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Construction of models for predicting wettability values after extraction at the fields of the Timan-Pechora province

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Построение моделей прогноза значений смачиваемости после экстракции на месторождениях Тимано-Печорской провинции

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Domestic standards for conducting laboratory studies on core samples of oil and gas formations provide for purification from hydrocarbons using extraction. Purification prepares core samples for the main types of research. A number of different solvents and special extraction and distillation apparatus are used. Core samples placed in the apparatus undergo purification cycles for a long time with high-temperature exposure. However, extraction leads to distorted ideas about the natural wettability of the rock surface, which is subject to change and, as a rule, hydrophilizes. In this regard, it is of scientific and practical interest to assess the wettability of the rock at various stages of sample preparation – before and after the extraction procedure. The purpose of the research is to analyze the wettability of core samples before extraction from hydrocarbons using statistical research methods. The work analyzes the effect of the porosity and permeability coefficient on the change in wettability. The results of the research showed that with the help of the conducted complex of laboratory studies using various statistical methods it was possible to create mathematical models for predicting the values of the wettability index for oil before extraction based on the filtration and capacity properties of core samples. The paper provides examples of the correlation fields analysis of various parameters before and after extraction. The multivariate statistical analysis conducted in the work made it possible to establish that it is most expedient to predict the wettability values after extraction differentially by wettability methods and by the studied formations. The multivariate models obtained in the work can be further used to predict changes in miscibility for some objects in the Timan-Pechora province.

Ключевые слова:
смачиваемость, керн, экстракция, петрофизика, статистические методы, коэффициент пористости, проницаемость, корреляционные поля, коллектор, нефть, флюид, фильтрация.

Отечественные стандарты по проведению лабораторных исследований на образцах керна пород нефтяных и газовых пластов предусматривают очистку от углеводородов с помощью экстракции. Очистка подготавливает образцы керна к основным видам исследований. При этом применяется ряд различных растворителей и специальные экстракционно-дистилляционные аппараты. Образцы керна, помещенные в аппараты, проходят циклы очистки в течение длительного времени с высокотемпературным воздействием. Однако экстракция приводит к искаженным представлениям об естественной смачиваемости поверхности породы, которая подвергается изменению и, как правило, гидрофилизируется. В связи с этим представляют научный и практический интерес оценки смачиваемости породы на различных этапах подготовки образцов – до и после процедуры экстракции. Цель исследований – анализ величины смачиваемости образцов керна до экстракции от углеводородов с применением статистических методов исследований. В работе проводится анализ влияния на изменение смачиваемости коэффициента пористости и проницаемости. Результаты исследований показали, что с помощью проведенного комплекса лабораторных исследований с использованием различных статистических методов удалось создать математические модели прогноза значений показателя смачиваемости по нефти до экстракции на основе фильтрационно-емкостных свойств образцов керна. В работе приведены примеры анализа корреляционных полей различных параметров до и после экстракции. Проведенный в работе многомерный статистический анализ позволил установить, что прогнозирование значений смачиваемости после экстракции наиболее целесообразно выполнять дифференцированно по методам смачиваемости и по изучаемым пластам. Полученные в работе многомерные модели в дальнейшем можно использовать для прогноза изменения смешиваемости для некоторых объектов в Тимано-Печорской провинции.

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Introduction

Wettability of reservoir rocks is one of the key characteristics that influence the distribution and filtration of formation fluids in the void space [1–6]. It is partial or complete spreading of liquid over a solid surface. For productive formations, such phases can include oil, brine water and gas. Therefore, determining wettability is a crucial task both for estimating hydrocarbon reserves and for oil and gas fields development. Various laboratory methods are used to determine wettability: the contact angle method, the Amott method (Amott–Harvey) [7, 8], the United States Bureau of Mines (USBM) methodology [9–11], the combined Amott–USBM method [12, 13], and the Tulbovich method (OST 39-180-85 Industrial Standard) [14]. Reservoirs have mixed wettability, since the void space surface is characterized by both hydrophilic and hydrophobic properties simultaneously, as different minerals in the reservoir rocks are of varying wettability types. This study examines three geological objects: Zadonian deposits of the Famennian substage in the Upper Devonian system (D3zd), the deposits of the Asselian-Sakmarian stage in the Lower Permian system (P1a + s) and the deposits of the Artinskian stage in the Lower Permian system (P1a). The study analyzes core data related to wettability by oil (Wet-O), by OST (Industrial Standart) (Wet-OST), and by Amott (Wet-A) both before (BE) and after (AE) extraction. Porosity coefficients (K_p) and permeability coefficients (K_{pr}) were also used for the analysis.

