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Development of a Statistical Model for Predicting the Oil Production Rate after Fracking by Geological and Technological Indicators

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Разработка статистической модели прогноза дебита нефти после гидроразрыва пласта на основе геолого-технологических показателей

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An increase in the productivity of wells at operational facilities is achieved through the use of various geological and technical measures. Hydraulic fracturing (HF) in production and injection wells is one of the effective methods for increasing oil recovery, involving low-permeability zones and interlayers in the development, a mechanism for a wider coverage of productive zones by waterflooding, which makes it possible to convert part of off-balance reserves into commercial ones. 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. Good agreement between model and experimental results is obtained.

Ключевые слова:
гидроразрыв, нефтеотдача пласта, дебит нефти, технологические параметры, карбонатные коллекторы, регрессионный анализ.

Повышение продуктивности скважин эксплуатационных объектов достигается за счет применения различных геолого-технических мероприятий. Гидравлический разрыв пласта (ГРП) в добывающих и нагнетательных скважинах является одним из эффективных методов увеличения нефтеотдачи пластов, вовлечения в разработку низкопроницаемых зон и пропластков, механизмом более широкого охвата продуктивных зон заводнением, что позволяет перевести часть забалансовых запасов в промышленные. По мнению экспертов, применение гидроразрыва пласта позволяет увеличить коэффициент извлечения нефти и газа на 10–15 %. Пермский край относится к старому нефтедобывающему региону Российской Федерации.На сегодняшний день более 60 % остаточных извлекаемых запасов нефти месторождений Пермского края сосредоточено в карбонатных отложениях. Большинство месторождений в настоящее время находится на поздних стадиях разработки. Эти месторождения, как правило, характеризуются наличием недренируемых зон с остаточными запасами и низкими дебитами скважин. Большая часть остаточных запасов месторождений сосредоточена в низкопроницаемых коллекторах с высокой степенью неоднородности и затрудненной фильтрацией флюидов. К сожалению, получаемые на практике результаты не всегда соответствуют предварительным расчетам и не достигают плановых дебитов нефти. В связи с изложенным встает задача прогнозирования эффективности операций ГРП с помощью математических методов анализа. На эффективность ГРП, несомненно, влияют как геологические, так и технологические параметры. В настоящей работе для карбонатных каширских (К) и подольских (Пд) продуктивных отложений одного из нефтяных месторождений Пермского края с помощью пошагового регрессионного анализа на основе геологических и технологических параметров выполнен прогноз начального дебита нефти после ГРП. Получено хорошее согласие модельных и экспериментальных результатов.

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Introduction

Perm Krai is an old oil producing region of the Russian Federation, most fields are at late stages of development. Today, more than 60 % of the remaining recoverable oil reserves of Perm Krai fields are concentrated in carbonate deposits [1]. Application of various geological and technical measures in producing wells is an effective method of obtaining additional oil production [2–8].

Hydraulic fracturing (HF) is an effective method of enhanced oil recovery. With the help of hydraulic fracturing technology, high well flow rates are achieved by significantly expanding the drainage zone and introducing remote and low-permeable areas to the development of reserves [9–27].

In connection with the mentioned above it arises the task of predicting the efficiency of hydraulic fracturing operations by mathematical methods of analysis [28–30]. The efficiency of hydraulic fracturing is undoubtedly influenced by both geological and technological parameters [31–45].

In the present work the forecast of the initial oil flow rate after hydraulic fracturing was carried out for carbonate Kashira (*K*) and Podolsk (P_d) productive deposits of one of the oil fields of Perm Krai with the help of step-by-step regression analysis on the basis of geological and technological parameters.

There are data on initial oil flow rate (Q_n) after hydraulic fracturing and several geological and technological parameters for 22 wells. The following parameters were taken as parameters affecting the efficiency of hydraulic fracturing: geological parameters – porosity (K_p), permeability (K_{pr}), oil saturation (K_n), oil saturated thickness (h_n), technological parameters – specific proppant consumption (q_n), dissection (K_r), downhole clamping pressure (Pz) and pre-fracturing fluid flow rate (Q_{zh}) (Table 1).

Correlation coefficients (*r*) and levels of statistical significance (*p*) were determined for paired dependencies (Table 2).

The table shows that the initial oil flow rate after hydraulic fracturing Q_n, porosity and oil saturation correlate well with all parameters. At the same time, there are statistically significant relationships between:

– clamping pressure at the face P_z with specific proppant consumption q_n and dismemberment K_r;

– dismemberment K_p and specific proppant consumption q_n;

– specific proppant flow rate qn and oil saturated thickness h_n.

Table 1

Ranges of variation and average values of sample parameters for Kashira and Podolsk deposits of Perm Krai

Parameter	Parameter variation range / average value
Initial oil flow rate after hydraulic fracturing, Q_n, tons per day	(7.5–4.4)/5.82
Porosity, K_p, %	(26.6–12.30)/17.69
Oil saturation, K_n, %	(74.0–59.0)/65.6
Permeability, K_{pr}, 10^{-3} μm^2	(91.41–3.2)/20.53
Oil saturated thickness, hn, m	(4.4–2.4)/3.42
Specific proppant consumption, q_p, t/m	(10.43–5.31)/8.24
Dismemberment, K_r, units.	(4.0–1.0)/2.45
Clamping pressure at the bottomhole, P_z, atm	(245.0–120.7)/172.27
Liquid flow rate before fracturing, Q_{zh}, m^3/day	(4.0–0.5)/1.89

Table 2

Correlation matrix for sampling of Kashira and Podolsk carbonate deposits during hydraulic fracturing at wells in Perm Krai field

