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STUDY OF OIL RECOVERY FROM RESERVOIRS OF DIFFERENT VOID TYPES WITH USE OF MULTIDIMENSIONAL STATISTICAL ANALYSIS

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ИССЛЕДОВАНИЕ ПРОЦЕССА НЕФТЕИЗВЛЕЧЕНИЯ В КОЛЛЕКТОРАХ РАЗЛИЧНОГО ТИПА ПУСТОТНОСТИ С ИСПОЛЬЗОВАНИЕМ МНОГОМЕРНОГО СТАТИСТИЧЕСКОГО АНАЛИЗА

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complex accumulation, naturally fractured reservoirs, pore type reservoir, oil production law, components of development scheme, well interaction analysis, correlation, correlation fields, multidimensional regression analysis, mathematical models, factors forming oil rate in different reservoirs, linear discriminant functions, authenticity of reservoir detection, oil rate formation scenarios, efficiency of pressure maintenance system

Oil recovery laws that take into account distribution of reservoirs with different void types within the same accumulation. Carbonate field data of development of Tournaisian-Famennian oil accumulation was used. For comparison purposes data of development of the field with similar oil properties but reservoir of clastic grain rock and pore type were used. One injector and neighbor producers were used as components of applied production scheme. The type of reservoir within one development object was determined by several studies including pressure build-up curve processed by Warren-Root method. At the first stage correlation coefficients between injection and production of neighbor well were calculated. Calculation was done for different time and with assumption, according to which correlation coefficient is a quantitative measure of interactions between two wells. It is determined that use of correlation coefficient for pore reservoirs is significantly differ to the character of its behavior for fracture reservoir type. Multidimensional mathematical models that characterize flooding and allow determining producer's rate were obtained with considered void type. Linear discriminant functions are built with considered void type of reservoir. Analysis of those functions determined that replacement of oil by water in clastic and carbonates porous rocks and carbonate naturally fractured reservoirs follow different scenarios.

Ключевые слова:
сложнопостроенная залежь, коллектор трещинного типа, коллектор порового типа, закономерности нефтеизвлечения, элемент системы разработки, оценка взаимодействия между скважинами, корреляция, корреляционные поля, многомерный регрессионный анализ, математические модели, факторы, формирующие дебит нефти в различных коллекторах, линейные дискриминантные функции, достоверность распознавания коллекторов, сценарии формирования дебита нефти, эффективность системы поддержания пластового давления.

Изучены вопросы установления закономерностей осуществления процессов нефтеизвлечения, учитывающих распространение в пределах одной залежи коллекторов с различными видами пустотности. С этой целью привлечены промысловые материалы по разработке турне-фаменской карбонатной залежи нефтяного месторождения, а также для сравнения – данные о разработке залежи нефти со схожими свойствами нефти, но с терригенным гранулярным коллектором порового типа. Для рассмотрения в статье приняты элементы реализованных систем разработки, представляющих собой одну нагнетательную и соседние добывающие скважины. Тип коллектора в пределах элемента разработки принимался по материалам различных исследований, в том числе по кривой восстановления давления, обработанной по методике Уоррена–Рута. На первом этапе решения поставленной задачи рассчитаны значения коэффициентов корреляции между приемистостью нагнетательной скважины и дебитами соседних добывающих для различных моментов времени, при этом расчет производился в предположении, что коэффициент корреляции является численной мерой взаимодействия между двумя скважинами. Установлено, что изменение коэффициента корреляции во времени для поровых коллекторов значительно отличается от характера его же поведения для коллектора трещинного типа. В дальнейшем проведенные исследования позволили получить многомерные математические модели, характеризующие процесс заводнения и позволяющие определять дебиты добывающих скважин, расположенных вблизи очагов нагнетания, с учетом типа пустотности коллектора на рассматриваемом участке залежи. Анализ линейных дискриминантных функций, построенных с учетом типа пустотности коллектора, позволил установить, что процесс вытеснения нефти водой в терригенных поровых, карбонатных поровых и карбонатных трещинных коллекторах происходит по различным сценариям.