Typically, wettability studies are conducted on core samples that are cleaned of hydrocarbons using various solvents such as chloroform, a benzyl alcohol mixture, toluene, etc. The surface of the samples cleaned in this way leads to a change in the core wettability [15–17]. As a result, the obtained data on wettability characteristics can vary significantly. To verify the changes during the core samples preparation, parameter measurements are taken before and after the extraction [18–20]. In this context, the issue of predicting the wettability parameter without conducting additional research becomes relevant. For this purpose, a method for predicting the wettability parameter after extraction was developed.

The theoretical potential of using statistical methods to solve geological and field-related problems is discussed in works [21, 22]. The application of various statistical methods and the examples of solving similar tasks can be found in works [23–45].

Database analysis

To prove the changes in the rock wettability occured during the extraction process, we compare mean wettability values obtained by these methods before and after extraction using Student's *t*-test (see table).

It is evident that the mean values of Wet-O before and after extraction are statistically different, with the mean values of Wet-O after extraction being lower than those before extraction.

For Wet-OST, the average values after extraction are higher than those before. It is also worth noting that for the P1a formation, the mean wettability values before and after extraction are not statistically different.

For Wet-A, the mean values after extraction are also higher than those before it, these differences are statistically significant. It is noteworthy that there is a more pronounced difference in the mean values before and after wetting when moving from the bottom to the top of the section.

To assess the influence of K_p and K_{pr} on the considered wettability variants across the layers, correlation fields were constructed between these values and the wettability values of BE and AE. Examples of such fields for Wet-O before and after extraction and along with the K_p and K_{pr} coefficients are shown in Fig. 1, *a, b*.

The analysis of the constructed correlation fields shows that before extraction, the values of Wet-OB are hardly controlled by the values of K_p. After the extraction, it is observed that the value of Wet-OA decreases according to the statistically significant correlation. It indicates that

Mean values of wettability parameters

Layers	Mean values BE	Mean values AE	*t*-criterion – upper row, *p*-value criterion – lower row
	Wet-OB	Wet-OA	
D3zd	0.381 ± 0.201, n = 52	0.234 ± 0.158, n = 52	4.125848 0.000076
P1a + s	0.328 ± 0.161, n = 38	0.160 ± 0.132, n = 38	4.991228 0.000004
P1a	0.392 ± 0.185, n = 10	0.230 ± 0.112, n = 10	2.360851 0.029715
Layers	Wet-OSTB	Wet-OSTA	
D3zd	0.263 ± 0.162, n = 52	0.407 ± 0.209, n = 52	-3.91049 0.000166
P1a + s	0.279 ± 0.190, n = 38	0.438 ± 0.192, n = 38	-3.63070 0.000518
P1a	0.250 ± 0.250, n = 10	0.434 ± 0.293, n = 10	-1.51017 0.148355
Layers	Wet-AB	Wet-AA	
D3zd	-0.139 ± 0.257, n = 52	0.176 ± 0.227, n = 52	-6.61459 0.0000001
P1a + s	-0.020 ± 0.248, n = 38	0.258 ± 0.243, n = 38	-4.93620 0.000005
P1ar	-0.139 ± 0.356, n = 10	0.261 ± 0.345, n = 10	-2.55131 0.0200045

