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DEVELOPMENT OF PROBABILISTIC AND STATISTICAL MODELS FOR EVALUATION OF THE EFFECTIVENESS OF PROPPANT HYDRAULIC FRACTURING (ON EXAMPLE OF THE Tl-Bb RESERVOIR OF THE BATYRBAYSKOE FIELD)

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РАЗРАБОТКА ВЕРОЯТНОСТНО-СТАТИСТИЧЕСКИХ МОДЕЛЕЙ ДЛЯ ОЦЕНКИ ЭФФЕКТИВНОСТИ ПРИМЕНЕНИЯ ПРОПАНТНОГО ГИДРАВЛИЧЕСКОГО РАЗРЫВА ПЛАСТА (НА ПРИМЕРЕ ОБЪЕКТА Тл-Бб БАТЫРБАЙСКОГО МЕСТОРОЖДЕНИЯ)

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hydraulic fracturing of formations, prediction, average annual increase in oil production rate, clastic reservoir, Batyrbayskoe field, geological and technological parameters, technical parameters, probabilistic model, statistical model, complex probability, combination of probabilities, Pearson's criterion.

The main factors affecting the efficiency of proppant hydraulic fracturing of Tl-Bb clastic reservoir depending on various parameters are statistically studied. There are 36 hydraulic fracturing treatments pumped from 2008 to 2016 with an average increase in oil production rate of 8.6 tons per day. Probabilistic statistical models were built to determine the parameters that influence the effectiveness of hydraulic fracturing. The average annual increase in oil production is used as a dependent variable; geological, technological and technical parameters are used as independent variables. To determine the degree of impact of parameters wells are divided into two classes of effectiveness: Q_o > 8 tons/day (class 1), Q_o < 8 tons/day (class 2). For the first class of each parameter individual statistical models are built for prediction and its probability is calculated. For the combined use of individual models complex probability is calculated separately for geological technological and technical indicators. As a result, regression models are built using step-by-step regression analysis. The standard error of the model for geological and technological parameters is 2.0 tons/day and 2.2 tons/day for technical. The joint consideration of geological technological and technical parameters in the regression model reduces the standard error to 1.5 tons/day. It is concluded that a separate description of the processes of hydraulic fracturing allows evaluating the efficiency of hydraulic fracturing in specific geological and technological conditions at the design stage, based on the use of developed individual models. After the hydraulic fracturing performed using the developed models considering technical conditions it is possible to preliminary estimate the effectiveness of hydraulic fracturing. The developed methodology for predicting the efficiency of hydraulic fracturing, performed on the Tl-Bb reservoir, is recommended to be used at other reservoirs of the field after correction of the built models. On the other fields where information for building the probabilistic and statistical models is available, it is necessary to develop new probabilistic and statistical models.

Ключевые слова:
гидравлический разрыв пластов, прогнозирование, среднегодовой прирост дебита нефти, терригенный коллектор, Батырбайское месторождение, геолого-технологические показатели, технические показатели, вероятностная модель, статистическая модель, комплексная вероятность, сочетание вероятностей, критерий Пирсона.

Проведен статистический анализ основных факторов, влияющих на эффективность пропантного гидравлического разрыва пластов (ГРП) на терригенном коллекторе объекта Тл-Бб, в зависимости от различных параметров. На объекте в период 2008–2016 гг. выполнено 36 операций ГРП со средним приростом дебита нефти 8,6 т/сут. Для определения параметров, влияющих на эффективность ГРП, построили вероятностно-статистические модели. В качестве зависимой переменной использован среднегодовой прирост дебита нефти, в качестве независимых переменных – геологические, технологические и технические показатели. Для определения степени влияния показателей скважины разделены по эффективности на два класса: $Q_н$ > 8 т/сут (класс 1); $Q_н$ < 8 т/сут (класс 2). Для 1-го класса каждого показателя построены индивидуальные статистические модели для прогноза и вычислена вероятность по ним. Для совместного использования индивидуальных моделей рассчитана комплексная вероятность отдельно для геолого-технологических и технических показателей. В результате построены регрессионные модели с помощью пошагового регрессионного анализа. Стандартная ошибка модели по геолого-технологическим показателям составляет 2,0 т/сут, по техническим – 2,2 т/сут. Совместный учет в регрессионной модели геолого-технологических и технических показателей уменьшает стандартную ошибку до 1,5 т/сут. В заключение сделаны выводы, что раздельное описание процессов выполнения ГРП позволяет на стадии проектирования на основании использования разработанных индивидуальных моделей оценить эффективность применения ГРП в конкретных геолого-технологических условиях. После проведения операции ГРП по разработанным моделям в соответствии с техническими условиями представляется возможным предварительно провести оценку эффективности. Разработанную методику прогноза эффективности ГРП, выполненную по объекту Тл-Бб, рекомендуется после корректировки построенных моделей использовать на других объектах данного месторождения. На других месторождениях, где имеется информация для построения вероятностно-статистических моделей, необходимо разработать новые вероятностно-статистические.