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Introduction

A zone of reservoirs of pore and fracture type is a key feature of a number of Tournaisian-Famennian oil formations in Perm region. That was obtained by researches [1, 2]. Features of reservoirs this kind are described in papers [3, 4]. Based on the results of pressure build-up curves processing in accordance with Warren-Root method that is described in papers [5-12] it was determined that zones of fracture reservoirs are directed from south-west to north-east. These zones complicate geological structure of accumulation and development processes. Evaluation of the efficiency of pressure maintenance system and determination of replacement processes of oil by water depending on reservoir void type are on the front burner. Significant volume of field data allows using mathematical statistics in order to overcome this challenge [13].

This paper describes study of mentioned challenge with use of units of field development that represent one injection and neighbor production wells. Each of the units is located in different void type reservoirs. Injector Well 1 is located within carbonate reservoirs of fracture type. Injector Well 2 is located within carbonate reservoirs of pore type. Data on clastic reservoirs of pore type are involved in the study of probability laws of oil replacement processes. An injector Well 3 is located within that reservoir. Oil of clastic and carbonate reservoirs has similar composition and properties.

Mathematical modeling and analysis of interaction between producers and injectors

For all units of field development selected to study following data were obtained: volume of injected water $(V_{\mathrm{H_2O}})$, injectability of injectors (Pr) and oil rates of producers (Q_o).

Correlation links between injected water volume and injectability of injectors are:

Well 1 – $Pr = 23.5 + 0.0293V_{\mathrm{H_2O}}$ at $r = 0.92$;

Well 2 – $Pr = 34.6 + 0.0228V_{\mathrm{H_2O}}$ at $r = 0.87$;

Well 3 – $Pr = 12.8 + 0.0301V_{\mathrm{H_2O}}$ at $r = 0.90$.

That shows $V_{\mathrm{H_2O}}$ and Pr correlate quite well. Accumulated injectability Pr^n is involved into analysis. Table 1 shows models of change of Pr^n with time (t).

Table 1 – Dependency of Pr^n on t

Well	Regression equation	Coefficient R^2
1	$Pr^n = 242.8 - 0.0006t^5 + 0.001t^4 - 0.187t^3 +$ $+ 11.04t^2 - 57.74t$	0.99
2	$Pr^n = -916.1 + 0.005t^3 - 1.884t^2 + 295.4t$	0.99
3	$Pr^n = 16.26 + 0.402t^2 + 84.06t$	0.99

Analysis of dependency data presented in the table 1 show that for Well 1, located in the zone of naturally fractured reservoirs Pr^n changes in accordance with more complicated law, than for Wells 2 and 3 located in pore type reservoirs.

In order to determine influence of injected water on average day oil rates Q_o correlation coefficients r between $V_{\mathrm{H_2O}}$, Pr, Pr^n and Q_o were calculated. It is supposed that based on r values it is possible to evaluate influence of injected in an injector well water on oil rates of producers. At the first stage r was determined for 3-months period from start of injection. Then r was calculated further for 1 month.

Let us have a look on r values change in three producers located in different reservoirs zones. Analysis is performed with use of Q_o data from the producers located nearby.

For Well 1 analysis is done based on 5 neighbor producers which are located in naturally fractured reservoirs. For Well 2 7 neighbor producers located in pore-type reservoir. Analysis of Well 3 is performed based on data of 4 neighbor producers located in pore-type reservoir; rocks are presented by clastic sediments. The space between injectors and producers is varying in the range of 334 to 960 m. Maximum difference in r values during time change is observed at $r(Pr^n - Q_\mathrm{o})$. Thus, typical curves of $r(Pr^n - Q_\mathrm{o})$ change for three producers are look like it is presented on Fig. 1.