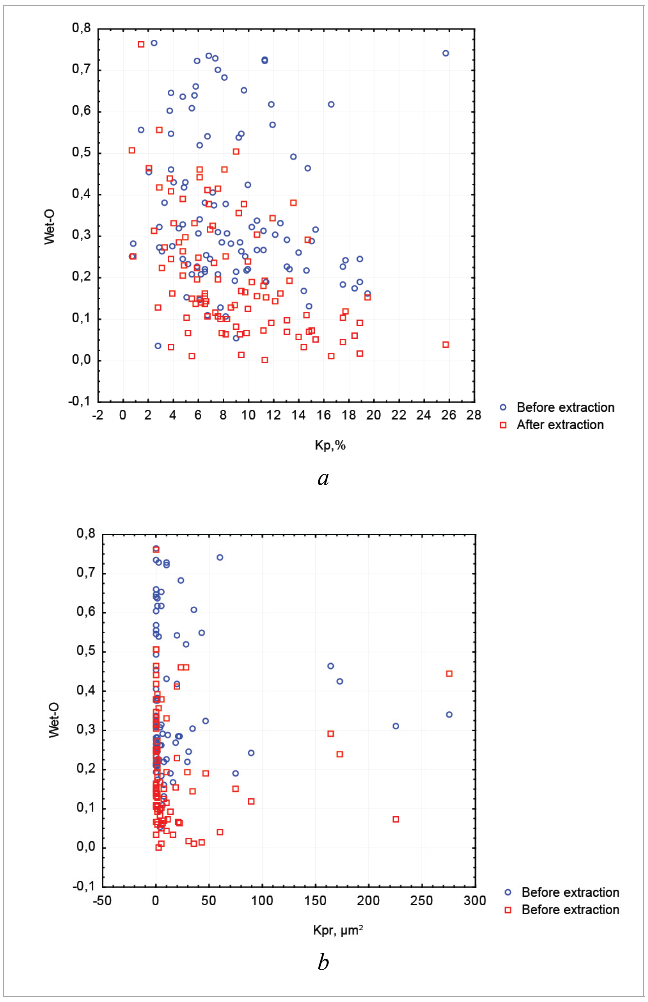

Fig. 1. Correlation fields: *a* – between K_p and Wet-OB, Wet-OA; *b* – between K_{pr} and Wet-OB, Wet-OA

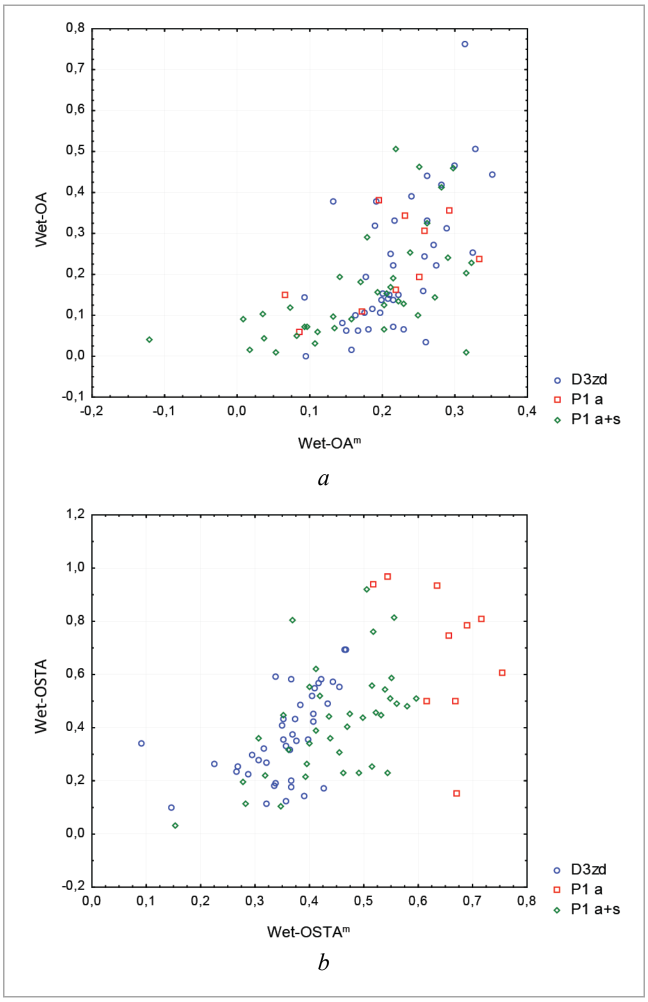

Fig. 2. Correlation fields: *a* – between Wet-OA and Wet-OA^m; *b* – between Wet-OSTA and Wet-OSTA^m

