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Статья / Article

Forecasting Hydraulic Fracturing Results Using Information Amount Theory

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Прогнозирование результатов гидроразрыва пласта с использованием теории информации

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oil reservoir, hydraulic fracturing, information amount theory, water cut.

Hydraulic fracturing allows you to increase production from wells and reduce the time it takes to extract oil from reservoirs. The article examines the carbonate formations of the Perm region. Hydraulic fracturing is being actively carried out on these formations. To properly plan hydraulic fracturing, it is necessary to determine the main factors that affect oil production after hydraulic fracturing. The study used information amount theory to identify the main factors that influence the results of hydraulic fracturing. For the area considered, the main factors were: pre-frac water cut, fracture width, fracture length, pre-frac oil production rate. Having data on these parameters, it is possible to predict hydraulic fracturing with high reliability. The regression model is built by the method of multiple linear regression. To determine the group features, a statistical analysis of the key parameters was performed to draw box plots of the mean, maximum, median, quartile and minimum values for each parameters. First, we analyzed the results for all parameters. The graph show that the productivity increases with increasing the oil production rate after fracking and the fracture width, and the group B had the largest amount; therefore its production is expected to be large. The others parameters were similar in the groups A and B. The absolute deviation of the second model calculated values of the oil production rate after hydraulic fracturing from its values in the field regress from 1,287 to 0,662 compared in the first model calculated values. The relative deviation from 4.1 % in first model to 2.4 % in the second model calculated values. The results obtained will allow us to quickly predict hydraulic fracturing in new wells.

Ключевые слова:
нефтяной пласт, гидроразрыв пласта, теория информации, обводненность.

Гидроразрыв пласта позволяет увеличить дебиты скважин и сократить время извлечения нефти из пластов. В статье рассмотрены карбонатные отложения Пермского края. На этих залежах активно проводится гидроразрыв пласта. Для правильного планирования гидроразрыва пласта необходимо определить основные факторы, влияющие на дебит нефти после мероприятия. В исследовании использовалась теория информации для выявления основных факторов, влияющих на результаты гидроразрыва пласта. Для рассматриваемых месторождений основные факторы – обводненность до мероприятия, ширина трещины, длина трещины, дебит нефти до мероприятия. Имея данные об этих параметрах, можно с высокой достоверностью прогнозировать проведение гидроразрыва пласта. Построена модель прогнозирования результатов ГРП методом множественной линейной регрессии. Проведен статистический анализ ключевых параметров с построением диаграмм размаха среднего, максимального, медианного, квартильного и минимального значений для каждого параметра. Данные по скважинам разделили на две группы и выполнен анализ результатов по всем параметрам. Получено, что коэффициент продуктивности увеличивается с увеличением дебита нефти после гидроразрыва пласта и ширины трещины, причем наибольшее значение характеризовало группу B; поэтому ожидается, что дебит в этой группе будет большим. Остальные параметры в группах A и B были схожими. Абсолютное отклонение рассчитанных по второй модели значений дебита нефти после гидроразрыва пласта составило от 1,287 до 0,662 по сравнению с расчетными значениями по первой модели. Относительное отклонение от 4,1 % в первой модели до 2,4 % во второй модели. Полученные результаты позволят оперативно прогнозировать проведение гидроразрыва пласта на новых скважинах.

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Introduction

Hydraulic fracturing is a popular method for increasing well production rates [1]. Fractures change permeability near the wellbore. For successful hydraulic fracturing, it is necessary to study the relationship between hydraulic fracturing parameters and the operational characteristics of the oil reservoir [2]. In [3] it is noted that the length of the fracture, the number of fractures and the distance between wells must be taken into account when optimizing hydraulic fracturing in wells. Also, when forecasting, it is necessary to take into account the influence of the initial flow rate, wellbore diameter, fluid viscosity, formation permeability, wellbore diameter on the production of a horizontal well [4]. Poroelastic characteristics of porous media, such as skeletal compressibility and elastic modulus, influence the behavior of porous rocks and their cracking [5]. The nonlinearity of fluid flow affects the shape of the outflow vector and return flow through fracture zones, as well as the amount of fluid to be exchanged between fractures and the porous zone. Accordingly, these parameters also affect the well's design flow rate after hydraulic fracturing. When fluid moves through the perforations, a vortex flow occurs near the entrance to the crack, which causes turbulence. Eddy influences the fluid flow to the well [6]. The rate of injection of hydraulic fracturing fluid, its viscosity and the location of perforations in the oil reservoir also affect the results of hydraulic fracturing. The results of hydraulic fracturing can be assessed by the relationship between the width of the hydraulic fracture and the filling of proppant. In this case, it is necessary to take into account the size of proppant particles, sand concentration, fluid injection volume and proppant crushing rate [7, 8]. Injecting a larger proppant leads to an increase in the intensity of its shielding from the walls of fractures [9]. Cracks become more dispersed, and the laws of crack development become more complex. The greater the difference in the strength parameters of the proppant and matrix, the stronger the cracks are filled with proppant.