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Introduction

Hydraulic fracturing of reservoirs in production wells is an effective method of improved oil recovery. Hydraulic fracturing helps to achieve high well rates by significant enlargment of the drainage zone and involvement of remote and low-permeability areas to recovery [1–21]. The papaer presents a statistical analysis of the main factors affecting the effectiveness of proppant fracturing depending on various parameters on the clastic reservoir Tl-Bb of Batyrbayskoe field located in Perm region. Such a statistical analysis is carried out on carbonate and clastic reservoirs of other Perm region fields [22, 23].

Study of the effect of geological, technological and technical factors on the effectiveness of hydraulic fracturing

There were 36 hydraulic fracturing treatments performed on Tl-Bb reservoir in 2008–2016. The average increase in oil production rate was 8.6 tons/day. In order to determine the parameters that affect the effectiveness of hydraulic fracturing, probabilistic and statistical models are built. Average growgh of oil production is used as a dependent variable. Geological, technological and technical parameters presented in Table 1 are used as independent variables.

In order to determine the degree of influence of geological, technological and technical parameters on the effectiveness of hydraulic fracturing, individual statistical models are built aimed to forecast the growth values considering the following conditions:

- if Q_o > 8 tons/day the hydraulic fracturing is very effective (class 1);
- if Q_o < 8 tons/day the hydraulic fracturing is not effective (class 1).

The method of building the individual probability and statistical models is given in [24–30]. The models for the Batyrbayskoe field Tl-Bb reservoir are given in Table 2.

Examples of graphical representation of built probabilistic models for K_{calc}, $h_{n.o.-b}$, P_i, P_f are shown in Fig. 1.

It is shown that the constructed functions of K_{calc} and $h_{n.o.-b}$ have an inverse character. However, ranges of probability variations differ significantly. In the first case, the probability P (K_{calc}) has a much larger range of changes than in the second one.

Table 1

Parameters used to built probabilistic and statistical models

Geological and technological	Technical
Compartmentalization K_{calc}, units	Consumption of the mixture Q_{cons}, m^3/min
Piezoconductivity θ, cm^2/s	Volume of the fracturing fluid $V_{f.f}$, m^3
Productivity K_{prod}, m^3/day/MPa	Proppant mass M_{prop}, tons
Permeability of the near reservoir zone K_{perm}^{near}, μm^2	Concentration of proppant K_{prop}, kg/m^3
Permeability of the distant reservoir zone K_{perm}^{dist}, μm^2	Initial pressure at hydraulic fracturing P_i, atm
Reservoir pressure before hydraulic fracturing P_{res}, MPa	Average pressure at hydraulic fracturing P_{av}, atm
Net oil-bearing thickness $h_{n.o.-b}$, m	Final pressure at hydraulic fracturing P_f, atm
Skin effect S	Gel volume V_{gel}, m^3
Gamma-ray logging data GK, μR/h	
Reference depth H_{ref}, m	
Altitude H_a, m	
Cumulative oil production $Q_{c.o}$, tons	
Cumulative water production $Q_{c.w}$, tons	

Table 2

Individual models built to predict assignement of wells to the first class for the Batyrbayskoe field Tl-Bb reservoir