the fields are characterized not only by different strengths of the relationship between K_{pr} and Wet-OB, Wet-OA, but also by a significant drift in the values of Wet-OB and Wet-OA relative to each other.

Similar fields were constructed and analyzed for the Wet-OST and Wet-A methods. Analysis of the constructed fields shows that, both for the studied methods and reservoirs, the correlation fields are characterized by different types.

Development of predictive models for wettability values after extraction

The data presented above show that the wettability values obtained by different methods vary significantly. Therefore, the prediction of wettability values after extraction will be carried out differentially by methods and layers. In addition to the coefficients K_p and K_{pr}, the age of the studied reservoirs was also included in the analysis. The reservoir D3zd was assigned an index (I_r) – 1, reservoir P1a+s – 2, reservoir P1a – 3.

For Wet-O across all reservoirs combined, the multivariate model is represented as follows:

$$\text{Wet-OA}^m = 0.268 - 0.022176K_p + 0.075532I_r + 0.000523K_{pr}$$

with $R = 0.584$, $p < 0.0000001$, and a standard error of 0.120.

The wettability model by oil after extraction was formed in the sequence given in the regression equation. It shows that the model formation started with K_p, followed by I_r, and at the final step, K_{pr} was used. The values of the R coefficients, which describe the strength of statistical relationships, changed as follows: 0.501; 0.562; 0.584. The values of Wet-OA^m calculated with this formula were compared with Wet-O (Fig. 2, *a*).

For the wettability by Wet-OST, the following multivariate model is obtained:

$$\text{Wet-OSTA}^m = 0.275 + 0.205466\,I_r - 0.018862K_p - 0.000793K_{pr}$$

with $R = 0.579$, $p < 0.0000001$, and a standard error of 0.177.

The wettability model by OST after extraction was formed in the sequence given in the regression equation. This shows that the model formation started with I_r, followed by K_p, and at the final step, K_{pr} was used. The values of the R coefficients, which describe the strength of statistical relationships, changed as follows: 0.402; 0.555; 0.579.

Using this formula, the values of Wet-OSTA^m were calculated and compared with Wet-OSTA (Fig. 2, *b*).

From Fig. 2, *a*, it is clear that the correlation between Wet-OA and Wet-OA^m is a positive nonlinear relationship, within which various types of correlations are observed differentially across layers.