Parameter	Q_n, ton/day	K_p, %	K_n, %	K_{pr}, 10^{-3} mkm^2	h_n, m	q_p, t/m	K_p, units	P_z, atm	Q_{zh} m^3/day
Q_n, ton/day	1	r = 0.7577 p = 0.000	r = 0.7595 p = 0.000	r = 0.7978 p = 0.000	r = –0.6168 p = 0.002	r = 0.5214 p = 0.013	r = 0.5011 p = 0.018	r = –0.6375 p = 0.001	r = 0.7189 p = 0.000
K_p, %		1	r = 0.7946 p = 0.000	r = 0.8716 p = 0.000	r = –0.6369 p = 0.001	r = 0.4752 p = 0.025	r = 0.5989 p = 0.003	r = –0.5797 p = 0.005	r = 0.5412 p = 0.009
K_n, %			1	r = 0.7509 p = 0.000	r = –0.4346 p = 0.043	r = 0.4650 p = 0.029	r = 0.5603 p = 0.007	r = –0.6226 p = 0.002	r = 0.5928 p = 0.004
K_{pr}, 10^{-3} mkm^2				1	r = –0.6028 p = 0.003	r = 0.3953 p = 0.069	r = 0.3720 p = 0.088	r = –0.5521 p = 0.008	r = 0.5344 p = 0.010
h_n, m					1	r = –0.5901 p = 0.004	r = –0.3762 p = 0.084	r = 0.4081 p = 0.059	r = –0.2529 p = 0.256
q_p, t/m						1	r = 0.4395 p = 0.041	r = –0.6653 p = 0.001	r = 0.3906 p = 0.072
K_r, units							1	r = –0.6700 p = 0.001	r = 0.2453 p = 0.271
P_z, atm								1	r = –0.4200 p = 0.052
Q_{zh}, m^3/day									1

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

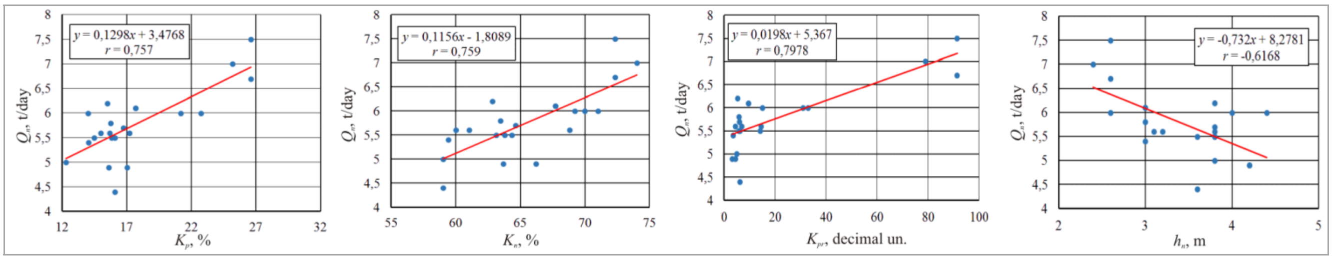

Fig. 1. Dependences of initial oil flow rate after hydraulic fracturing with geological parameters: porosity (K_p), oil saturation (K_n), permeability (K_{pr}), oil saturated thickness (h_n)

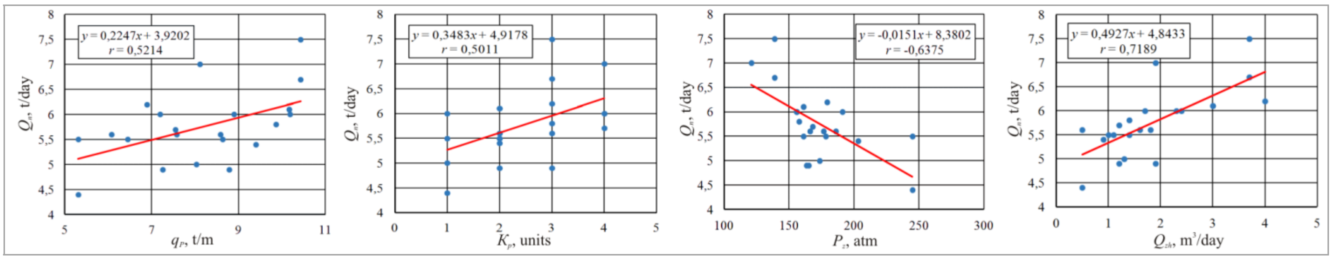

Fig. 2. Dependences of initial oil flow rate after hydraulic fracturing with technological parameters: specific proppant flow rate (q_p), dissection (K_r), downhole clamping pressure (P_z), pre-fracturing fluid flow rate (Q_{zh})

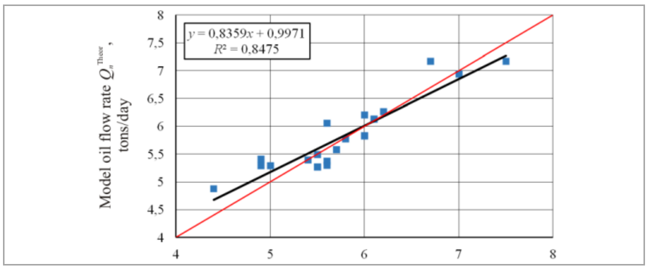

Fig. 3. Correlation field of the modeled $\left(Q_n^{\text{Theor}}\right)$ and actual (Q_n) values of initial oil flow rate after hydraulic fracturing for wells of the Kashir and Podolsk wells carbonate deposits of the Perm Krai field

For the parameters of the initial sample with high correlation coefficients and low levels of statistical significance correlation fields were constructed: for geological parameters (Fig. 1) and for technological parameters (Fig. 2).