Analysis of diagram given in Fig. 1 shows that change of r between Pr^n and Q_o – $r(Pr^n - Q_\mathrm{o})$ for wells of interest are unique. It has to be noted,

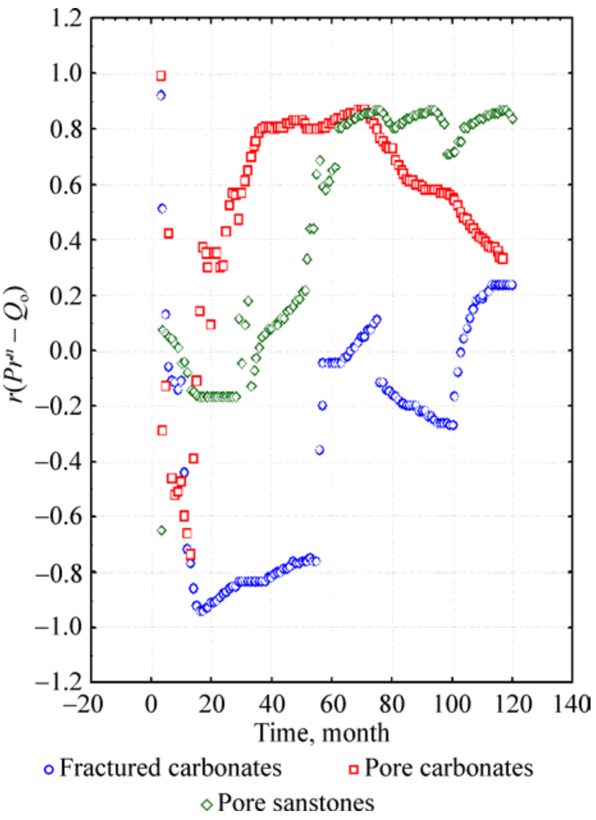


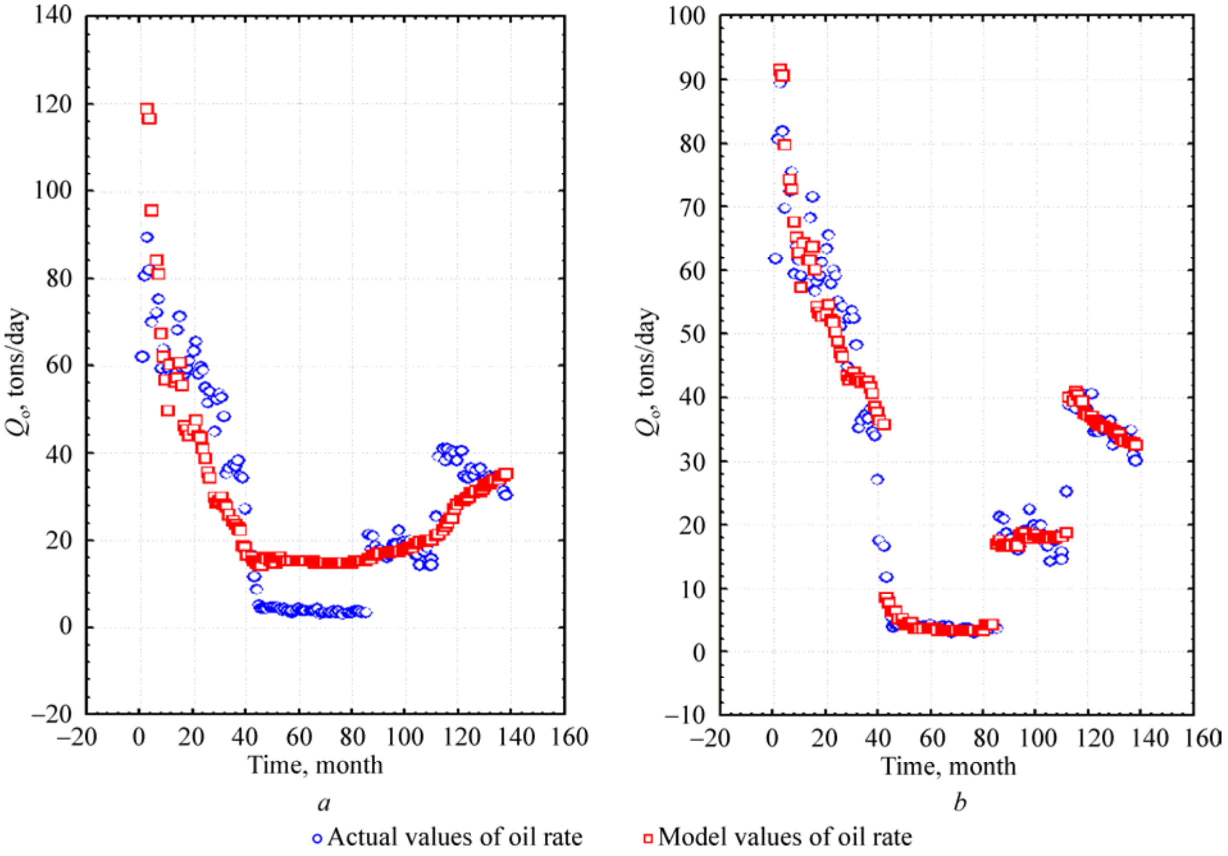
Fig. 1. Change of r coefficient between Pr^n and Q_o in time for producers