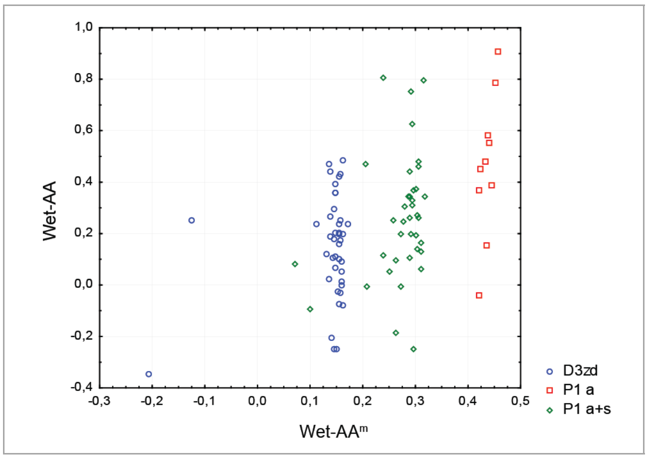

Fig. 3. Correlation fields between Wet-AA^{m} and Wet-AA

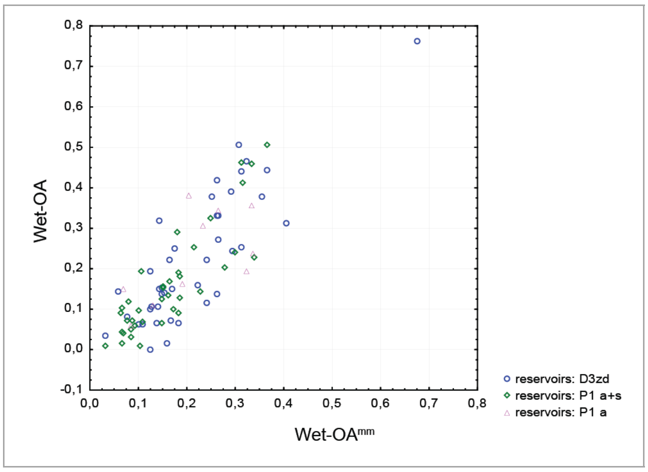

Fig. 4. Correlation fields between Wet-OA and Wet-OA^{m}

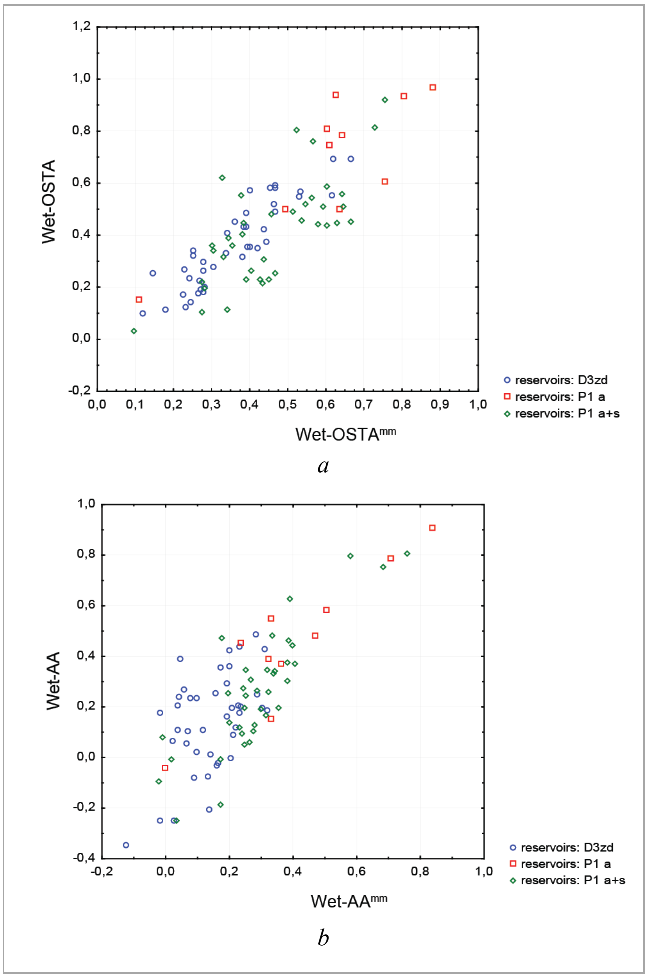

Fig. 5. Correlation fields: *a* – between Wet-OSTA and Wet-OSTA^{mm} considering the reservoirs; *b* – between Wet-AA and Wet-AA^{mm}

From Fig. 2, *b*, it is evident that the relationships between Wet-OSTA and Wet-OSTA^{m} across the studied layers vary significantly. It should be noted that the predicted values of Wet-OSTA^{m} exhibit a sequential blending of correlation fields relative to each other.

For wettability by Wet-A, the multivariate model has the following form:

$$\text{Wet-AA}^{M} = 0.0067 + 0.129934 I_r - 0.0011317 K_{pr} + 0.003315 K_{pr}$$

with $R = 0.471$, $p < 0.00008$, and a standard error of 0.219.

The wettability model by Amott after extraction was formed in the sequence given in the regression equation. It shows that the model formation started with I_r, followed by K_{pr}, and at the final step, K_p was used. The values of the R coefficients, which describe the strength of statistical relationships, changed as follows: 0.405; 0.468; 0.471.