According to the values of correlation coefficients r of dependences of oil flow rate Q_n on geological and technological parameters and the level of statistical significance p the degree of influence of these parameters on the initial oil flow rate after hydraulic fracturing is determined.

Using regression analysis it is constructed a multivariate regression equation, in which the dependent variable is the model value of oil flow rate after hydraulic fracturing, and the independent variables are the sample parameters, for which the level of statistical significance $p < 0.05$.

In general, the equation is written as follows:

$$Q_n^{\text{Theor}} = a_o + a_1 K_p + a_2 K_n + a_3 K_{pr} + a_4 h_n + a_5 q_p + a_6 K_r + a_7 P_z + a_8 Q_{zh}$$

where a_0, a_1, ..., a_8 – regression coefficients determined by the least squares method.

In our case, a multivariate equation was obtained for the whole sample by the method of stepwise regression analysis:

$$Q_n^{\text{Theor}} = 5.857–0.054 K_p + 0.025 K_n + 0.011 K_{pr} – 0.356 h_n – 0.028 q_p + 0.126 K_p – 0.002 P_z + 0.286 Q_{zh}.$$

Comparison of model and actual values of oil flow rate after hydraulic fracturing is shown in Fig. 3.

Absolute deviation of model values of initial oil flow rate from its actual values in the field is in the range from 0.006 to 0.511 t/day with the average of 0.219 t/d.

Relative deviation is in the range of 0.11 to 10.90 % with an average of 3.97 %.

Conclusion

As a result of the performed research it was established that:

1. The value of initial oil flow rate after hydraulic fracturing in Kashira and Podolsk carbonate deposits of one of the fields of Perm Krai is mainly influenced by geological parameters – porosity, oil saturation, permeability, oil saturated thickness and technological parameters – specific proppant flow rate, partitioning, downhole clamping pressure and pre-fracturing fluid flow rate.
2. The proposed method allows using the geological and technological parameters of the object to predict the value of the initial oil flow rate after hydraulic fracturing.

References

1. Poplygin V.V., Poplygina I.S. Povyshenie effektivnosti razrabotki mestorozhdenii Permskogo kraia [Improving the efficiency of development of deposits in the Perm region]. *Problemy razrabotki mestorozhdenii uglevodorodov i rudnykh poleznykh iskopaemykh*, 2014, no. 1, pp. 283-285.
2. Galkin V.I., Koltyrin A.N. Obosnovanie prognoznoi velichiny prirosta debita nefti posle primeneniia GTM s pomoshch'iu statisticheskogo metoda [Justification of the predicted value of oil flow rate increase after applying WST with the help of the statistical method]. *Izvestiia Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov*, 2023, vol. 334, no. 2, pp. 81-86. DOI: 10.18799/24131830/2023/2/3857
3. Kochnev A.A., Kozyrev N.D., Kochneva O.E., Galkin S.V. Razrabotka kompleksnoi metodiki prognoza effektivnosti geologo-tekhnicheskikh meropriiatii na osnove algoritmov mashinnogo obucheniia [Development of a comprehensive methodology for the forecast of effectiveness of geological and technical measures based on machine learning algorithms]. *Georesursy*, 2020, vol. 22. no 3, pp. 79-86. DOI: 10.18599/grs.2020.3.79-86
4. Yanfang W., Salehi S. Refracture candidate selection using hybrid simulation with neural network and data analysis techniques. *Journal of Petroleum Science and Engineering*, 2014, vol. 123, pp. 138-146. DOI: 10.1016/j.petrol.2014.07.036