In [10] the influence of such operational parameters on the results of hydraulic fracturing, such as the azimuth of the wellbore, the distance between fractures and their relative positions, is noted. When the anisotropy angle changes from 0° to 90°, the rock rupture pressure first increases and then decreases. As the injection rate increases, there is an obvious tendency for the burst pressure to decrease [11]. Under uniaxial stress, the change in anisotropy angle is close to 45° and the decrease in injection rate contributes to a more tortuous crack propagation path. Rocks with low injection rates and high anisotropy angles (> 45°) can achieve optimal fracturing results.

The propagation of cracks during hydraulic fracturing and the well flow rate depend on the stress field. In a saturated porous reservoir, the stress field is highly dependent on flow conditions, reservoir properties, and heterogeneity [12]. Flow boundary conditions are important if the time scale of pore diffusion from the injection well to the boundary occurs well before hydraulic fracturing begins.

The existence of natural fractures in the formation has a great influence on fluid filtration. The orientation and strength of natural fractures have a major influence on the width, volume and shape of the fracture after hydraulic fracturing [13]. The viscosity of the hydraulic fracturing fluid has a greater influence on fracture propagation and well production after hydraulic fracturing.

It is important to control the propagation of hydraulic fractures to improve hydrodynamic connectivity between wells. Natural fractures have a dominant influence on the propagation of hydraulic fractures, the second most important factor being stress [14].

Fluid injection pressure control may be limited by the performance of the field equipment. However, the influence of layered heterogeneity on crack propagation is still unclear [15–17].

To accurately predict the propagation of hydraulic fractures in a real formation, it is extremely important to take into account the roughness of real natural fractures and the uneven distribution of mechanical parameters [18, 19].

The inflow rate of the fracturing fluid decreases linearly, and the degree of proppant deposition increases linearly with increasing density of the fracturing fluid [20]. the proppant settlement rate increases by 3.5 times as the proppant particle size increases from 0.25 mm to 1.65 mm. Selecting a lower fracturing fluid density and smaller proppant particle size can provide higher fluid recovery efficiency.

In [21] calculated and verified the effects of productivity parameters of fractured horizontal wells in Bakken tight oil reservoirs using information amount theory. The results shows that the method is effective in verifying the impact a variety parameters on the wells productivities. The authors are proved that information amount theory, orthogonal experiment design (OED) and Grey Relational The analysis process and principles of the above methods are different from each other, but their results are similar. It is noted that the main factors influencing the efficiency of hydraulic fracturing are the length and width of the fracture, and the geological parameters of the formation.

In the presence of the main factors influencing the results of hydraulic fracturing, using regression analysis we can build a model for predicting the results of hydraulic fracturing [22, 23]. Comparison of indicators in a single probabilistic space makes it possible to build individual probabilistic models for predicting production after hydraulic fracturing [24–26].

The regression equations obtained from the least squares method are strong in terms of fitting the sensitive parameters and the model follows the same trend as the numerical simulation data [27, 28]. To build a nonlinear regression model, we need to accurately initialize the model parameters [29]. The least absolute deviation method has significantly lower efficiency than the least squares method [30, 31].

If the fracture array geometry is idealized as a set of regular and planar fractures, history matching and production forecast may be inaccurate [32]. You can also predict hydraulic fracturing results using a Decision Tree, but this is more labor-intensive [33].

