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Study of Geological and Production Characteristics Effect of the Tourneisian Formation on Well Production Water Cut

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Исследование влияния геолого-промысловых характеристик Турнейского пласта на обводненность продукции скважин

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carbonate reservoir, complex reservoir, core, fracturing, flooding, advanced watering, permeability, porosity, hydrodynamic studies, Warren-Root method, multivariate regression analysis, probabilistic-statistical model, differentiated model, correlation, linear discriminant analysis.

When performing research, a main indicators analysis for development of the Perm region field Tournaisian reservoir was made. It was established that the development object under consideration hads a high heterogeneity and fracturing, which was determined by interpreting the data of hydrodynamic studies. Wells of the central part of the main uplift with high values of water cut were used for the analysis. The study considered the main geological characteristics of the reservoir: porosity, permeability, oil saturation, net-to-gross ratio and reservoir thickness; technological indicators of development: oil, liquid rates and depression, as well as fracture parameters: openness, fracture permeability and proportion of fractured reservoir, calculated using the Warren-Root method. With the help of statistical methods, the relationships between the reservoir characteristics and the main development parameters were studied. In order to determine the parameters that had the maximum effect on the process of watering, regression equations were constructed, the analysis of which made it possible to establish that, depending on the value of watering, there were two groups of indicators that formed it. The obtained division was confirmed by comparing the average values of all indicators using Student's t-test and constructing a linear discriminant function. This made it possible to substantiate the need to build three multidimensional models. The first model was built for all studied wells, the second and third models - according to well data, depending on the degree of their water cut. As a result, the main parameters that affect the water cut index in each of the models were determined, in particular, the role of formation fracturing was determined. By comparing the actual and predicted water cut values, it was determined that the best forecast results were obtained using differentiated models.

Ключевые слова:
карбонатный коллектор, сложнопостроенная залежь, керн, трещиноватость, заводнение, опережающее обводнение, проницаемость, пористость, гидродинамические исследования, метод Уоррена – Рута, многомерный регрессионный анализ, вероятностно-статистическая модель, дифференцированная модель, корреляция, линейный дискриминантный анализ.

При выполнении исследований произведен анализ основных показателей разработки турнейского пласта месторождения Пермского края. Установлено, что рассматриваемый объект разработки имеет высокую неоднородность и трещиноватость, что определено путем интерпретации данных гидродинамических исследований. Для анализа были использованы скважины центральной части основного поднятия с высокими значениями показателя обводненности. В рамках исследования рассматривались основные геологические характеристики пласта: пористость, проницаемость, нефтенасыщенность, песчанистость и мощность пласта; технологические показатели разработки: дебиты нефти, жидкости и депрессия, а также параметры трещиноватости: раскрытость, проницаемость трещин и доля трещиноватого коллектора, вычисленные с помощью метода Уоррена – Рута. При помощи статистических методов были изучены зависимости между характеристиками пласта и основными параметрами разработки. С целью определения параметров, максимально влияющих на процесс обводнения, были построены уравнения регрессии, выполненный анализ которых позволил установить, что в зависимости от значения обводненности, наблюдаются две группы показателей, формирующих ее. Полученное разделение было подтверждено путем сравнения средних значений всех показателей с помощью *t*-критерия Стьюдента и построением линейной дискриминантной функции. Это позволило обосновать необходимость построения трех многомерных моделей. Первая модель построена по всем изучаемым скважинам, вторая и третья модели – по данным скважин в зависимости от степени их обводненности. В результате были определены основные параметры, влияющие на показатель обводненности в каждой из моделей, в частности определена роль трещиноватости пласта. Путем сравнения фактических и прогнозных значений обводненности было определено, что лучшие результаты прогноза получены при использовании дифференцированных моделей.

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Introduction

Water cut is the most important parameter for analysing oil field development. Often during the development of carbonate reservoirs rapid water breakthrough to the bottomholes of production wells can be observed [1–4]. It is due to the complex structure of the reservoir, in particular, the presence of fractures in the formation. Such reservoirs as a rule belong to fractured-porous type reservoirs, which are characterised by low values of rock slab permeability compared to fracture permeability, fracture porosity and fluid exchange between slabs and fracture systems.

The development of Perm region fields also faces such problems, as their carbonate deposits have a complex structure and heterogeneous lithological-facial composition [5–10]. One of the examples is the Tournaisian reservoir of the studied field.