5. Miel H., Hameed A.O.S., Hussein K.F. Modeling and monitoring the development of an oil field under conditions of mass hydraulic fracturing. *Trends in Sciences*, 2022, vol. 19, no. 8, pp. 3436-3436. DOI: 10.48048/tis.2022.3436
6. Kochnev A.A., Zotikov V.I., Galkin S.V. Analiz vliianiia geologo-tekhnologicheskikh pokazatelei na effektivnost' tekhnologii radial'nogo bureniia na primere ekspluatatsionnykh ob"ektov Permskogo kraia [Analysis of the influence of geological-technological parameters on the effectiveness of radial drilling technology on the example of operational objects in Perm region]. *Izvestiia Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov*, 2018, vol. 329, no. 12, pp. 20-29. DOI: 10.18799/24131830/2018/12/16
7. Raspopov A.V., Novokreshchennykh D.V. Analiz rezul'tatov primeneniia metodov intensifikatsii na karbonatnykh kollektorakh mestorozhdenii Permskogo kraia] [Results analysis of intensification methods application in carbonate reservoirs of Perm region fields]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe igornoe delo*, 2014, vol. 13, no. 10, pp. 73-82. DOI: 10.15593/2224-9923/2014.10.7
8. Votinov A.S. Opyt provedeniia tekhnologii propantnogo gidrorazryva plasta pri razrabotke karbonatnykh zalezhei nefti Permskogo kraia [Experience of implementing proppant hydraulic fracturing technology in the development of carbonate oil deposits in the Perm region]. *Magisterskii zhurn*, 2019, no. 2, pp. 26-32.
9. Kochnev A.A., Galkin S.V. Modelirovanie gidromonitornogo bureniia putem prognozirovaniia napravleniia radial'nogo kanala s uchetom napriazhennogo sostoianiia massiva gornykh porod [Modeling a hydromonitor drilling by predicting the direction of the radial channel taking into account the stress state of the rock mass]. *28-ia Rossiiskaia konferentsiia po matematicheskomu modelirovaniiu v estestvennykh naukakh. Materialy konferentsii AIP 2216, 080002-1-080002-6*. DOI: 10.1063/5.0004270
10. Chen J., Qu Z., Zhou L. et al. Numerical Study on the Hydraulic Fracturing Pattern in the Hard Roof in Response to Mining-Induced Stress. *Minerals*, 2023, vol. 13, no. 3, 308 p. DOI: 10.3390/min13030308
11. Hong-Yan Qu, Jian-Long Zhang, Fu-Jian Zhou et al. Evaluation of hydraulic fracturing of horizontal wells in tight reservoirs based on the deep neural network with physical constraints. *Petroleum Science*, 2023. DOI: 10.1016/j.petsci.2023.03.015
12. Wang Duo, LI Sanbai, Zhang Dongxiao et al. Understanding and predicting proppant bedload transport in hydraulic fracture via numerical simulation. *Powder Technology*, 2023, 118232 p. DOI: 10.1016/j.powtec.2023.118232
13. Alotaibi N., Dursun Serkan. Optimizing the Hydraulic Fracturing Fluid Systems Using the Completion and Production Data in Bakken Shale. *Middle East Oil, Gas and Geosciences Show*. OnePetro, 2023. DOI: 10.2118/213360-MS
14. Gai Jian. Prediction method for hydraulic fracturing effect of oil production well based on automatic machine learning technology. *Editorial Department of Petroleum Geology and Recovery Efficiency*, 2023, vol. 30, no 1, pp. 161-170. DOI: 10.13673/j.cnki.cn37-1359/te.202203015
15. Hakimi Mohammed Hail, Hamed Tamer E., Lotfy Naira M. et al. Hydraulic fracturing as unconventional production potential for the organic-rich carbonate reservoir rocks in the Abu El Gharadig Field, north western Desert (Egypt): Evidence from combined organic geochemical, petrophysical and bulk kinetics modeling results. *Fuel*, 2023, vol. 334. 126606 p. DOI: 10.1016/j.fuel.2022.126606
16. Appah D. Application of the theory of diffuse set to optimize hydraulic fracturing. *Journal of Petrol. Science and Eng.*, 1994, vol. 2, pp. 335-340. DOI: 10.1016/0920-4105(94)90051-5
17. Ruiting Wu. Some Fundamental Mechanisms of Hydraulic Fracturing. School of Civil and Environmental Engineering, Georgia Institute of Technology, 2006.
18. Tan Chaodong, He Jiayuan, Zhou Tong, Liu Jiankang, Song Wenrong. A study on the optimization of fracturing operation parameters based on PCA- BNN. *J. Southwest Pet Univ. (Sci Technol Ed)*, 2020, vol. 42 (6), pp. 56-62. DOI: 10.11885/j.issn.1674-5086.2020.05.12.05
19. Zhou D., He P. Major Factors affecting simultaneous frac results. *SPE Production and Operations Symposium, Proceedings*, 2015, vol. 2015, pp. 532-545. DOI: SPE-173633-MS