Because hydraulic fracturing models involve complex physics and uncertainties driven by many variables, there is a challenge in calibrating model results with actual field data [34, 35]

The greatest influence on the productivity of wells after hydraulic fracturing is exerted by bottomhole pressure and productivity indicators before hydraulic fracturing [36, 37]. The discovered cause-and-effect relationship between production and geological and technical factors coincides with the real physical mechanism [38].

Proper design of hydraulic fracturing significantly improves its productivity [39]. A key factor in developing hydraulic fracturing technology is optimizing fracture geometry [40]. This is confirmed by multiple equally probable implementations of fracture permeability prediction [41, 42].

In this study, based on information amount theory, the most important factors for predicting net production after hydraulic fracturing for a field in the Perm region were identified.

Oil deposits in the Perm region are characterized by high depletion of reserves, complex mining and geological conditions involving the development of heterogeneous carbonate reservoirs with low capacitance properties and reservoirs containing high viscosity oil. This is due to the fact that the region is a former oil producing area. It is inefficient to develop areas with similar conditions using natural methods or water flooding with traditional water, as recovery rates and oil recovery factors are very low, ranging from 2,5 to 30 % [43–45].

Method and study area

In the name of quickly and accurately discovering the key productivity factors in the design and construction of hydraulic fracturing wells, the theory is used to calculate and verify the twelve parameters of in 21 fractured wells in carbonate reservoirs, in order to learn about their correlation and impact on productivity.

In order to create a multi-variable model to estimate the oil production post-frac increase, the well sample is divided into two roughly parts, comprising wells Qo_post-frac less than 5,8 tons/day group A and wells Qo_post-frac greater than 5,8 tons/day group B.

Results show fracture length, fracture width, Propant Height, Net pay, bubble pressure, pre-frac productivity index, Proppant Total, Specific polymer consumption for placement of 1 ton of proppant, Main Frac fluid volume, pre-frac fluid production rate, pre-frac water cut and pre-frac oil production rate as secondary parameters.

Selecting twenty-one frac wells in one of the Perm oil fields: 484, 471, 16, 16, 9044, 510, 256, 483, 112, 29, 29, 452, 73, 73, 522, 165, 503, 515, 451, 50. Taking the oil field as an example to calculate the impact of various parameters on frac well productivity, the well parameters of the K-Pd (Kashirskiy and Podolskiy) carbonate reservoirs are presented in Table 1.

The following is a description of the fundamental Information amount theory process: divide the objects into two groups or intervals, A and B, based on a criterion; count the frequency of the factors in each group; compute the frequencies again to verify the degree of difference between the group A and B. The greater degree of the difference. The more different, the bigger information amount is, and the bigger influence degree is. Calculate and analyze the amount of information for each factors using this method. Procedures are as follows:

Each factor will be counted separately in different ranges and the frequencies of group A and group B will be calculated. Further calculation can obtain the distribution of the difference between A and B. the difference is greater so the amount of information is greater. The calculation steps are as follows:

(1) Count the separate frequency of parameters in group A and B.

(2) Convert the frequency into probability (%) $y_{A\theta}$ and $y_{B\theta}$ where θ is the interval serial number.

(3) Calculate average probability ratio $\bar{y}_{A\theta}$ in each interval. The formula is

$$\bar{y}_{A\theta} = 0.1(y_{\theta-2} + 2y_{\theta-1} + 4y_{\theta} + 2y_{\theta+1} + y_{\theta+2}). \quad (1)$$

(4) Calculate the average frequency ratio $\bar{y}_{A\theta} = \bar{y}_{B\theta}$.

(5) Calculate the diagnosis coefficient $Z_\theta : Z_\theta = 10\log(\bar{y}_{A\theta} / \bar{y}_{B\theta})$.

(6) Calculate the amount of information on each parameters change interval I_θ:

$$I_\theta = 1/2 Z_\theta \left(\bar{y}_{A\theta} - \bar{y}_{B\theta}\right). \quad (2)$$

(7) Calculate the total amount of information $I = \sum I_\theta$.

According to the above method, the information content of these twelve parameters is calculated as shown in Table 2.

In Table 3 in Fig. 1 shows the results of ranking geological and technological parameters.