General characteristics of the research object

To analyse the water cut ratio and construct the probabilistic-statistical models, the Tournaisian carbonate reservoir of Perm region field was selected. Exploitation of the reservoir started in September 1978. Intensive drilling and new wells commissioning took place in 1979–1982 and was completed in 1988. The initial flow rate of new wells was 0.7–6.0 t/d of water-free oil. Water cut increase has been observed after injection since 1983, and from 2007 to 2015, after that the percentage of water cut in production increased from 37 % to 72.6 % in 2016. At the same time, high water cut is currently the main reason for production-injection well conversion, and a set of measures aimed at restoring and levelling the injectivity profile is being carried out at the injection well [11–14].

The Tournaisian object has a complex geological structure: high number of permeable intervals in the section, complex mineralogical composition, macro- and micro heterogeneity, and high oil viscosity is also complicating factors. Analysis of core samples showed that the formation is dominated by interformal leach type pores and interformal channels. In reservoirs with slightly degraded reservoir properties, along with interformal pores there are sedimentary intraformal pores, and microfracturing was not found in the samples. However, large fractures are rather difficult to determine from the core samples, it is primarily due to core fracturing and the quality of the samples themselves (drilling fractures, transportation rules violation, etc.) [15–17]. It should also be noted that the data obtained characterises the initial state of the formation, often not developed [18–20]. An indirect factor of fractures presence can serve not only as a high rate of well production water cut, but also the results of hydrodynamic studies: permeability is higher than that determined from the core and petrophysical dependences.

Different methods of interpreting the pressure recovery curves were used to determine a number of parameters: product and tangent methods. To determine the fracture characteristics from the graphs of level recovery curves (LRC) and pressure recovery curves (PRC) were calculated with the Warren-Root method [21–29]. Using the given technique, formation fracturing, fracture opening and permeability were determined. As a result, a fracturing diagram was constructed using the obtained data to determine the distribution of the fractured reservoir over the area (Fig. 1).

The scheme analysis showed that high water cut values are usually observed in zones of increased fracturing. Therefore, 15 wells of the Tournaisian reservoir, located in the central and northern parts of the main uplift shown in Fig. 1, were selected for research, for which PRC was analysed and fracturing characteristics were calculated. The wells were selected according to high rates of well water cut at operation and high water cut rates ranging from 57.6 % to 99.4 %.

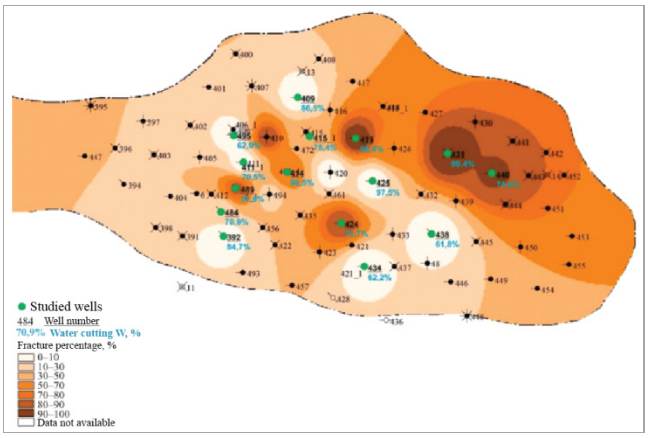

Fig. 1. Schematic of the fractured reservoir at object T

Table 1

Main statistical characteristics of the parameters

Value	Mean ± Degree of deviation Minimum - Maximum	Value	Mean ± Degree of deviation Minimum - Maximum
W, %	78.237 ± 14.881 57.650 – 99.390	K_{perm}, μm²	148.733 ± 231.335 5.911 – 967.811
Q_{oil}, m³/d	3.358 ± 3.052 0.270 – 11.970	$H_{eff.sat}$, m	12.166 ± 2.432 7.900 – 16.000
Q_{liq}, m³/d	19.658 ± 11.610 6.530 – 44.330	dP, MPa	4.284 ± 3.192 0.560 – 11.490
K_{sand}, unit fraction	0.552 ± 0.076 0.440 – 0.675	b_{fr}, μm	0.398 ± 0.417 0.000 – 0.988
K_{sat}, unit fraction	83.118 ± 5.613 75.269 – 91.392	ω_{fr}, unit fraction	75.490 ± 98.253 0.000 – 259.135
K_{sat}, unit fraction	14.910 ± 1.807 10.911 – 17.313	$K_{perm.fr}$, μm²	7.290 ± 7.362 0.000 – 27.910