20. Zhao H., Zhen Li., Zhu C., Ru Z. Reliability analysis models for hydraulic fracturing. *Journal of Petroleum Science and Engineering*, 2018, vol. 162, pp. 150-157. DOI: 10.1016/j.pet-ol.2017.12.048
21. Gao Haihong, Zhanqing Qu, Mei Zhao. Experimental study on the factors affecting the productivity of fractured horizontal well. *Journal of Southwest Petroleum University: Science & Technology Edition*, 2008, vol. 30 (4), pp. 73-76. DOI: 10.3863/j.issn.1000-2634.2008.04.018
22. Ruzhong T., Qingzhi W., Jian S., Zhanqing Q. Factors affecting productivity of stage fractured horizontal well. *Petroleum Drilling Techniques*, 2010, vol. 38 (2), pp. 80-83. DOI: 10.1007/978-3-642-28807-4_24
23. Lolon E.P., Cipolla C.L., Weijers L., Hesketh R.E., Grigg M.W. Evaluating horizontal well placement and hydraulic fracture spacing conductivity in the Bakken Formation North Dakota. *SPE Annual Technical Conference and Exhibition*. New Orleans, Louisiana, October 2009. DOI: 10.2118/124905-MS
24. Liu Yinghong, Li Zongtian, Zhao Bihua. Optimization of fracturing project for low permeable reservoir with orthogonal and analysis of experiments. *Fault-Block Oil & Gas Field*, 2000, vol. 7 (3), pp. 46-49. DOI: 10.1038/s41598-024-66114-w
25. Ivanov S.A., Rastegaev A.V., Galkin V.I. Analiz rezul'tatov primeneniia GRP (na primere Povkhovskogo mestorozhdeniia nefti) [Analysis of results of applying formation hydraulic fracturing in Povkhovsky oil field]. *Neftepromyslovoe delo*, 2010, no. 7, pp. 54-58.
26. Koltyrin A.N. Opyt primeneniia propantnogo GRP na terrigennom kollektore [Experience of application of proppant hydraulic fracturing of a formation in a Terrigenous reservoir]. *Geologiia geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2016, no. 4, pp. 28-31.
27. Koltyrin A.N. Povyshenie effektivnosti tekhnologii GRP na karbonatnom tipe kollektora [Efficiency enhancement of the technology of a formation hydraulic fracturing in a carbonate-type collector]. *Neftepromyslovoe delo*, 2016, no. 10, pp. 28-30.
28. Koltyrin A.N. Razrabotka metodiki i otsenka effektivnosti rabotosposobnosti veroiatnostno-statisticheskikh modelei dlia prognozirovaniia prirosta debita nefti v skvazhinakh posle provedeniia gidrorazryva plasta [Development of the method and estimation of applicability and efficiency of probability-statistical models for forecasting oil production rate increase in wells after hydraulic fracturing]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2022, no. 4 (364), pp. 49-58. DOI: 10.33285/2413-5011-2022-4(364)-49-58
29. Ivanov S.A. Postroenie statisticheskikh modelei prognoza GRP po geologo-tekhnologicheskim pokazateliam [Development of statistical model of hydraulic fracturing prediction by geological and technological indicators]. *Geologiia geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*. Moscow: VNIIOENG, 2009, no. 10, pp. 4-50.
30. Galkin V.I., Koltyrin A.N., Kazantsev A.S., Kondrat'ev S.A., Zhigalov V.A. Razrabotka statisticheskoi modeli prognoza effektivnosti propantnogo GRP po geologo-tekhnologicheskim pokazateliam dlia vereiskogo karbonatnogo neftegazonosnogo kompleksa [Development of a statistical model aimed at prediction of efficiency of proppant hydraulic fracturing of a formation, based on a reservoir geological-technological parameters, for Vereiskian carbonate oil- and gas-bearing complex]. *Neftepromyslovoe delo*, 2017, no. 3, pp. 48-54.
31. Ivanov S.A., Skachek K.G., Galkin V.I., Rastegaev A.V., Shikhov S.A. Issledovanie vliianiia geologo-tekhnologicheskim pokazatelei na effektivnost' gidrorazryva plasta (na primere Povkhovskogo mestorozhdeniia - plast BV8) [Study of geological and technologocal data impact on efficiency of formation hydraulic fracturing (illustrated by БВ(BV)8 Povkhovsky formation]. *Geologiia geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*. Moscow: VNIIOENG, 2009, no. 10, pp. 42-45.
32. Egorov D.S., Mikhailov N.N. Vliianie geologicheskikh faktorov na dinamiku debitov skvazhin v otlozheniiakh bazhenovskoi svity [Influence of geological factors of wells production rate dynamics in Bazhenov formation deposits]. *Neftepromyslovoe delo*, 2022, no. 10 (646), pp. 5-16. DOI: 10.33285/0207-2351-2022-10(646)-5-16