Equation of probability of belonging to the class 1	Scope of the model	Range of probability change
Geological and technological parameters		
$P(K_{\text{comp}}) = 0{,}671 - 0{,}0934K_{\text{comp}}$	1–6 units	0.110–0.577
$P(K_{\text{prod}}) = 0{,}0469 + 0{,}00891K_{\text{prod}}$	0.11–24.7 m^3/day·MPa	0.470–0.520
$P(K_{\text{perm}}^{\text{dist}}) = 0{,}631 - 1{,}644K_{\text{perm}}^{\text{dist}}$	0.0023–0.319 μm^2	0.105–0.827
$P(h_{\text{n.o.-b}}) = 0{,}550 - 0{,}021h_{\text{n.o.-b}}$	1.0–5.0 m	0.445–0.529
$P(GK) = 0{,}675 + 0{,}0633GK$	1.0–6.6 μR/h	0.257–0.610
$P(H_{\text{a}}) = 3{,}531 - 0{,}0025H_{\text{a}}$	1104–1232 m	0.408–0.730
$P(Q_{\text{c.w}}) = 0{,}662 - 0{,}00009Q_{\text{c.w}}$	2084.5–64746.2 tons	0.096–0.643
$P(\theta) = 0{,}519 - 0{,}0000282\theta$	19–6889 cm^2·s	0.326–0.520
$P(K_{\text{perm}}^{\text{near}}) = 0{,}629 - 1{,}138K_{\text{perm}}^{\text{near}}$	0.0019–0.54 μm^2	0.014–0.628
$P(P_{\text{res}}) = 0{,}001 + 0{,}0551P_{\text{res}}$	2.1–14.5 MPa	0.115–0.797
$P(S) = 0{,}536 - 0{,}0117S$	–4.3–18.2	0.325–0.587
$P(H_{\text{ref}}) = -0{,}290 + 0{,}0053H_{\text{ref}}$	1388–1644 m	0.445–0.580
$P(Q_{\text{c.o}}) = 0{,}469 + 0{,}0000081Q_{\text{c.o}}$	9284.4–130060.2 tons	0.477–0.574
Technical parameters		
$P(Q_{\text{cons}}) = 1{,}677 - 0{,}3313Q_{\text{cons}}$	2.6–4.2 m^3/min	0.285–0.815
$P(M_{\text{prop}}) = 0{,}521 - 0{,}0011M_{\text{prop}}$	9.0–30.5 tons	0.487–0.511
$P(P_{\text{i}}) = 1{,}009 - 0{,}0014P_{\text{i}}$	220–700 atm	0.029–0.701
$P(P_{\text{f}}) = 0{,}339 + 0{,}0044P_{\text{f}}$	235–698 atm	0.441–0.642
$P(V_{\text{liq}}) = 0{,}327 + 0{,}0059V_{\text{liq}}$	12–70 m^3	0.397–0.740
$P(K_{\text{prop}}) = -0{,}019 + 0{,}0061K_{\text{prop}}$	600–1000 kg/m^3	0.352–0.596
$P(P_{\text{av}}) = 1{,}446 - 0{,}0029P_{\text{av}}$	220–450 atm	0.141–0.808
$P(V_{\text{gel}}) = 0{,}586 - 0{,}0007V_{\text{gel}}$	56.0–173.6 m^3	0.464–0.546

The largest range of change for P_{i} belongs to $P(P_{\text{i}})$, P_{f} has a small value of $P(P_{\text{f}})$.

The generalized probability is calculated to use combined geological and technological individual probabilities:

$$P_{\text{comp}} = \frac{\prod P_{\text{r.c.p}i}}{\prod P_{\text{r.c.p}i} + \prod (1 - P_{\text{r.c.p}i})},$$

where $P_{\text{r.c.p}i}$ are the probabilities: $P(K_{\text{comp}})$, $P(\theta)$, $P(K_{\text{prod}})$, $P(K_{\text{perm}}^{\text{near}})$, $P(K_{\text{perm}}^{\text{dist}})$, $P(P_{\text{res}})$, $P(h_{\text{n.o.-b}})$, $P(S)$, $P(GK)$, $P(H_{\text{ref}})$, $P(H_{\text{a}})$, $P(Q_{\text{c.o}})$, $P(Q_{\text{c.w}})$, $P(Q_{\text{cons}})$, $P(V_{\text{f.l}})$, $P(M_{\text{prop}})$, $P(K_{\text{prop}})$, $P(P_{\text{i}})$, $P(P_{\text{a}})$, $P(P_{\text{f}})$, $P(V_{\text{gel}})$.

When calculating P_{comb} the combination of probabilities is used at which the average probabilities of P_{comb} are most strongly different in the studied classes at equal value of m. Combinations of probabilities are given in Table 3.