Analysis of the geological factors and development parameters effect on well water cut

The dynamics of water cut depends not only on time and stage of development, but also on reservoir properties [30, 31]. Therefore, various reservoir characteristics as geological data and development parameters are used for analysis in this paper:

1. Geological parameter:
– net-to-gross ratio (according to well log interpretation results) (K_{sand}, unit fraction);
– oil saturation coefficient (according to well log interpretation results) (K_{sat}, unit fraction);
– porosity coefficient (according to well log interpretation results) (K_p, unit fraction);
– permeability coefficient (according to well log interpretation results) (K_{perm}, μm²);
– effective oil saturated thickness (according to well log interpretation results) ($H_{eff.sat}$, m).
2. Fracture parameter:
– fracture opening (b_{fr}, μm);
– fracture ratio (ω_{fr}, unit fraction);
– fracture permeability coefficient ($K_{perm.fr}$, μm²).
3. Development parameter:
– water cut (W, %);
– liquid flow rate (Q_{liq}, t/d);
– oil flow rate (Q_{oil}, m³/d);
– depression (calculated as the difference between the reservoir pressure on PRC and bottomhole pressure) (dP, MPa).

To carry out the assessment of the data used in the paper, their statistical parameters were calculated, shown in Table 1.

Table 2

Correlation matrix of geological and physical parameters and development parameters

Parameter	W	Q_{oil}	Q_{liq}	K_{sand}	K_{sat}	K_p	K_{perm}	$N_{eff.sat}$	dP	b_{fr}	ω_{fr}	$K_{perm.fr}$
W	1	–0.350*	0.433*	0.144	–0.313*	–0.447*	–0.461*	0.121	–0.418*	0.101	0.156	0.408*
Q_{liq}		1	0.651*	–0.291*	0.153	0.201*	0.135	–0.119	0.378*	–0.021	0.249*	0.091
Q_{oil}			1	–0.250*	–0.055	–0.159	–0.167	–0.088	0.103	0.073	0.292*	0.404*
K_{sand}				1	–0.636*	–0.283*	–0.428*	0.650*	0.005	–0.061	0.482*	–0.047
K_{sat}					1	0.703*	0.503*	–0.696*	–0.002	0.213*	–0.426*	–0.157
K_p						1	0.536*	–0.211*	0.059	0.333*	0.015	–0.049
K_{perm}							1	–0.209*	–0.039	0.464*	–0.156	–0.258*
$H_{eff.sat}$								1	–0.094	0.237*	0.558*	0.024
dP									1	–0.098	–0.419*	–0.327*
b_{fr}										1	0.042	–0.152
ω_{fr}											1	0.398*
$K_{perm.fr}$												1

N o t e : * – statistically significant correlation ($p < 0.05$).

Table 3

Characteristics of multidimensional equations

N	W	Free term	Q_{oil}	Q_{liq}	K_{sand}	K_{sat}	K_p	K_{perm}	$H_{eff.sat}$	DP	b_{fr}	ω_{fr}	$K_{perm.fr}$	R^2
3	58–62.1	61.970*	–	–	–	–	–	–	–	–	–5.218*	–	–	0.995
4	58–63.0	62.290*	–	–	–	–	–	–	–	–	–5.605*	–	–	0.960
5	58–70.5	68.615	–	–	–11.182	–	–	–0.007	–	–	–	0.031	0.199	1
6	58–70.9	66.897	–	–	–1.775	–	–	–0.007	–0.189	–	–	0.047	–0.283	1
7	58–72.7	76.432	–11.207	3.476	–	–	0.289	–	–	–1.463	–	–0.039	–	0.999
8	58–74.6	60.179	–	–	–4.182	–0.001	0.419	–0.018	–	0.028	11.134	0.025	–	1
9	58–75.4	–8.706	0.066	–	–	0.709	–0.182	–0.018	1.384	–	7.916	0.019	0.157	1
10	58–84.7	–69.38	–	–0.020	–5.836	1.196	0.078	–0.017	2.718	0.329	4.729	–	0.872	1
11	58–86.5	61.246*	–5.294*	1.630*	–	–	0.617*	–0.008*	–	–0.445*	3.794*	0.007*	–0.170*	0.999
12	58–97.5	65.414*	–5.927*	1.752*	–	–	0.540	–0.007*	–0.303	–0.248	4.315*	0.017	–0.217*	0.999
13	58–98.5	60.131*	–3.073*	1.507*	60.612	–0.686	2.589	–0.005	–	–2.007*	–	–0.074*	–	0.989
14	58–99.0	72.261*	–4.071*	1.245*	–	–	–	–0.007	–	–0.488	–	–	–	0.964
15	58–99.4	76.479*	–2.998*	0.844*	–	–	–	–0.011	–	–0.715	–	–	–	0.884