33. Galkin V.I., Kondrat'ev S.A., Putilov I.S. Razrabotka metodiki otsenki effektivnosti gidrorazryva plasta po kompleksu geologo-tekhnologicheskikh pokazatelei (na primere vizeiskogo terrigennogo neftegazonosnogo kompleksa Kuedinskogo vala neftianykh mestorozhdenii Permskogo kraia) [Development of the methodology for evaluating the effectiveness of a formation hydraulic fracturing on the basis of a set of complex geological-technological parameters (with the example of Visean terrigenous oil and gas complex of Kuedinsky swell of oil fields located in Perm territory)]. *Neftepromyslovoe delo*, 2015, no. 7, pp. 23-26.
34. Galkin V.I., Koltyrin A.N. Razrabotka metodiki prognozirovaniia tekhnologicheskikh pokazatelei raboty skvazhiny posle primeneniia geologo-tekhnicheskikh meropriiatii [Development of a method for forecasting technological indicators of a well operation after application of geological-technical measures]. *Neftepromyslovoe delo*, 2020, no. 7 (619), pp. 18-28. DOI: 10.30713/0207-2351-2020-7(619)-18-28
35. Farkhutdinova M.Kh. Analiz vliianiia geologo-tekhnologicheskikh parametrov skvazhin i protsessa gidravlicheskogo razryva plasta na ego effektivnost' [Analysis of the influence of geological and technological parameters of wells and hydraulic fracturing on its efficiency]. *Neftegazovoe delo*, 2014, no. 3, pp. 33-48.
36. Kochnev A.A., Kozyrev N.D., Kochneva O.E., Galkin S.V. [Razrabotka kompleksnoi metodiki prognoza effektivnosti geologo-tekhnicheskikh meropriiatii na osnove algoritmov mashinnogo obucheniia [Development of a comprehensive methodology for the forecast of effectiveness of geological and technical measures based on machine learning algorithms]. *Georesursy*, 2020, vol. 22, no. 3, pp. 79-86. DOI: 10.18599/grs.2020.3.79-86
37. Alimkhanov R., Samoylova I. Application of Data Mining Tools for Analysis and Prediction of Hydraulic Fracturing Efficiency for the BV8 Reservoir of the Povkh Oil Field (Russian). *SPE Russian Oil and Gas Exploration & Production Technical Conference and Exhibition, 14-16 October 2014*. Moscow, Russia, 2014. SPE-171332-RU. DOI: 10.2118/171332-RU
38. Aryanto A., Kasmungin S., Fathaddin F. Hydraulic fracturing candidate-well selection using artificial intelligence approach. *Journal of Natural Gas Science and Engineering*, 2018, vol. 2, no. 2, pp. 53-59. DOI: 10.33021/jmem.v2i02.322
39. Akmal Aulia, Daein Jeong, Ismail Mohd Saaid, Dina Kania, Noaman A. El-Khatib. A Random Forests-based sensitivity analysis framework for assisted history matching. *Journal of Petroleum Science and Engineering*, 2019, vol. 181, Art.106237. DOI: 10.1016/j.petrol.2019.106237
40. Klemens Katterbauer, Santiago Arango, Shuyu Sun, Ibrahim Hoteit. Multi-data reservoir history matching for enhanced reservoir forecasting and uncertainty quantification. *Journal of Petroleum Science and Engineering*, 2015, vol. 128, pp. 160-176. DOI: 10.1016/j.petrol.2015.02.016
41. Yu T., Xie X., Li L., Wu W. Comparison of Candidate-Well Selection Mathematical Models for Hydraulic Fracturing. *Fuzzy Systems & Operations Research and Management. Springer, Cham*, 2015, vol. 367, pp. 289-299. DOI: 10.1007/978-3-319-19105-8-27
42. Ma X., Liu Z. Predicting the oil field production using the novel discrete GM (1, N) model. *The Journal of Grey System*, 2015, vol. 27, iss. 4, pp. 63-73.
43. Dieng Assan, Khizhniak G.P. Prognoz effektivnosti gidravlicheskogo razryva plasta po geologicheskim pokazateliam [Prediction of a hydraulic fracturing efficiency by geological indicators]. *Neftepromyslovoe delo*, 2023, no. 1 (649), pp. 25-28. DOI: 10.33285/0207-2351-2023-1(649)-25-28
44. Dieng A., Khizhniak G.P. Analysis of the Efficiency of Hydraulic Fracturing on the Example of the Oil Field in the Perm Region]. *Innovatsionnye issledovaniia: opyt, problemy vnedreniia rezul'tatov i puti resheniia: sbornik statei Natsional'noi (Vserossiiskoi) nauchno-prakticheskoi konferentsii s mezhdunarodnym uchastiem (22 oktiabria 2022, Kirov)*. Ufa: OMEGASCIENCE, 2022, pp. 240-244 (elektronnaia versiia - na saite https://os-russia.com).
45. Dieng A., Khizhniak G.P. Ispol'zovanie geologicheskikh parametrov produktivnykh otlozhenii dlia prognoza effektivnosti gidrorazryva [Using geological parameters of productive deposits to predict the efficiency of hydraulic fracturing]. *Problemy razrabotki mestorozhdenii uglevodorodnykh i rudnykh poleznykh iskopaemykh. Materialy XV Mezhdunarodnoi nauchno-tekhnicheskoi konferentsii, Perm', 18-21 October 2022*. Perm' - Ekaterinburg, 2022, pp. 207-212.