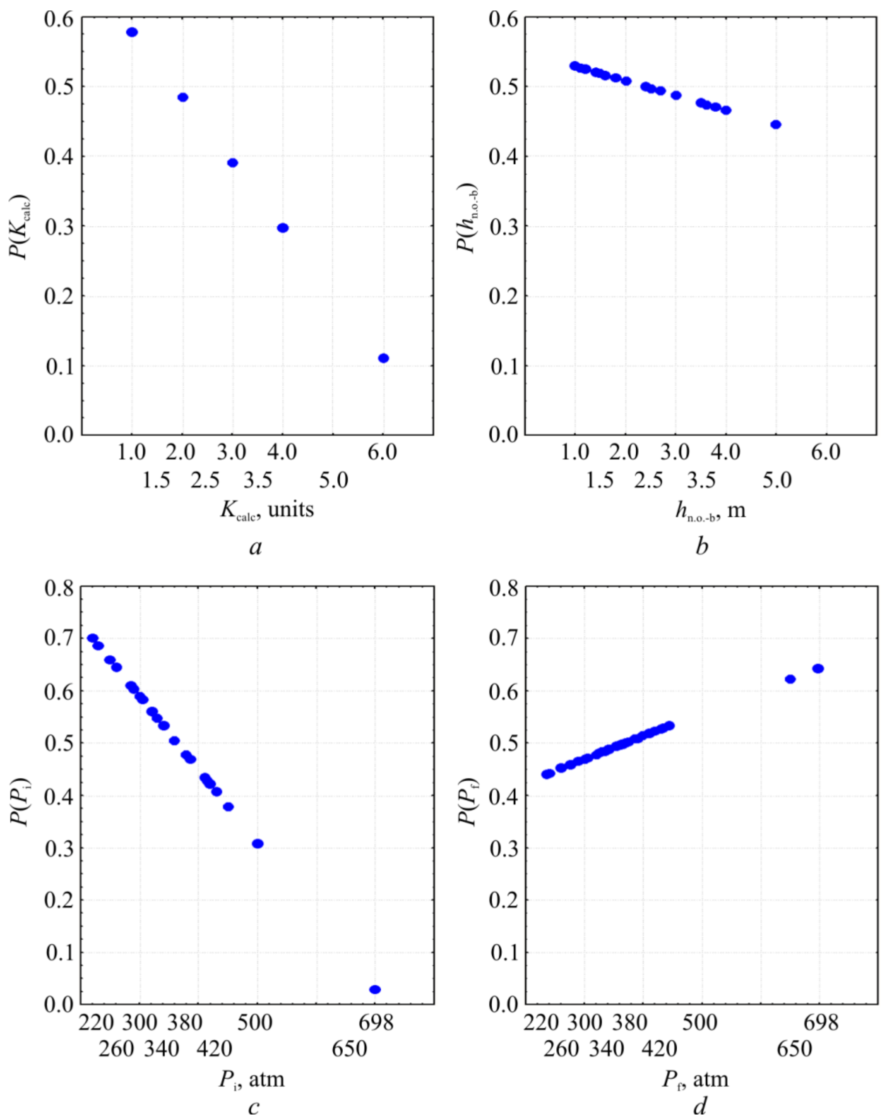

Fig. 1. Functions: *a* – $P(K_{calc})$ of K_{calc}; *b* – $P(h_{n.o.\text{-}b})$ of $h_{n.o.\text{-}b}$; *c* – $P(P_i)$ of P_i; *d* – $P(P_f)$ of P_f

It is observed that if m = 2 the probabilities $P(K^{near}_{perm})$ and $P(Q_{c.w})$ are used. If m = 3 these conditions are satisfied $P(K^{dist}_{perm})$, then successively all other probabilities and at the final step when m = 13 – $P(Q_{c.o})$ (see Table 3). Similar calculations were performed on technical parameters (Table 4).

Table 3 shows that if m = 2 the probabilities $P(P_{av})$ and $P(P_i)$ were used. If m = 3 these conditions are satisfied $P(Q_{cons})$, then successively all other probabilities and at the final step at m = 8 – $P(M_{prop})$ (Table 4).

Based on values of P_{comb}, calculated using geological, technological and technical parameters, the functions of changes of P_{comb} of m for each well are plotted (Fig. 2).

Note that for geological and technological parameters the values of P_{comb} were calculated for 13 parameters, so the values of P_{comb} vary from 2 to 13, for technical – by 8, so the values vary from 2 to 8.

The graphs built consist of two parts. The first part of the graphs is built for wells with Q_o < 8 tons/day. The second part of the graphs is built from wells with Q_o > 8 tons/day.