N o t e : * – statistically significant parameter.

Table 4

Comparison of mean values using Student's t-test

Parameter	Mean – W > 84,7 %	Mean – W < 84,7 %	t	p
W	69.326*	96.060*	–6.568*	0.0000
Q_{liq}	4.603*	0.870*	2.681*	0.0189
Q_{oil}	15.916	27.144	–1.929	0.0758
K_{sand}	0.554	0.549	0.099	0.9222
K_{sat}	84.335	80.684	1.206	0.2491
K_p	15.641*	13.451*	2.643*	0.0203
K_{perm}	189.083	68.036	0.952	0.3584
$H_{eff.sat}$	12.400	11.700	0.511	0.6177
dP	5.178	2.498	1.619	0.1294
b_{fr}	0.337	0.523	–0.804	0.4358
ω_{fr}	74.477	77.517	–0.054	0.9574
$K_{perm.fr}$	7.287	7.299	–0.003	0.9977

N o t e : * – statistically significant parameter.

In order to assess the effect of the studied parameter on W wells, the values of matching correlation coefficients r were calculated, given in Table 2.

In total, 66 values of r were calculated, of which 36 are statistically significant. Note that the value of W has significant correlations with Q_{oil}, Q_{liq}, K_{sat}, K_P, K_{perm}, dP. The correlation coefficients with the considered parameters vary in the range from –0.69 to 0.7. Thus, the highest r-value of the studied parameter W has with permeability and porosity coefficients, and the lowest – with fracture opening inside the formation. We think that between the studied parameters, which effect the W value, there are fairly close relationship (r = 0.101). The highest correlation coefficients are observed between porosity and oil saturation coefficients (r = 0.703), between the coefficient of gross sand ratio and oil saturated thickness (r = 0.650).

A minimum (W = 55.6 %) to maximum (W = 99.4) range has been ranked to identify the set of parameters that have differentiated W value across the whole range [32–36]. This set of values was used to assess the effect of the studied parameters on W quantity by stepwise regression analysis in the following scheme: the first multidimensional regression equation is constructed at n = 3, the second at n = 4 and up to n = 15. Thus 13 multidimensional regression equations are constructed, which are given in Table 3.

Analysis of the constructed multidimensional models of W values showed that there are two groups of data that influence the W value at its different values. Note that in the first and second steps of the model construction, in the range of water cut from 57.6 to 63 %, the W value is statistically effected only by the fracture opening parameter (b_{fr}). Further, with the inclusion to the well model with water cut ranging from 70.5 to 84.7 %, various effects on W value are noted. When adding to the well model with water cut more than 84.7 %, W value performance is consistently effected by fluid flow (Q_{fl}), oil fluid flow (Q_{oil}), permeability coefficient (K_{perm}) and depression (dP). All this shows that the formation of W values within two selected groups, with W = 84.7 %, occurs differently.

For a more complete statistical analysis, we compared the mean values in the groups of wells with W > 84.7 % and W < 84.7 % using Student's t-criterion (Table 4) which is calculated with the following formula:

$$t = \frac{M_1 - M_2}{\sqrt{m_1^2 + m_2^2}},$$

Table 5

Comparison of forecast and actual values of general and differentiated model

Actual *W*, %	Model W_M^o, %	Model W_M^{1+2}, %
57.6	58.6	57.4
61.8	56.3	60.4
62.2	63.5	63.3
62.9	60.4	64.3
70.5	71.1	75.2
70.9	74.6	71.5
72.7	77.8	73.1
74.6	76.1	74.7
75.4	76.4	70.8
84.7	87.7	82.7
86.5	94.2	86.6
97.5	95.2	97.9
98.5	90.4	97.3
98.6	95.3	98.7
99.4	96.1	99.6