Билиографический список

1. Поплыгин, В.В. Повышение эффективности разработки месторождений Пермского края / В.В. Поплыгин, И.С. Поплыгина // Проблемы разработки месторождений углеводородов и рудных полезных ископаемых. – 2014. – № 1. – С. 283–285.
2. Галкин, В.И. Обоснование прогнозной величины прироста дебита нефти после применения ГТМ с помощью статистического метода / В.И. Галкин, А.Н. Колтырин // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2023. – Т. 334, № 2. – С. 81–86. DOI: 10.18799/24131830/2023/2/3857

3. Разработка комплексной методики прогноза эффективности геолого-технических мероприятий на основе алгоритмов машинного обучения / А.А. Кочнев, Н.Д. Козырев, О.Е. Кочнева, С.В. Галкин // Георесурсы. –2020. –Т. 22. no 3. – С. 79–86. DOI: 10.18599/grs.2020.3.79-86
4. Yanfang, W. Refracture candidate selection using hybrid simulation with neural network and data analysis techniques / W. Yanfang, S. Salehi // Journal of Petroleum Science and Engineering. – 2014. – Vol. 123. – P. 138–146. DOI: 10.1016/j.petrol.2014.07.036
5. Miel, H. Modeling and monitoring the development of an oil field under conditions of mass hydraulic fracturing / H. Miel, A.O.S. Hameed, K.F. Hussein // Trends in Sciences. – 2022. – Vol. 19.– № 8. – P. 3436–3436. DOI: 10.48048/tis.2022.3436
6. Кочнев, А.А. Анализ влияния геолого-технологических показателей на эффективность технологии радиального бурения на примере эксплуатационных объектов Пермского края / А.А. Кочнев, В.И. Зотиков, С.В. Галкин // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2018. – Т. 329, № 12. – С. 20–29. DOI: 10.18799/24131830/2018/12/16
7. Распопов, А.В. Анализ результатов применения методов интенсификации на карбонатных коллекторах месторождений Пермского края / А.В. Распопов, Д.В. Новокрещенных // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое игорное дело. – 2014. – Т. 13, № 10. – С. 73–82. DOI: 10.15593/2224-9923/2014.10.7
8. Вотинов, А.С. Опыт проведения технологии пропантного гидроразрыва пласта при разработке карбонатных залежей нефти Пермского края / А.С. Вотинов // Магистерский журнал. – 2019. – № 2. – С. 26–32.
9. Кочнев, А.А. Моделирование гидромониторного бурения путем прогнозирования направления радиального канала с учетом напряженного состояния массива горных пород / А.А. Кочнев, С.В. Галкин // 28-я Российская конференция по математическому моделированию в естественных науках: материалы конференции AIP 2216, 080002-1-080002-6. DOI: 10.1063/5.0004270
10. Numerical Study on the Hydraulic Fracturing Pattern in the Hard Roof in Response to Mining-Induced Stress. / J. Chen, Z. Qu, L. Zhou [et al.] // Minerals. – 2023. – Vol. 13, № 3. – P. 308. DOI: 10.3390/min13030308
11. Evaluation of hydraulic fracturing of horizontal wells in tight reservoirs based on the deep neural network with physical constraints / Qu Hong-Yan, Zhang Jian-Long, Zhou Fu-Jian [et al.]. – Petroleum Science, 2023. DOI: 10.1016/j.petsci.2023.03.015
12. Understanding and predicting proppant bedload transport in hydraulic fracture via numerical simulation / Wang Duo, LI Sanbai, Zhang Dongxiao [et al.] // Powder Technology. – 2023. – P. 118232. DOI: 10.1016/j.powtec.2023.118232
13. Alotaibi, N. Optimizing the Hydraulic Fracturing Fluid Systems Using the Completion and Production Data in Bakken Shale / N. Alotaibi, Serkan Dursun // Middle East Oil, Gas and Geosciences Show. – OnePetro, 2023. DOI: 10.2118/213360-MS
14. Gai, Jian. Prediction method for hydraulic fracturing effect of oil production well based on automatic machine learning technology / Jian Gai // Editorial Department of Petroleum Geology and Recovery Efficiency. – 2023. – Vol. 30, no 1, – P. 161–170. DOI: 10.13673/j.cnki.cn37-1359/te.202203015
15. Hydraulic fracturing as unconventional production potential for the organic-rich carbonate reservoir rocks in the Abu El Gharadig Field, north western Desert (Egypt): Evidence from combined organic geochemical, petrophysical and bulk kinetics modeling results / Hakimi Mohammed Hail, Hamed Tamer E., Lotfy Naira M. [et al.] // Fuel. – 2023. – Vol. 334. – P. 126606. DOI: 10.1016/j.fuel.2022.126606
16. Appah, D. Application of the theory of diffuse set to optimize hydraulic fracturing / D. Appah // Journal of Petrol. Science and Eng. – 1994. – Vol. 2. – P. 335–340. DOI: 10.1016/0920-4105(94)90051-5
17. Ruiting, Wu. Some Fundamental Mechanisms of Hydraulic Fracturing / Wu. Ruiting // School of Civil and Environmental Engineering, Georgia Institute of Technology. – 2006.
18. A study on the optimization of fracturing operation parameters based on PCA- BNN / Tan Chaodong, He Jiayuan, Zhou Tong, Liu Jiankang, Song Wenrong // J. Southwest Pet Univ. (Sci Technol Ed). – 2020. – Vol. 42(6). –P. 56–62. DOI: 10.11885/j.issn.1674-5086.2020.05.12.05
19. Zhou, D. Major Factors affecting simultaneous frac results / D. Zhou, P. He // SPE Production and Operations Symposium, Proceedings. – 2015. – Vol. 2015. – P. 532–545. DOI: SPE-173633-MS
20. Reliability analysis models for hydraulic fracturing / H. Zhao, Li. Zhen, C. Zhu, Z. Ru // Journal of Petroleum Science and Engineering. – 2018. – Vol. 162. – P. 150–157. DOI: 10.1016/j.pet-ol.2017.12.048
21. Gao, Haihong. Experimental study on the factors affecting the productivity of fractured horizontal well / Haihong Gao, Zhanqing Qu, Mei Zhao // Journal of Southwest Petroleum University: Science & Technology Edition. – 2008. – Vol. 30(4). – P. 73–76. DOI: 10.3863/j.issn.1000-2634.2008.04.018
22. Factors affecting productivity of stage fractured horizontal well / T. Ruzhong, W. Qingzhi, S. Jian, Q. Zhanqing // Petroleum Drilling Techniques. – 2010. – Vol. 38(2). – P. 80–83. DOI: 10.1007/978-3-642-28807-4_24
23. Evaluating horizontal well placement and hydraulic fracture spacing conductivity in the Bakken Formation North Dakota / E.P. Lolon, C.L. Cipolla, L. Weijers, R.E. Hesketh, M.W. Grigg // SPE Annual Technical Conference and Exhibition. – New Orleans, Louisiana, October 2009. DOI: 10.2118/124905-MS