Analysis of the graphs shows that values of P_{comb} as a function of m over the studied wells vary considerably. Changes in average values of P_{comb}

for wells with different efficiency of fracturing according to 13 geological and technological data and 8 technical indicators are shown in Fig. 3.

Comparison of changes in values of P_{comb} calculated by geological, technological and technical parameters shows that the direction of change in values for wells with Q_o > 8 tons/day and wells with Q_o < 8 tons/day are the same. The difference in the first case lies in the fact that the curve characterizing the changes by technical parameters is located below the curve describing the effect on geological and technological indicators of the hydraulic fracturing effectiveness. Position of curves P_{comb} has the opposite shape in the second case. The functions given indicate that conditions for hydraulic

Table 3

Combination of probabilities calculated by geological and technological parameters

Parameter	Combination of probabilities P_{comb}											
	2	3	4	5	6	7	8	9	10	11	12	13
$P(S)$						+	+	+	+	+	+	+
$P(\theta)$									+	+	+	+
$P(H_a)$								+	+	+	+	+
$P(h_{n.o.\text{-}b})$											+	+
$P(K_{perm}^{dist})$		+	+	+	+	+	+	+	+	+	+	+
$P(H_{ref})$										+	+	+
$P(GK)$					+	+	+	+	+	+	+	+
$P(K_{comp})$				+	+	+	+	+	+	+	+	+
$P(K_{perm}^{near})$	+	+	+	+	+	+	+	+	+	+	+	+
$P(P_{res})$			+	+	+	+	+	+	+	+	+	+
$P(K_{prod})$							+	+	+	+	+	+
$P(Q_{c.o})$												+
$P(Q_{c.w})$	+	+	+	+	+	+	+	+	+	+	+	+
Q_o^m > 8.0 tons/day	0.612	0.642	0.653	0.676	0.682	0.685	0.679	0.688	0.691	0.692	0.690	0.690
Q_o^m < 8.0 tons/day	0.438	0.403	0.373	0.349	0.352	0.336	0.334	0.329	0.325	0.328	0.328	0.325
$\frac{t_{1-2}}{p_{1-2}}$	$\frac{2.6832}{0.01118}$	$\frac{3.4469}{0.0015}$	$\frac{3.3824}{0.0018}$	$\frac{4.5432}{0.0001}$	$\frac{4.1864}{0.0001}$	$\frac{4.3256}{0.0001}$	$\frac{4.1849}{0.0002}$	$\frac{4.5627}{0.0001}$	$\frac{4.5796}{0.0001}$	$\frac{4.4268}{0.0001}$	$\frac{4.4268}{0.0001}$	$\frac{4.4710}{0.0001}$

Table 4

Combination of probabilities calculated by technical parameters

Parameter	Combination of probabilities P_{comb}						
	2	3	4	5	6	7	8
$P(P_i)$	+	+	+	+	+	+	+
$P(M_{prop})$							+
$P(K_{prop})$				+	+	+	+
$P(V_{gel})$						+	+
$P(P_{av})$	+	+	+	+	+	+	+
$P(P_f)$					+	+	+
$P(Q_{cons})$		+	+	+	+	+	+
$P(V_{1.f})$			+	+	+	+	+
Q_o^m > 8.0 tons/day	0.569	0.572	0.582	0.579	0.589	0.591	0.591
Q_o^m < 8.0 tons/day	0.425	0.398	0.396	0.396	0.396	0.392	0.391
$\frac{t_{1-2}}{p_{1-2}}$	$\frac{1.9864}{0.0551}$	$\frac{2.2044}{0.0343}$	$\frac{2.7551}{0.0293}$	$\frac{2.0152}{0.0518}$	$\frac{2.2394}{0.0317}$	$\frac{2.2717}{0.0295}$	$\frac{2.2866}{0.0285}$