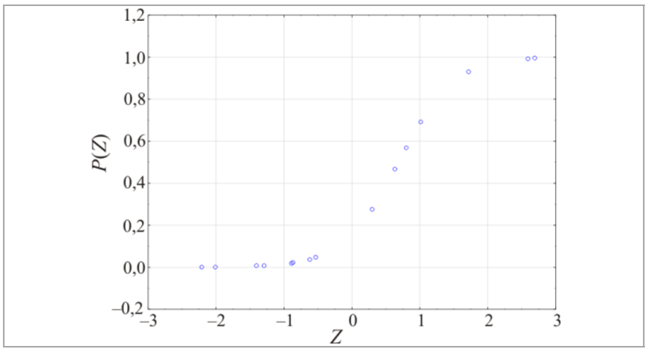

Fig. 2. Dependence of *P(Z)* on *Z*

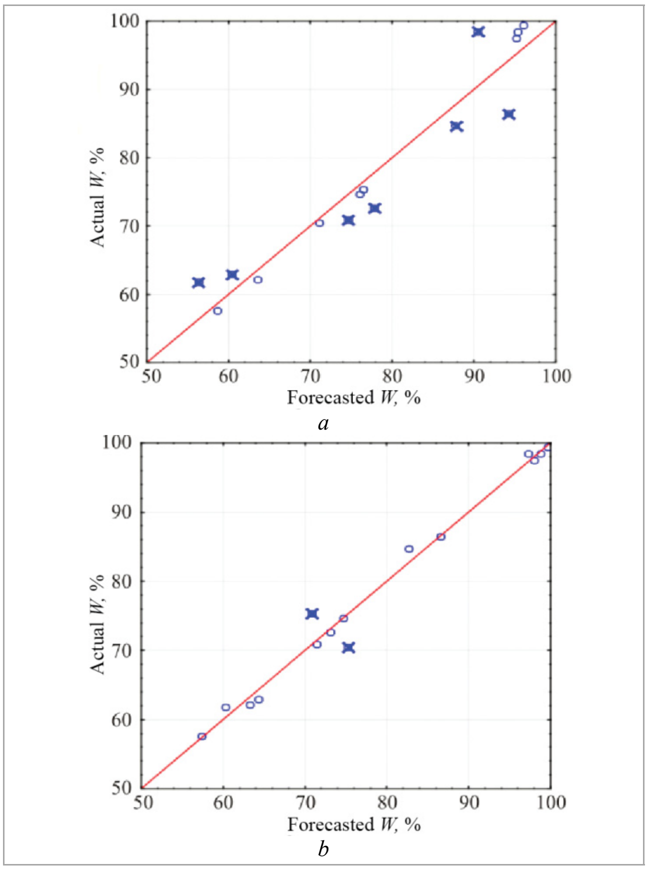

Fig. 3. Comparison of forecasted and actual values of the general and differentiated model: *a* – method: general model; *b* – method: differentiated models

where M_1 is the arithmetic mean of the first group; M_2 is the arithmetic mean of the second group compared; m_1 is the standard error of the first group; m_2 is the standard error of the second group.

The results of the analysis show a big difference between the two groups in the porosity and oil saturation coefficients. It indicates that highly porous and saturated zones are watered in the studied deposit. It can also be stated that highly watered wells operate at a higher depression.

Linear discriminant analysis (LDA) is used to integrated assessment of the parameters effect on water cut within the groups. Matrices of centred square sums and mixed products are made, and the sample matrix is calculated. Next, the inverse sample covariance matrix is found to determine the LDA coefficients. Then the boundary value of discriminant functions (R_o) is calculated which divides the sample into two subsets. The reliability of classification is determined using Pearson's χ^2 criterion. Application of statistical analysis methods for solving similar problems in scientific research are given in the following papers [37–45]. Here the value of $W < 84.7$ % (class 1), $W < 84.7$ % (class 2) acts as a classifier. The linear discriminant function has the following form:

$$Z = -0.582\,K_p + 1.117\,b_{fr} - 0.177\,dP + 0.048\,Q_{liq} + 8.044,$$

at $R = 0.79$, $\chi 2 = 10.52$, $p = 0.032$.

It can be seen that the linear discriminant function (LDF) constructed is statistically significant. The correct recognition was 86 %. The posterior probability values *P(Z)* were calculated from this function. The relationship between *Z* and *P(Z)* is shown in Fig. 2.

