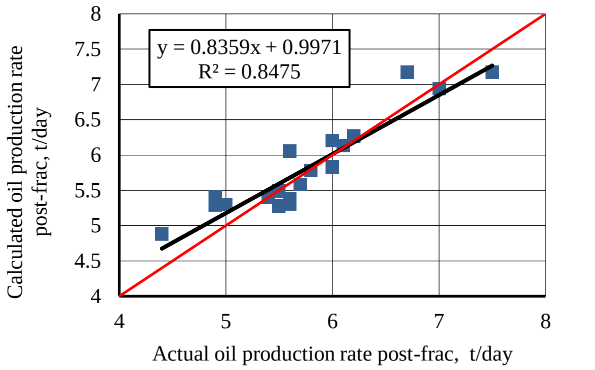

Figure 3. Correlation field of calculated (q_o^{Cal}) and actual (q_o) values of oil production rate post-frac for wells of the Kashirsky and Podolsk carbonate deposits of the Perm region field

4. CONCLUSIONS

As a result of the research carried out, it was established:

1. The value of the oil production rate after hydraulic fracturing in the Kashirsky and Podolsky carbonate deposits of one of the fields in the Perm Territory is mainly influenced by geological parameters- porosity, oil saturation, permeability, gross pay thickness and technological parameters- specific proppant consumption, compartmentalization, closure pressure at the bottom-hole and liquid production rate before hydraulic fracturing.

2. The proposed method allows, using the geological and technological parameters of the productive formation, to predict the value of the oil production rate after hydraulic fracturing.

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Persian Abstract

چکیده

به گفته کارشناسان، استفاده از شکست هیدرولیک می تواند ضریب بازیافت نفت و گاز را 10تا 15درصد افزایش دهد .قلمرو پرم متعلق به منطقه قدیمی تولید نفت فدراسیون روسیه است .تا به امروز، بیش از 60درصد از ذخایر نفت قابل استحصال باقیمانده میادین منطقه پرم در ذخایر کربناته متمرکز شده است .اکثر رشته ها در حال حاضر در مراحل پایانی توسعه هستند .این میدان ها، به عنوان یک قاعده، با وجود مناطق زهکشی نشده با ذخایر باقیمانده و نرخ جریان چاه کم مشخص می شوند .بیشتر ذخایر باقیمانده میدان ها در مخازن با نفوذپذیری کم با درجه ناهمگنی بالا و فیلتراسیون سیال دشوار متمرکز شده است .متأسفانه، نتایج به دست آمده در عمل همیشه با محاسبات اولیه مطابقت ندارد و به نرخ های تولید نفت برنامه ریزی شده نمی رسد .در ارتباط با موارد فوق، مشکل پیش‌بینی اثربخشی عملیات شکست هیدرولیکی با استفاده از روش‌های تحلیل ریاضی مطرح می‌شود .اثربخشی شکست هیدرولیکی بدون شک تحت تأثیر پارامترهای زمین‌شناسی و فناوری است .در این مقاله، برای ذخایر مولد کربنات کشیرسکی (K) و پودولسکی (Pd) یکی از میادین نفتی در منطقه پرم، با استفاده از تحلیل رگرسیون گام به گام بر اساس پارامترهای زمین‌شناسی و فناوری، پیش‌بینی نفت اولیه نرخ تولید پس از شکست هیدرولیک ساخته شد .توافق خوبی بین نتایج مدل و تجربی به دست آمده است