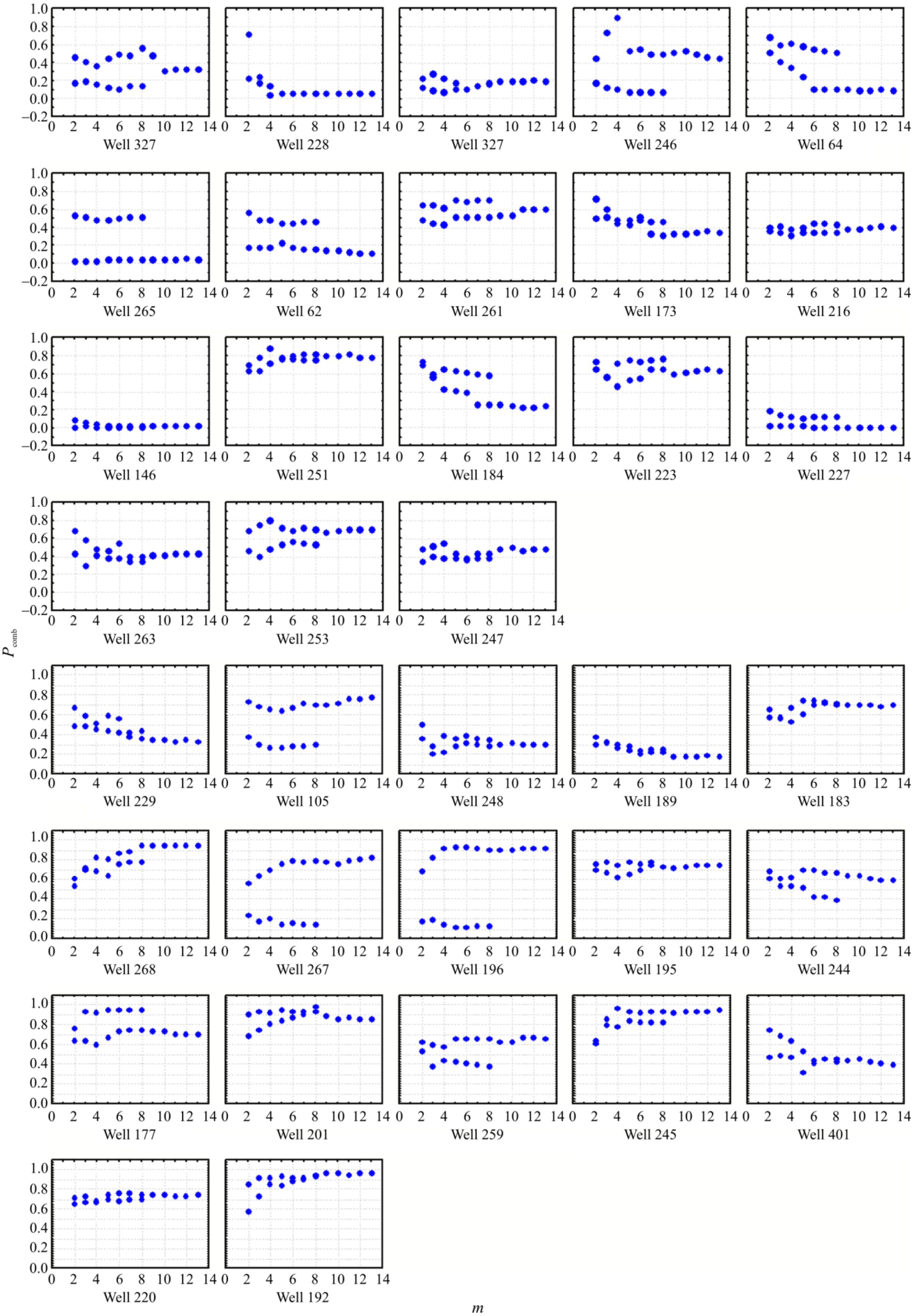

Fig. 2. Functions P_{comb} of m for wells

fracturing affect the effectiveness of hydraulic fracturing more significantly than the technology itself. That is illustrated well by the nature of the change in P_{comp} while increasing values of m as a result of calculations for specific wells, shown in Fig. 2. That is clearly seen in wells No. 327, 246 with low hydraulic fracturing effectiveness, in wells No. 105, 268, 267, 196, 259, 245, 220 with

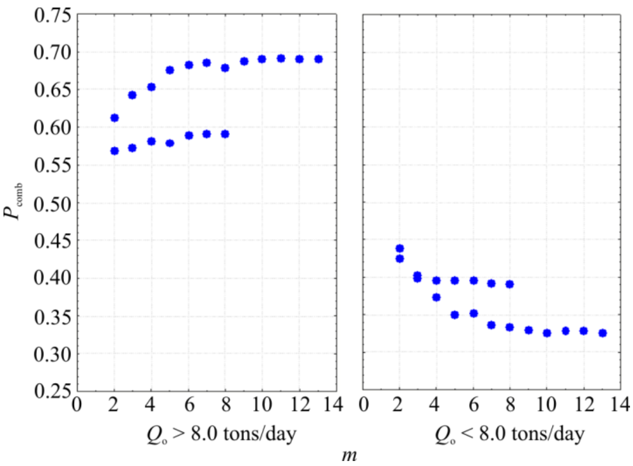

Fig. 3. Functions P_{comb} of m for geological, technological and technical parameters for the classes studied