The speed and time of water movement at specified distances were estimated. In Fig. 1 shows an image of the computational hydrodynamic model.

Multiple linear regression

By definition, multiple linear regression is a method to compare several independent variables to one dependent variable. This approach accounts for the effect of all variables simultaneously and fits a linear relationship to each variable; however, a multiple linear regression assumes a linear among the input and output variables.

Eq. 2 illustrates the model with n predictor variables X_1, X_2 …., X_n and response q_{Cl}, as follows:

$$q_{Cl} = A_0 + A_1 x_{1i} + A_2 x_{2i} + \ldots + A_n x_{ni}. \quad (3)$$

According to the values of the correlation coefficients r of the dependences of the actual production rate q_0, on the factors and statistical significance p, the degree of the influence of these factors on the first model calculated oil production rate after hydraulic fracturing is determined. Further, the regression model is built by the method of multiple linear regression.

The regression equation in the first model after statistical simulation is written as follow:

$$q_{C1} = 8{,}711 - 1{,}217h + 1{,}263L_f - 0{,}010W_f. \quad (4)$$

Relationship between the results from first model calculated q_{C1} and q_0 values for wells of the Kashirsky and Podolsky carbonate deposits of Perm region fields shown in Fig. 2.

The significance of independent variables was confirmed by using the analysis of variance (ANOVA) as shown in Table 4. In contrast, the P-value is the probability value that is determined from F-distribution curve. With a known degree of freedom of a factor and a residual for given F-statistic, the P-value of that factor can be determined. The red F-value value in the table implies that the factor has the highest level of significance to the output response. From the ANOVA table, the level of significance is the fracture width and the oil production rate after hydraulic fracturing.

To determine the group features, a statistical analysis of the key parameters was performed to draw box plots of the mean, maximum, median, quartile and minimum values for each parameters (fig. 3). First, we analyzed the results for all parameters. The graph show that the productivity increases with increasing the oil production rate after fracking and the fracture width, and the group B had the largest amount; therefore its production is expected to be large. The others parameters were similar in the groups A and B. These results revealed that hydraulic fracturing increased the oil production volume for fracture width has large amount of injected proppant and fluids per unit length. Although group B contained wells with higher productivity under the influence of hydraulic fracturing design parameters.

Table 1

Geological and technological parameters of wells

№	Qo_post-frac, t/d	L_f, m	W_f, mm	H_f, m	h, mm	P_b, Mpa	I_p, m^3/d·MPa	m_p, t	q_p, Kg/t	V_f	Qf, t/d	W_c, %	Qo_pre-frac, t/d
256	0.3	117.5	3	10.3	8.4	3.9	0.9	20	10.2	93	1.3	32.2	0.8
9044	1.6	251.6	2.8	5	4	7.5	0.7	23	10.5	116	2.8	2.3	2.5
16	2.7	153.5	1.8	5.4	3.4	5.3	0.5	26	10.6	111	0.3	22.9	0.2
112	3.7	287.2	2.8	4.7	3.2	7.5	4.0	25	11.3	123	16.0	90.2	1.4
510	4.1	163.5	3	4.9	5	5.3	0.5	26	10.6	119	2.9	11.2	2.3
29	4.9	219.5	2.5	5	4.2	4.2	0.6	29	10.6	132	1.9	41.9	1.0
452	5.5	248.7	2.4	5.5	3.8	5.3	0.2	24	9.7	104	1.0	33.0	0.5
483	5.6	152.9	3	4.4	3.2	5.3	0.4	27	8.7	111	0.5	20.4	0.3
471	5.6	175.4	2.5	4.9	3.8	5.0	1.1	29	10.5	111	1.8	20.5	1.3
515	5.7	292.9	3.9	4.9	4	5.3	0.6	30	9.4	117	0.9	11.3	0.7
484	5.8	132.2	2	4.5	3.8	5.3	1.4	29	11.7	152	1.3	10.5	1.2
73	6.1	149.2	2.6	4	3	5.3	5.0	29	9.5	118	3.0	36.0	1.7
165	6.2	246.8	2.6	4.9	3.8	5.3	1.6	25	9.1	101	4.0	48.0	1.7
503	6.6	273.0	3.5	4.5	4.4	5.3	0.5	32	9.7	133	2.4	25.7	1.6
73	6.7	213.0	2.7	10.5	2.6	7.52	4.4	26	9.8	118	3.7	36.0	2.0
29	7.0	213.4	4.2	5.9	2.6	7.5	0.6	20	11.0	129	1.7	32.6	1.0
522	8.2	160.9	4.4	10.3	3.8	7.52	0.1	26	9.8	123	0.6	19.0	0.4
484	8.3	111.1	5.3	0.5	4.4	5.3	1.4	34	10.8	139	1.9	10.5	1.7
451	8.6	170.7	4.2	5	4	4.5	1.9	31	8.5	120	5.2	22.7	3.6
50	8.8	112.8	3.8	4.5	4.2	6.3	0.9	25	9.8	109	4.1	22.2	2.9
16	11.3	193.4	2.5	6.6	3.4	7.52	0.5	25	12.0	135	0.8	23.8	0.6