Using this formula, the values of Wet-AA^{m} were calculated and compared with Wet-AA (Fig. 3)

It is evident that the correlation between Wet-AA and Wet-AA^{m} for the studied layers differ significantly both in type and in the strength of the statistical linear relationships. The type of correlation fields for the layers shows that there are practically non-intersecting fields for the predicted values of Wet-AA^{m}, while such a strong differentiation is not observed for the values of Wet-AA . Therefore, for all types of wettability, the models were developed separately for each layer.

As an example of model construction by reservoirs, the Wet-O method is used.

For the D3zd reservoir the model has the following form:

$$\text{Wet-OA}^{mr-D3zd} = 0.571 - 0.034350 K_p$$

with $R = 0.585$, $p < 0.00006$, and a standard error of 0.135.

It is evident that for this reservoir the predicted values are formed only by $K_{p.}$

For the P1a + s reservoir the model has the following form:

$$\text{Wet-OA}^{mr-P1a+s} = 0.328 - 0.015923 K_p + 0.000811 K_{pr}$$

with $R = 0.584$, $p < 0.00067$, and a standard error of 0.108.

The wettability model by oil after extraction for the P1a + s was formed in the sequence given in the regression equation. The values of the R coefficients, which describe the strength of statistical relationships, changed as follows: 0.528; 0.584. It is also evident that the formation of values occurred mainly due to the K_p values.

For P1a reservoir the model has the following form:

$$\text{Wet-OA}^{mr-P1a} = 0.452 - 0.017234 K_p$$

with $R = 0.588$, $p < 0.07344$, and a standard error of 0.096.

It is seen that the formation of values occurred mainly due to the K_p values.

The developed models using this extraction method show that the formation of model values occurred mainly due to K_p.

Using the mentioned formulas, the values of Wet-OA$^{mr-D3zd}$, Wet-OA$^{mr-P1a+s}$, Wet-OA^{mr-P1a} and

(Wet-OA^{mm}) were calculated and compared with Wet-OA (Fig. 4).

It can be seen that there is a close correlation between Wet-OA and Wet-OA^{mm} across the entire range of values. Notably, the conducted statistical extraction modeling by reservoirs, firstly, allowed us to eliminate the nonlinearity between the values of Wet-OA and Wet-OA^{mm}, secondly, determine that the values of Wet-OA^{m} mainly depend on K_p.

Similar differentiated models for the reservoirs were developed using the Wet-OST and Wet-A methods. According to these models, the values of Wet-OSTA^{mm} and Wet-AA^{mm} were calculated and compared with the values of Wet-OSTA and Wet-AA (Fig. 5, *a, b*)

It can be seen from Fig. 5, *a*, that after constructing multivariate models, considering the values differentiated by reservoirs, the correlation fields are characterized by a close relationship.

From Fig. 5, *b,* it is evident that after constructing multivariate models with the values separate for each layer, the correlation field has a close relationship.

Conclusion

Thus, the analysis showed that the mean values of wettability by oil before and after extraction are statistically significant, while the average values after extraction are lower than before extraction.

For wettability by OST and Ammot, the mean values after extraction are higher than before. It should be noted that according to the OST method for the P1a reservoir, the average wettability values before and after extraction do not differ statistically.

The performed multivariate statistical analysis showed that predicting the wettability values after extraction is most rational when performed in a differentiated manner, considering not only the methods of wettability but each studied reservoir.

The mathematical models for predicting wettability values after extraction are developed for the Zadonian deposits of the Famennian substage in the Upper Devonian system, the deposits of the Asselian-Sakmarian and Artinskian stage of the Lower Permian system. The coefficients of the terms in the resulting multivariate models allow for a quantitative assessment of the relationship between wettability, porosity, and permeability of the rock for various deposits. Subsequently, these multivariate models can be used to predict the wettability of core samples where no special studies have been conducted, as well as for forecasting this parameter across the oil field area.

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