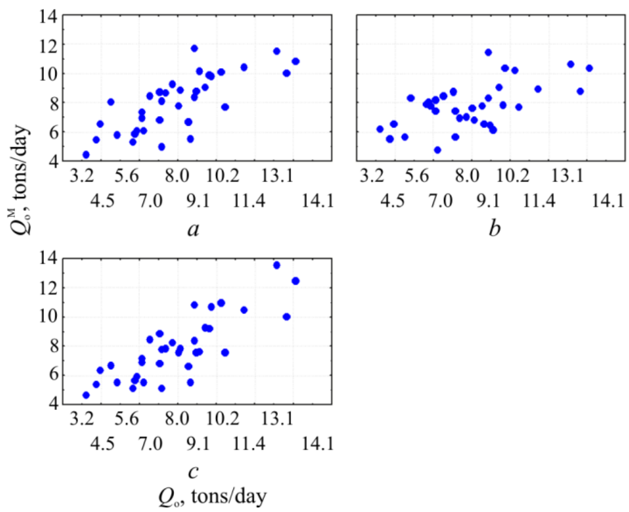

Fig. 4. Correlation fields between Q_o and $Q_o^{\text{M-r.c.p}}$, calculated by probabilities: *a* – geological and technological parameters; *b* – technical parameters; *c* – geological, technological and technical parameters

high effectiveness of hydraulic fracturing. On contrary, for low effectiveness of hydraulic fracturing: the curves of technical parameters are located higher than curves of geological and technological parameters which is observed in wells No. 64, 265, 62, 261, 184, 223, 227, 247. That is the case for a group with high effectiveness of hydraulic fracturing (wells No. 177, 201, 192).

Thus, the effectiveness of hydraulic fracturing for different conditions is selective. Neverthelles, that can be predicted using the probabilistic and statistical models.

Regression models were built for geological, technological and technical parameters with help of step-by-step regression analysis from the values of P_{comp} for different m. According to geological and technological parameters the model is written as

$$Q_o^{\text{m-r.c.pGT}} = 4.970 + 43.0056 P_{\text{comp}_m^{10}} - 55.4604 P_{\text{comp}_m^{11}} + 30.7730 P_{\text{comp}_m^{12}} - 12.3732 P_{\text{comp}_m^{19}}$$

if R = 0.697, p < 0.00038, the standard error is 2.0 t/day.

According to technical parameters, the following model is obtained:

$$Q_o^{\text{m-r.c.pT}} = 4.727 + 14.2158 P_{\text{comp}_m^{4}} - 23.6382 P_{\text{comp}_m^{5}} + 15.8918 P_{\text{comp}_m^{6}},$$

if R = 0.588, p < 0.0039, the standard error is 2.2 t/day. A correlation field between Q_o and $Q_o^{\text{M-r.c.p}}$ is shown in Fig. 4.

Combined assessment of geological, technological and technical conditions of hydraulic fracturing with the use of calculations based on the formulas given above can be performed in the way:

$$Q_o^{\text{m-r.c.pGT-T}} = 4.727 - 0.075 Q_o^{\text{m-r.c.pGT}} - 0.3712 Q_o^{\text{m-r.c.pT}} - 0.0608 (Q_o^{\text{m-r.c.pGT}})^2 + 0.2411 Q_o^{\text{m-r.c.pGT}} Q_o^{\text{m-r.c.pT}} - 0.0759 (Q_o^{\text{m-r.c.pT}})^2$$

if $R = 0.820$, $p = 0.00000$, the standard error is 1.5 t/day. Graphic representation of function $Q_o^{\text{m-r.c.pGT-T}}$ of $Q_o^{\text{m-r.c.pGT}}$ and $Q_o^{\text{m-r.c.pT}}$ is shown in Fig. 5.