differences presented by change curves $r(Pr^n - Q_o)$ in time for pore carbonate and pore clastic reservoirs are significantly smaller than differences presented by curves which characterize pore and naturally fractured reservoirs. The same calculation of r was done between V_{H_2O} and $Q_o - r(Pr - Q_o)$ and between V_{H_2O} and $Pr - Q_o - r(Pr - Q_o)$.

To account complex influence of coefficients r on Q_o multidimensional regression analysis is used. Average current oil rate Q_o is a function of following factors: $r(V_{H_2O} - Pr)$, $r(Pr - Q_o)$, $r(Pr^n - Q_o)$. For instance, multidimensional model of producer, located in naturally fractured reservoir is

$$Q_o^m = -124.337 r(V_{H_2O} - Pr) -$$
$$-1.719 r(Pr - Q_o) + 57.033 r(Pr^n - Q_o) +$$
$$+182.540$$

if $R = 0{,}85$, $p < 0{,}0000$, forecast error is 6,1 tons/day. Values of Q_o^m were calculated by mentioned formula. Graphical comparison of Q_o and Q_o^m in time is presented in Fig. 2, *a*.



a *b*

Fig. 2. Change of Q_o and Q_o^m in time: *a* – multidimensional model; *b* – multidimensional time model

Analysis of Fig. 2, *a* shows there are 4 sections within the graph. First section is in the rage of 0 to 42 months and values Q_o^m correlate well. For the second section if $43 < t < 84$ months then Q_o^m exceeds Q_o. Then Q_o и Q_o^m correlate poor, but in this range there are 2 more subsections. Third section is in the range of 85 to 112 months; fourth is within a range of 113 to 138 months. To account a ratio of Q_o and Q_o^m in the same time frames as in Fig. 2, *a*, multidimensional models are built.

Multidimensional mathematical time modeling and analysis of interaction between producers and injectors

Time multidimensional models for determination of oil rates Q_o^{mt} by an injector, located in naturally fractured reservoir are shown in table 2.

Table 2 shows that formation of model values Q_o^{mt} in time is appeared to be different. That is proved by coefficients *r* and values of absolute terms of regression equation. Note, that in the range of 85–112 months the model is characterized by statistically negligible criteria.

Values of Q_o^m were calculated by 138 values.

Comparison of Q_o and Q_o^m in time is presented on Fig. 2, *b*. Analysis shows Q_o and Q_o^m are equal in general. Note, there is low correlation between Q_o and Q_o^m in time frame of 85–112 months that is quantitatively proved by *r* values, given in the Table 2. Based on calculation results, performed by common and time models for this producer correlation fields between Q_o and Q_o^m, Q_o and Q_o^{mt} are built (Fig. 3).

Correlation fields between values of Q_o^m, calculated by common model and values of Q_o^{mt}, calculated by time models with actual oil rates Q_o, are slightly different in terms of correlation link (Fig. 3). First case: $r = 0.86$, second one: $r = 0.98$.