24. Liu, Yinghong. Optimization of fracturing project for low permeable reservoir with orthogonal and analysis of experiments / Yinghong Liu, Zongtian Li, Bihua Zhao // Fault-Block Oil & Gas Field. – 2000. – Vol. 7(3). – P. 46–49. DOI: 10.1038/s41598-024-66114-w
25. Иванов, С.А. Анализ результатов применения ГРП (на примере Повховского месторождения нефти) / С.А. Иванов, А.В. Растегаев, В.И. Галкин // Нефтепромысловое дело. – 2010. – № 7. – С. 54–58.
26. Колтырин, А.Н. Опыт применения пропантного ГРП на терригенном коллекторе / А.Н. Колтырин // Геология геофизика и разработка нефтяных и газовых месторождений. – 2016. – № 4. – С. 28–31.
27. Колтырин, А.Н. Повышение эффективности технологии ГРП на карбонатном типе коллектора / А.Н. Колтырин // Нефтепромысловое дело. – 2016. – № 10. – С. 28–30.
28. Колтырин, А.Н. Разработка методики и оценка эффективности работоспособности вероятностно-статистических моделей для прогнозирования прироста дебита нефти в скважинах после проведения гидроразрыва пласта / А.Н. Колтырин // Геология, геофизика и разработка нефтяных и газовых месторождений. – 2022. – №4 (364). – С. 49–58. DOI: 10.33285/2413-5011-2022-4(364)-49-58
29. Иванов, С.А. Построение статистических моделей прогноза ГРП по геолого-технологическим показателям / С.А. Иванов // Геология геофизика и разработка нефтяных и газовых месторождений. – М: ОАО «ВНИИОЭНГ», 2009. – № 10. – С. 46–50.
30. Разработка статистической модели прогноза эффективности пропантного ГРП по геолого-технологическим показателям для верейского карбонатного нефтегазоносного комплекса / В.И. Галкин, А.Н. Колтырин, А.С. Казанцев, С.А. Кондратьев, В.А. Жигалов // Нефтепромысловое дело, 2017. – № 3. – С. 48–54.
31. Исследование влияния геолого-технологическим показателей на эффективность гидроразрыва пласта (на примере Повховского месторождения – пласт БВ8) / С.А. Иванов, К.Г. Скачек, В.И. Галкин, А.В. Растегаев, С.А. Шихов // Геология геофизика и разработка нефтяных и газовых месторождений. – М: ОАО «ВНИИОЭНГ», 2009. – № 10. – С. 42–45.
32. Егоров, Д.С. Влияние геологических факторов на динамику дебитов скважин в отложениях баженовской свиты / Д.С. Егоров, Н.Н. Михайлов // Нефтепромысловое дело. – 2022. – № 10(646). – С. 5–16. DOI: 10.33285/0207-2351-2022-10(646)-5-16
33. Галкин, В.И. Разработка методики оценки эффективности гидроразрыва пласта по комплексу геолого-технологических показателей (на примере визейского терригенного нефтегазоносного комплекса Куединского вала нефтяных месторождений Пермского края) / В.И. Галкин, С.А. Кондратьев, И.С. Путилов // Нефтепромысловое дело. –2015. – № 7. – С. 23–26.
34. Галкин, В.И. Разработка методики прогнозирования технологических показателей работы скважины после применения геолого-технических мероприятий / В.И. Галкин, А.Н. Колтырин // Нефтепромысловое дело. – 2020. – № 7 (619). – С. 18–28. DOI: 10.30713/0207-2351-2020-7(619)-18-28
35. Фархутдинова, М.Х. Анализ влияния геолого-технологических параметров скважин и процесса гидравлического разрыва пласта на его эффективность / М.Х. Фархутдинова // Нефтегазовое дело. – 2014. – № 3. – С. 33–48.
36. Разработка комплексной методики прогноза эффективности геолого-технических мероприятий на основе алгоритмов машинного обучения / А.А. Кочнев, Н.Д. Козырев, О.Е. Кочнева, С.В. Галкин // Георесурсы. – 2020. – Т. 22, № 3. – С. 79–86. DOI: 10.18599/grs.2020.3.79-86
37. Alimkhanov, R. Application of Data Mining Tools for Analysis and Prediction of Hydraulic Fracturing Efficiency for the BV8 Reservoir of the Povkh Oil Field (Russian) / R. Alimkhanov, I. Samoylova // SPE Russian Oil and Gas Exploration & Production Technical Conference and Exhibition, 14-16 October 2014. Moscow, Russia, 2014. SPE-171332-RU. DOI: 10.2118/171332-RU
38. Aryanto, A. Hydraulic fracturing candidate-well selection using artificial intelligence approach / A. Aryanto, S. Kasmungin, F. Fathaddin // Journal of Natural Gas Science and Engineering. 2018. – Vol. 2. – № 2. – P. 53-59. DOI: 10.33021/jmem.v2i02.322
39. A Random Forests-based sensitivity analysis framework for assisted history matching / Akmal Aulia, Daein Jeong, Ismail Mohd Saaid, Dina Kania, Noaman A. El-Khatib // Journal of Petroleum Science and Engineering. – 2019. – Vol. 181. – Art.106237. DOI: 10.1016/j.petrol.2019.106237
40. Multi-data reservoir history matching for enhanced reservoir forecasting and uncertainty quantification / Klemens Katterbauer, Santiago Arango, Shuyu Sun, Ibrahim Hoteit // Journal of Petroleum Science and Engineering. – 2015. – Vol. 128. – P. 160–176. DOI: 10.1016/j.petrol.2015.02.016
41. Comparison of Candidate-Well Selection Mathematical Models for Hydraulic Fracturing / T. Yu, X. Xie, L. Li, W. Wu // Fuzzy Systems & Operations Research and Management. Springer, Cham, – 2015. – Vol. 367. – P. 289–299. DOI: 10.1007/978-3-319-19105-8-27
42. Ma, X. Predicting the oil field production using the novel discrete GM (1, N) model / X. Ma, Z. Liu // The Journal of Grey System. – 2015. – Vol. 27. Iss. 4. – P. 63-73.
43. Диенг, Ассан. Прогноз эффективности гидравлического разрыва пласта по геологическим показателям / Ассан Диенг, Г.П. Хижняк // Нефтепромысловое дело. – 2023. – № 1(649). – С. 25–28. DOI: 10.33285/0207-2351-2023-1(649)-25-28
44. Dieng, A. Analysis of the Efficiency of Hydraulic Fracturing on the Example of the Oil Field in the Perm Region / A. Dieng, G.P. Khizhniak // Инновационные исследования: опыт, проблемы внедрения результатов и пути решения: сборник статей Национальной (Всероссийской) научно-практической конференции с международным участием (22 октября 2022 г, г. Киров). – Уфа: OMEGASCIENCE, 2022. – С. 240–244 (электронная версия – на сайте https: // os - russia.com)
45. Диенг, А. Использование геологических параметров продуктивных отложений для прогноза эффективности гидроразрыва / А. Диенг, Г.П. Хижняк // Проблемы разработки месторождений углеводородных и рудных полезных ископаемых: материалы XV Международной науч.-техн. конф. (г. Пермь, 18–21 октября 2022 г.). – Пермь – Екатеринбург, 2022. – С. 207–212.

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