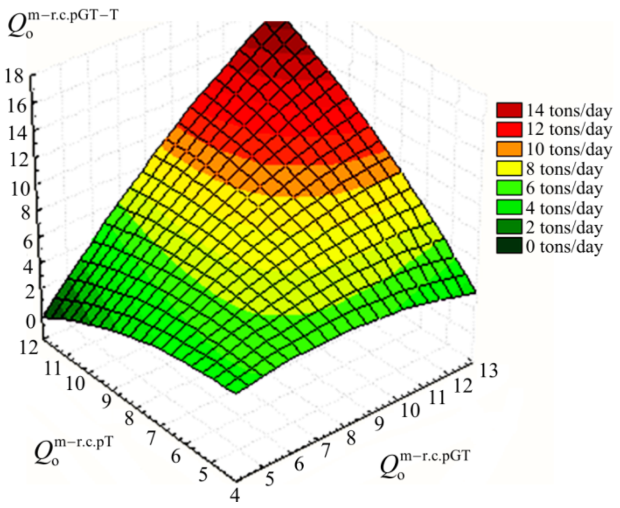

Fig. 5. Function $Q_o^{\text{m-r.c.pGT-T}}$ of $Q_o^{\text{m-r.c.pGT}}$ and $Q_o^{\text{m-r.c.pT}}$

Statistical estimation of working capacity of probabilistic and statistical models built can be performed using the Pearson's criterion χ^2. The calculation is done using the formula

$$\chi^2 = N_1 N_2 \sum_{i=1}^{e} \frac{1}{M_1 + M_2} \left(\frac{M_1}{N_1} - \frac{M_2}{N_2} \right)^2,$$

where N_1, N_2 are the numbers of wells with real values of increments in oil production rates, with model values of incremental oil production rates for the three developed scenarios; M_1, M_2 are numbers of values that got the interval given, for the two classes studied respectively; e is the number of intervals. In order to calculate the values of χ^2 particular distributions of Q_o, $Q_o^{\text{m-r.c.pГT}}$, $Q_o^{\text{m-r.c.pT}}$ are built (Table 5).

Values of χ^2 (given in Table 6) are calculated according to Table 5.

Distributions of frequencies for Q_o and $Q_o^{\text{m-r.c.pGT}}$, $Q_o^{\text{m-r.c.pT}}$, $Q_o^{\text{m-r.c.pGT-T}}$ are not statistically different. The minimal difference is obtained by comparing Q_o with $Q_o^{\text{m-r.c.pGT-T}}$.

Table 5

Distribution of values Q_o and $Q_o^{\text{m-r.c.pGT}}$, $Q_o^{\text{m-r.c.pT}}$, $Q_o^{\text{m-r.c.pGT-T}}$

Parameter	Variation intervals Q_o, tons/day						
	2–4	4–6	6–8	8–10	10–12	12–14	14–16
Q_o	0.085	0.142	0.314	0.285	0.085	0.057	0.028
$Q_o^{\text{m-r.c.pGT}}$	0.057	0.114	0.314	0.314	0.171	0.028	–
$Q_o^{\text{m-r.c.pT}}$	–	0.114	0.485	0.285	0.085	0.028	–
$Q_o^{\text{m-r.c.pGT-T}}$	–	0.257	0.371	0.171	0.143	0.058	–

Table 6

Statistical characteristics of models

Real increment of flow rates	Model increment of flow rates	χ^2 / p
Q_o	$Q_o^{\text{m-r.c.pGT}}$	0.196641 / 0.906358
	$Q_o^{\text{m-r.c.pT}}$	0.1944501 / 0.907329
	$Q_o^{\text{m-r.c.pGT-T}}$	0.101302 / 0.95610

Note: χ^2 – top line, significance level – bottom line.

Conclusion

1. Separate description of processes of hydraulic fracturing at the design stage based on application of individual models developed allows evaluating the efficiency of hydraulic fracturing in specific geological and technological conditions. Thanks to that, it is possible to rank the candidate wells for hydraulic fracturing according to the degree of their prospects.

2. After the hydraulic fracturing performed using the individual models developed that is possible to evaluate the results in accordance with the specific conditions.

3. Using the data of assessment of a particular scenario that occurred before hydraulic fracturing and data obtained after probabilistic and statistical models got used, it is possible to estimate oil production growth rates.

4. It is recommended (after some changes) to use the hydraulic fracturing prediction method

developed for a Batyrbayskoe field Tl-Bb reservoir for other reservoirs of the field. For other fields having experience of hydraulic fracturing (i.e. information for building the probabilistic and statistical models) it is necessary to develop new probabilistic and statistical models using the technology given in detais in this paper.

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