Authors suggest a hypothesis that value of Q_o^m, calculated by the common data is in charge of oil rated formation due to water injection. Values of Q_o^{mt} are formed by water injection and other techniques (they are not a subject of this article) of reservoir stimulation

Table 2 – Models to calculate Q_o^{mt}

Time frame, month	Coefficients of base / *p*			Absolute term / *p*	*R* / *p*
	$r(V_{\text{H}_2\text{O}} - Pr)$	$r(Pr - Q_\text{o})$	$r(Pr^n - Q_\text{o})$		
0–42	–81.2298 0.021634	6.5303 0.495413	31.6133 0.000000	144.339 0.000026	0.871 0.00000
43–84	–34.4540 0.469092	–0.7467 0.528889	94.1672 0.001472	125.0308 0.069976	0.815 0.0000
85–112	282.870 0.491273	–101.588 0.631770	50.634 0.660733	–199.380 0.567275	0.206 0.78420
113–138	170.859 0.285989	64.840 0.529289	–27.324 0.180338	–137.853 0.357782	0.842 0.00000

The foregoing allows evaluating the influence of injected volume of water on oil rates through the calculation of differential parameter *dQ* by following formula:

$$dQ = (Q_\text{o}^{mt} - Q_\text{o}^m) / Q_\text{o}^{mt}.$$

Change of *dQ* for wells of interest in all the cases is unique.

For Well 1 based on the calculations, performed by common and time models, comparison of Q_o and Q_o^m is performed including 5 neighbor producers (Fig. 4, *a*).

Correlation links between Q_o^m values, calculated by common models and actual oil rated Q_o ($r = 0.69$, $p = 0.000$) is much weak, than

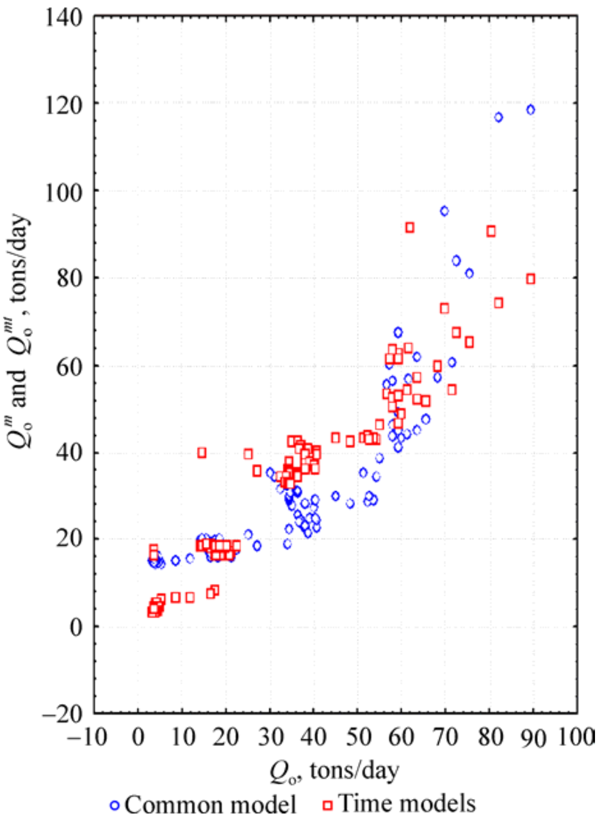


Fig. 3. Correlation fields

between Q_o^{mt}, calculated though differential models, and Q_o ($r = 0.99$, $p = 0.000$). The equation of regression between Q_o и Q_o^m, calculated by common models is

$$Q_o = 9.932 + 0.860\ Q_o^m .$$

Equation of regression between Q_o и Q_o^{mt}, calculated by differential models, is

$$Q_o = –0.001 + 0.999\ Q_o^{mt} .$$

Analysis of correlation coefficients and regression equations shows that second equation describes the process of formation of Q_o values for 5 producers.

In order to compare average values of Q_o^m and Q_o for each well *t*-statistics is used. Calculation results are presented in Table 3 (calculation is done on the injection Well 1).

Analysis of results shows that for average values there is a statistical correlation between Q_o and Q_o^m for wells 1d, 2d, 3d and 4d. For 5d well average value of Q_o and Q_o^m are statistically different. For injection wells 2 and 3 calculation is done in the same way.

Values of Q_o and Q_o^m are compared based on the calculation of common time models for the injection Well 2 using 7 producers (Fig. 4, *b*).