Table 2

Determining the information content of the "fracture length" attribute

№	Intervals of fracture length	Shooting frequency		Probability %		Average probability %		Average probability ratio	Diagnosis coefficient	Information amount
		A	B	y_A	y_B	$\bar{y}_A$	$\bar{y}_B$	$(\bar{y}_A)/(\bar{y}_A)$	Dc	IA
1	111–131	1	2	9.1	20.0	8.2	12.00	0.68	–1.66	3.18
2	131–151	1	1	9.1	10.0	11.8	12.00	0.98	–0.07	0.01
3	151–171	3	2	27.3	20.0	15.5	13.00	1.19	0.75	0.92
4	171–191	1	0	9.1	0.0	10.9	9.00	1.21	0.84	0.80
5	191–211	0	1	0.0	10.0	7.3	11.00	0.66	–1.80	3.35
6	211–231	1	2	9.1	20.0	7.3	10.00	0.73	–1.38	1.89
7	231–251	1	1	9.1	10.0	8.2	9.00	0.91	–0.41	0.17
8	251–271	1	0	9.1	0.0	9.1	6.00	1.52	1.80	2.79
9	271–291	1	1	9.1	10.0	8.2	5.00	1.64	2.14	3.40
10	more 291	1	0	9.1	0.0	6.4	2.00	3.18	5.03	10.97
	–	11	10	100	100	92.72	89.00	12.70	5.23	27.46

Table 3

Parameters ranking of information amount theory

Parameters	IA	Rank
H_f, m	2,041	12
m_p, t	5,923	11
h, mm	14,914	10
q_p, Kg/t	17,252	9
W_c, %	18,271	8
P_b, MPa	25,515	7
L_f, m	27,464	6
I_p, m^3/day·MPa	33,188	5
V_f	44,093	4
W_f, mm	49,398	3
Qo_pre-frac, t/d	62,653	2
Q_f, t/d	62,738	1