It is seen that when *Z* changes from negative to positive values, the value of *P(Z)* increases from 0.00 to 0.99. The value of *Z* for the first group changes from 2.04 to 0.98, the mean value is 0.71, for the second group – from 0.15 to 2.48, the mean value of *Z* for the group is 1.43. On the graph of posterior probability, the analysis of ratios *P(Z)* from *Z* shows that with increasing *Z* values the posterior probabilities of attribution to the class of high-watered wells increases. All this allows us to understand that the formation of *W* parameters passed differently, depending on their values.

Therefore, to forecast the effect of the considered parameters on the water cut ratio, three groups of *W* forecasted models were constructed: a general model, including all 15 wells, and differentiated models, the wells in which were divided into two groups depending on the values greater or less than $W = 84.7$ %.

When all data were used, a multidimensional regression equation was obtained:

$$W_M^o = 1.65Q_{liq} - 4.7dP - 0.006\,K_{пр} - 0.19\omega_{fr} + 142\,K_{sand} + 5.44K_p - 1.44K_{sat} + 40.92.$$
$$R^2 = 0.92.$$

The model formation took place in the sequence given in the regression equation. The value of *R* coefficient describing the strength of statistical relationship varied as follows: 0.325; 0.536; 0.623; 0.671; 0.828; 0.853; 0.922. As we can see from the results, using the general model, there are seven parameters effecting the water cut ratio: the fluid flow rate and the fractures segments has the greatest effect, also the model depends on a large number of geological parameters.

Using the formula, the W_M^o values for all wells were calculated and compared with the actual *W* values (Table 5 and Fig. 3, *a*).

The wells were divided into two groups to construct the differentiated model. The well model, where $W < 84.7$ %, has the following form:

$$W_{м}^{1} \text{ (group 1)} = 0.75\,K_{perm.fr} + 0.77\,H_{eff.sat} - 0.02\,K_{perm} + 2.51\,K_{p} + 7.4\,b_{fr} + 15.95. \quad R^2 = 0.91.$$

The model formation took place in the sequence given in the regression equation. The value of R coefficient describing the strength of correlation varied as follows: 0.508; 0.635; 0.698; 0.832; 0.912.

For wells with water cut more than 84.7 %, the constructed model has the following expression:

$$W_{м}^{2} \text{ (group 2)} = 2.77\,dP + 0.54\,K_{perm.fr} + 0.12\,Q_{liq} + 81.82. \quad R^2 = 0.98.$$

The model formation took place in the sequence given in the regression equation, where the value of the R coefficient varied as follows: 0.576; 0.937; 0.985. Using these formulas, the W_m values for the first and second groups were calculated and compared with the actual values of W.

It should be noted that the analysis of the constructed models shows that using the differentiated model, five parameters have the greatest effect on the water cut ratio for wells with $W < 84.7$ %, for wells with $W > 84.7$ % – three parameters. At the same time, in both groups the fracture permeability parameter has the effect.

We compared the forecasted and actual parameters of the general and differentiated models. According to the obtained equations, the model $W_{м}^{o}$ values were calculated using all data, $W_{м}^{1+2}$ values for differentiated models, which were compared with the actual value of W (see Table 5), on which basis the graphs were plotted (see Fig. 3).

As can be seen from the comparison, the first variant of model construction has a lower correlation coefficient ($r = 0.960$) and a large number of wells (see Fig. 1) that are outside the confidence level. While the differentiated models showed better convergence of actual and model values ($r = 0.991$). The W value of only two wells from the forecasted model deviates from the actual data (see Fig. 1). Comparison of two variants (differentiated and general models) shows that in case of models' application for two groups much better matching of forecasted and actual W values is observed.

Conclusion

Fifteen wells of the Tournaisian site in Perm region with high values of water cut ratio were analysed in the research. It was determined that geological characteristics of the reservoir and fracture parameters have a great effect on the water cut process, but the degree of specific parameters effect used in the study changes with water cut increase.

The constructed models showed that, using all data, the correlation coefficient between the actual and forecasted W values of the general model is $r = 0.960$. Construction of differentiated models with their division by W value allowed to increase the correlation coefficient between actual and forecasted data up to $r = 0.991$. Thus, according to the study of water cut values formation from the studied parameters, we can conclude that using differentiated models allows making more reliable assessment of various parameters effect on the well water cut.

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