Results on the Fig. 4, *b* prove that correlation in the first case ($r = 0.72$, $p = 0.000$) is slightly less, than in the second one ($r = 0.81$, $p = 0.000$).

In accordance with calculation of common and time models for the injector 3, located in pore-type clastic reservoir comparison of Q_o and Q_o^m is done using 4 producers (Fig. 4. *c*).

First case correlation ($r = 0.69$, $p = 0.000$) is slightly less, than second one ($r = 0.78$, $p = 0.000$). Comparison of correlation fields, presented in Fig. 4 shows that they are different to each other based on analysis of actual and model oil rates, obtained by common and differential models. Strong difference in correlation fields is observed between the values of model and actual oil rates, obtained influence of injector 1 (naturally fractured reservoir). For wells of pore-type reservoirs model and actual values of oil rate are less obvious (wells 2, 3).

Comparison of average values of parameters in different reservoir zones in accordance with *t*-criteria is presented in Table 4.

In the average values of the Table 3 statistical differences is observed only for *dQ* value obtained during the analysis of 3 injectors.

Use of discriminant analysis to study features of flooding of reservoirs with different void type

At the final stage of analysis of influence of $r(V_{H_2O} - Pr)$, $r(Pr - Q_o)$, $r(Pr^n - Q_o)$, Q_o^m, Q_o^{mt}, dQ values, determined for different reservoir types, on oil rates discriminant analysis is used. A method is based on construction of linear discriminant functions (LDF) [14, 15]. During construction of LDF трещинные naturally fractured carbonate reservoirs have higher values of mentioned above