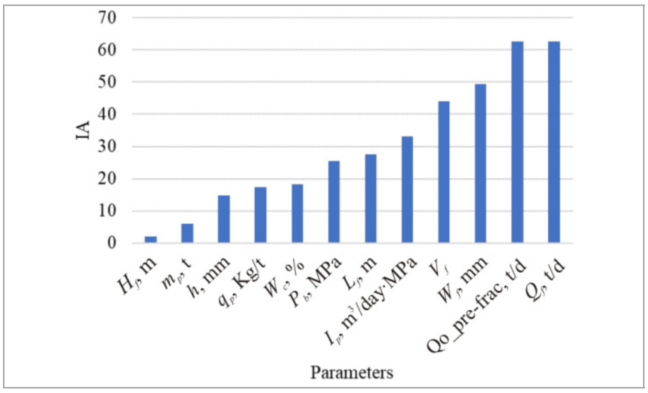

Fig. 1. Information amount comparison of different parameters

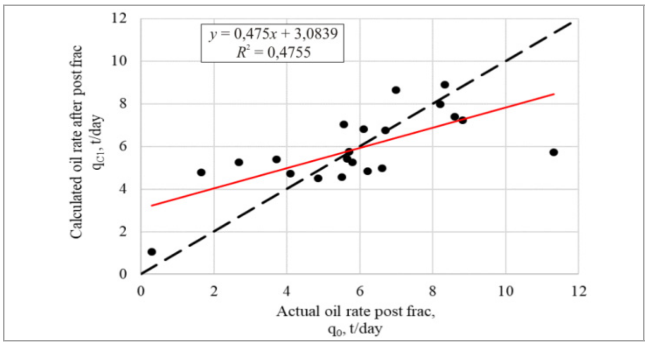

Fig. 2. Relationship between the results from first model calculated and actual values oil production rate post-frac for wells of the Kashirsky and Podolsky carbonate deposits of Perm region fields

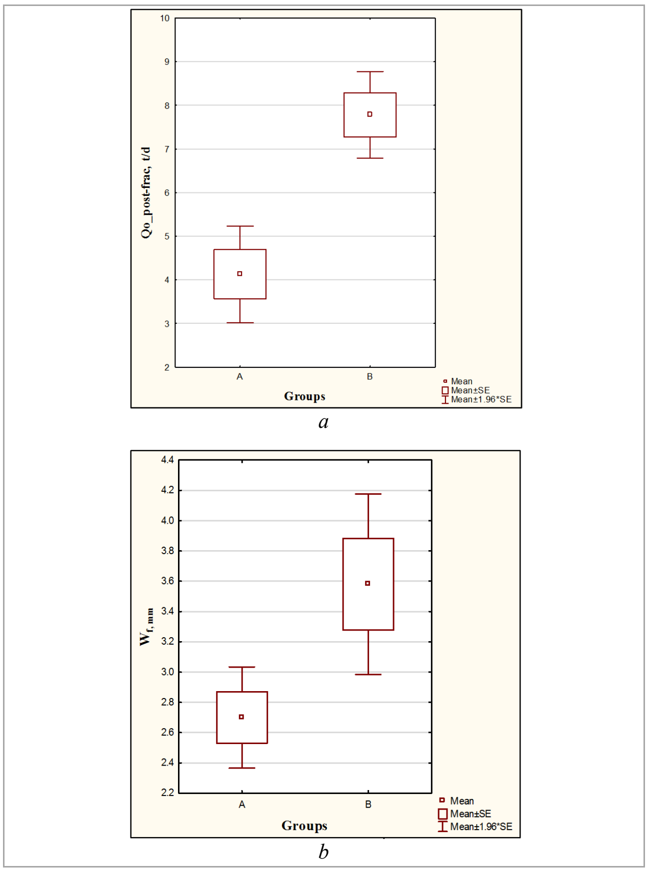

Fig. 3. Variable distribution of the groups A and B based on keys factors: (*a*) the Qo_post-frac and (*b*) the W_f

Table 4

Parameters ranking of information amount theory

Variables	Mean A	Mean B	*t*-value	*df*	*p*	Valid N A	Valid N B	Std.Dev. A	Std.Dev. B	*F*-ratio	*p*
Qo_post-frac, t/d	4.128	7.782	-4.774	19	0.0001	11	10	1.874	1.605	1.363	0.652
L_f, m	199.536	184.430	0.590	19	0.5624	11	10	62.744	53.709	1.365	0.651
W_f, mm	2.700	3.580	-2.587	19	0.0181	11	10	0.566	0.961	2.888	0.114
H_f, m	5.409	5.670	-0.252	19	0.8035	11	10	1.655	2.962	3.204	0.084
h, mm	4.255	3.620	1.248	19	0.2271	11	10	1.464	0.689	4.514	0.033
P_b, Mpa	5.445	6.206	-1.495	19	0.1514	11	10	1.127	1.204	1.142	0.833
I_p, m³/d·Mpa	0.967	1.668	-1.153	19	0.2634	11	10	1.053	1.690	2.573	0.157
m_p, T	26.182	27.300	-0.706	19	0.4888	11	10	3.060	4.165	1.852	0.351
q_p, Kg/T	10.347	10.012	0.825	19	0.4198	11	10	0.844	1.017	1.453	0.567
V_f	117.218	122.520	-0.883	19	0.3884	11	10	15.301	11.778	1.688	0.444
Q_f, t/d	2.794	2.744	0.033	19	0.9737	11	10	4.467	1.513	8.713	0.003
W_c, %	26.949	27.660	-0.086	19	0.9322	11	10	23.997	10.640	5.086	0.022
Qo_pre-frac, t/d	1.108	1.712	-1.609	19	0.1242	11	10	0.744	0.971	1.706	0.417