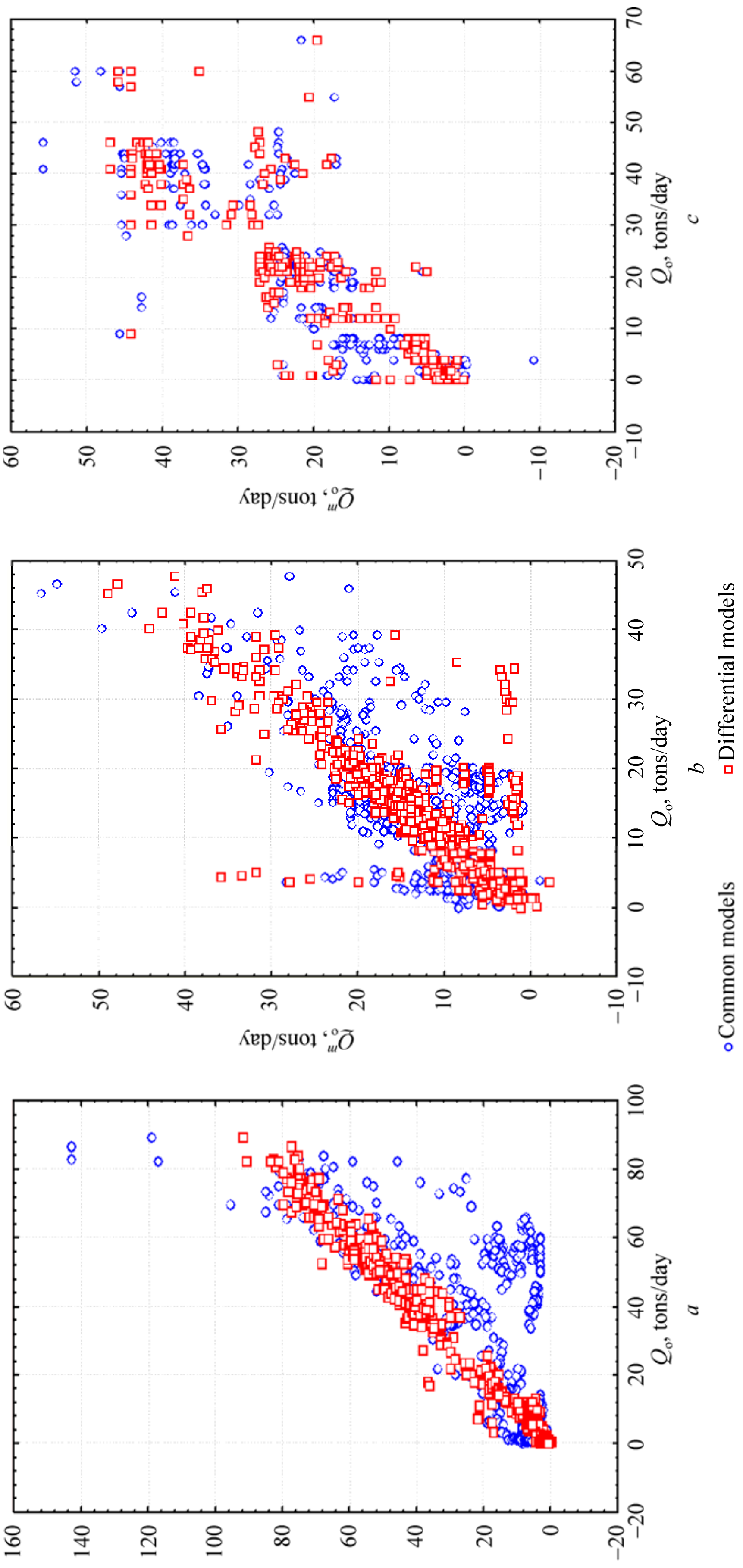


Fig. 4. Correlation fields between Q_o and Q_o^m: *a* – Well 1; *b* – Well 2; *c* – Well 3

Table 3 – Comparison of average values of Q_o and Q_o^m

Neighbor producers	Q_o, tons/day	Q_o^{mc}, tons/day (common model)	Q_o^{mt}, tons/day (time models)	$\frac{t^{mc}}{p}$	$\frac{t^{mt}}{p}$
1d	28.3 ± 22.6	27.6 ± 18.9	28.7 ± 22.6	0.25076 0.802186	0.05076 0.902186
2d	18.3 ± 19.4	17.8 ± 18.3	17.9 ± 18.5	0.21526 0.829729	0.211665 0.833527
3d	2.4 ± 3.2	2.3 ± 1.1	2.3 ± 2.7	0.081919 0.9347771	0.066063 0.947376
4d	19.3 ± 26.5	18.4 ± 23.3	18.4 ± 25.3	0.295935 0.767506	0.285291 0.775638
5d	56.2 ± 11.4	18.4 ± 23.3	56.2 ± 10.9	17.12945 0.000000	0.011606 0.990748

Table 4 – Comparison of average parameter by well

Parameter	Well			$\frac{t}{p}$		
	1	2	3	Well 1–2	Well 1–3	Well 2–3
$r(V_{H_2O} - Pr)$	0.91 ± 0.02	0.91 ± 0.02	0.91 ± 0.02	0.307 0.7586	0.353 0.7237	0.026 0.9791
$r(Pr - Q_o)$	–0.26 ± 0.24	–0.09 ± 0.17	–0.29 ± 0.30	–6.171 0.0000	1.014 0.3109	6.411 0.0000
$r(Pr^n - Q_o)$	–0.70 ± 0.38	–0.67 ± 0.40	–0.57 ± 0.41	–0.705 0.4809	–2.918 0.0037	–1.986 0.0479
Q_o^m, tons/day	28.3 ± 19.4	14.4 ± 21.3	5.4 ± 6.8	5.043 0.00000	6.140 0.00000	1.005 0.3156
Q_o^{mt}, tons/day	28.1 ± 21.5	16.3 ±18.9	5.6 ± 23.1	4.576 0,00000	5.576 0.00000	0.877 0.3810
dQ	–0.79 ± 1.45	–0.39 ± 0.71	–2.197 ± 0.81	–2.6828 0.0077	–4.193 0.00000	5.124 0.0000

parameters that are calculated by models with closest producers. Here, relationship between them and injector 1 is evaluated. Pore carbonate reservoirs obtained from closest producers are used in the model. The subject of study is influence of injector 2 is analysed. Pore reservoirs of sandstones represent modeling data, obtained by 4 producers, located nearby injector 3.

Based on these data following LDF were constructed:

$$Z_1 = 12.1046\,r(V_{H_2O} - Pr) - 0.03597r(Pr - Q_o) - $$
$$- 0.23894r(Pr^n - Q_o) - 0.00209\;Q_o^m + $$
$$+ 0.01268\;Q_o^{mt} - 0.06982dQ - 8.55129$$

if $R = 0.970$, $\chi^2 = 6726{,}37$, $p = 0.000000$;

$$Z_2 = 0.856605\,r(V_{H_2O} - Pr) + 2.406087r(Pr - Q_o) + $$
$$+ 1.270443r(Pr^n - Q_o) + 0.029147\;Q_o^m - $$
$$- 0.069647\;Q_o^{mt} + 0.29827dQ + 0.686364$$

if $R = 0.718$, $\chi^2 = 1366.184$, $p = 0.000000$.

Based on these functions Z_1 and Z_2 (presented in Fig. 5) were calculated.

Fig. 5 shows that values of Z_1 and Z_2 are distinguished quite well within reservoir groups that are studied. Average value of Z_1 for naturally fractured reservoirs equals to +3.034, for pore carbonate reservoirs equals to +2.156, for pore sandstones equals to –6.338. Average value of Z_2 for naturally fractures reservoirs equals to –1.318, for pore carbonate reservoirs equals to –1.133, for pore sandstones equals to –0,148. Authenticity of reservoir

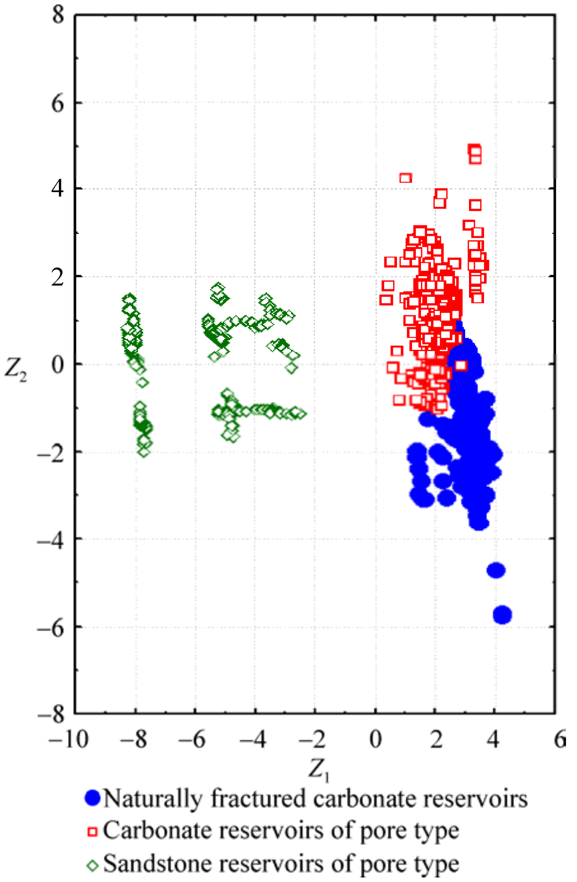


Fig. 5. Distribution of Z_1 and Z_2 values
for different void type reservoirs

identification for naturally fractures carbonates is 83.5%, pore type carbonates – 96.4% and pore sandstones – 100.0%. This shows that influence of injectors 1-3 on producer’s oil rate is characterized by different values of criteria, chosen for analysis. Thus, it can be stated that water injection and oil replacement for studied reservoirs form different scenarios of oil rate. Therefore, in the analysis of pressure maintenance system efficiency for different reservoirs it has to be taken into account.

Conclusion

1. In presence of reservoirs of both pore and fracture types within the same accumulation replacement of oil by water has to be studied differentially for each accumulation zone.
2. To overcome challenges of Tournaisian-Famennian accumulation development multidimensional mathematical models are obtained. Models characterize flooding processes and allow to evaluate oil rate of producers, located nearby injection heart with considered void type of reservoir zone.
3. Analysis of linear discriminant functions, built with considered reservoir void type, allowed determining that oil rate and replacement of oil by water in porous clastic, porous carbonate and naturally fractured carbonate reservoirs are different for each scenario.

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