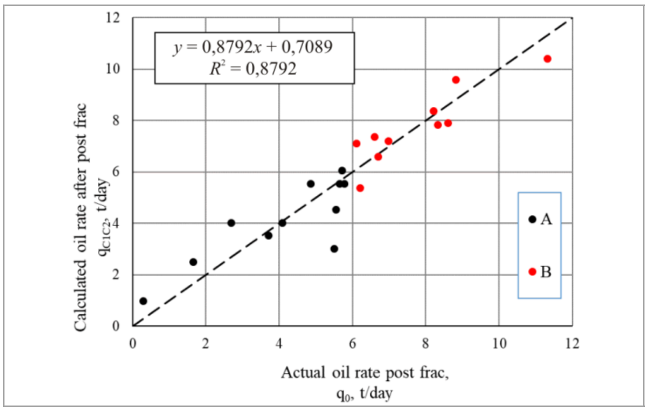

Fig. 4. Relationship between the results from second model calculated ($q_{C21\text{-}2}$) and actual (q_0) values oil production rate post-frac

The regression equation in the group A (q_{C1C2}^1) and B (q_{C1C2}^2) are obtained after simulation in statistical software, in which the dependent variable is the calculated rate of the oil production post-frac in the second model ($q_{C21\text{-}2}$), and the independent variables are the sampling factors for which the level of statistical significance $p < 0{,}05$.

The regression equations of the group A and B are shown in the Eq. (5) and Eq. (6).

$$q_{C1C2}^1 = -9{,}156 + 0{,}508\, m_p \qquad (5)$$

$$q_{C1C2}^2 = 33{,}841 - 0{,}26\, W_c - 1{,}552\, W_f - 0{,}344\, m_p - 0{,}634\, P_b. \qquad (6)$$

Relationship between the results from second model calculated ($q_{C21\text{-}2}$) and actual (q_0) values oil production rate post-frac for wells of the Kashirsky and Podolsky carbonate deposits of Perm region fields shown in Fig. 4.

The absolute deviation of the second model calculated values of the oil production rate after hydraulic fracturing from its values in the field regress from 1,287 to 0,662 compared in the first model calculated values. The relative deviation from 4.1 % in first model to 2.4 % in the second model calculated values.

$$q_0 = -0.7828 + 0.1933 q_{C1} + 1.0198 q_{C2}^{1\text{-}2} + 0.0662 q_{C1} \cdot q_{C1} - 0.1389 q_{C1} \cdot q_{C2}^{1\text{-}2} + 0.0559 q_{C2}^{1\text{-}2} - q_{C2}^{1\text{-}2} \qquad (7)$$

Conclusions

Hydraulic fracturing increases the production of hydrocarbons from oil reservoirs and reduces oil production time. In order to optimize hydraulic fracturing at wells, it is necessary to identify the most important factors and with proper planning we will obtain the maximum increase in oil production.

In this study, we used information amount theory and identified the main factors influencing the results of hydraulic fracturing in the Perm region. The main factors for the study area were: well productivity index before hydraulic fracturing, well production rate before hydraulic fracturing, fracture geometric parameters. For operational prediction of hydraulic fracturing, we left 4 factors and showed that the model has sufficient accuracy.

As a result of this study, a new model was obtained that makes it possible to estimate the production rate of wells after hydraulic fracturing in the study area with minimal error.

Nomenclature:

L_f – fracture length
W_f – fracture width
H_f – Propant Height
h – Net pay
P_b – bubble pressure
I_p – pre-frac productivity index
m_p – Proppant Total
q_p – Specific polymer consumption for placement of 1 ton of proppant
V_f – Main Frac fluid volume
Qf – pre-frac fluid production rate
Wc – pre-frac water cut
Qo_pre-frac – pre-frac oil production rate
q_{C1} – oil production rate after hydraulic fracturing
q_0 – actual oil production rate

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