ISSN 2712-8008
Volume / Том 21 №3 2021
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622.550.8.012:519.2
Review / Обзор

Studying the Influence of Changing Sandstone and Aleurolite Reservoir Properties on Quality of Geological Modeling

Aleksey Yu. Vishnyakov

PermNIPIneft branch of LUKOIL-Engineering LLC in Perm (3a Permskaya st., Perm, 614015, Russian Federation)

Исследование влияния изменения коллекторских свойств песчаника и алевролита на качество геологического моделирования

А.Ю. Вишняков

Филиал ООО «ЛУКОЙЛ-Инжиниринг» «ПермНИПИнефть» в г. Перми (Россия, 614066, г. Пермь, ул. Пермская, 3а)

Received / Получена : 14.02.2021. Accepted / Принята: 30.04.2021. Published / Опубликована: 01.07.2021

Keywords:
reservoir rock, core, porosity, rock density, permeability, aleurolite, sandstone, geological model, hydrodynamic model, regression equations, statistical analysis, reservoir porosity and permeability, correlation fields, dispersion, *t*-criterion.

Initial data when creating both geological and hydrodynamic reservoir models can lead to errors in modeling results and a subsequent distortion of the economic assessment and prospects of an oil or gas field.

In order to improve the predictive reliability of reservoir hydrodynamic models, a core material study for the Tula facilities of four fields at the Babkinskaya anticline was carried out.

The ratios of porosity (K_p), rock density (ρ) and permeability (K_{perm}) values for sandstones and aleurolites were analyzed. Using a statistical core sampling based on porosity, density and permeability parameters, a separation by sedimentation processes was carried out for all considered lithological differences. For aleurolite and sandstone, we can speak about the differentiation of characteristics during formation of reservoir properties.

The values of parameters K_p, ρ and K_{perm}, determined from laboratory core studies, were combined into a single statistical sample for the possibility of developing a methodology that would be aimed at describing K_{perm} using integrated laboratory studies, namely by adding rock ρ to the analysis.

As a result of the statistical analysis, it was found that permeability in intervals with low reservoir properties was controlled with the same degree by both porosity and rock density for all lithological differences. At the same time, the presence of highly permeable reservoirs for sandstones and unavailability of them for aleurolite was noted. For all lithological differences, relationships were established between permeability coefficient not only with porosity, but also with rock density. The methodology for constructing statistical models to calculate permeability from the values of porosity and rock density was implemented separately for the fields of the eastern and western sample parts of the Babkinskaya anticline.

The described approach to taking into account the influence of rock density on permeability made it possible to determine the differentiated influence of lithotypes on the filtration characteristics of the reservoir.

When modeling a reservoir, it is necessary to transfer from linearity to nonlinearity and take into account that the problem of permeability distribution in the reservoir being solved is somewhat more complicated: in different areas, sometimes permeability is not controlled by porosity in principle, but somewhere only this parameter prevails.

The methodical approach is recommended for 3D modeling. Revealing the relationships between the parameters was more important when developing a methodology for the model matching in the interwell space. A reliable permeability evaluation for the majority of wells will significantly improve efficiency of hydrodynamic modeling. At the same time, it is necessary to comprehensively take into account the identified relationships between the petrophysical characteristics of production facilities. The use of the approach based on the analysis of petrophysical characteristics allows obtaining a more reliable and less subjective hydrodynamic model of the reservoir.

Ключевые слова:
коллектор, керн, пористость, плотность породы, проницаемость, алевролит, песчаник, геологическая модель, гидродинамическая модель, уравнения регрессии, статистический анализ, фильтрационно-емкостные свойства, корреляционные поля, дисперсия, *t*-критерий.

Исходные данные при создании как геологических, так и гидродинамических моделей пласта могут привести к погрешности результатов моделирования и последующему искажению экономической оценки и перспектив нефтяного или газового месторождения.

С целью повышения прогностической надежности гидродинамических моделей пласта проведено исследование кернового материала тульского объекта четырех месторождений Бабкинской седловины.

Проводился анализ соотношения значений пористости ($K_п$), плотности породы (ρ) и проницаемости ($K_{пр}$) для песчаников и алевролитов. С помощью статистической выборки образцов керна на основе показателей пористости, плотности и проницаемости проведено разделение по процессам осадконакопления для всех рассматриваемых литологических разностей. Для алевролита и песчаника можно говорить о дифференциации характеристик в процессе формирования коллекторских свойств.

Значения параметров $K_п$, ρ и $K_{пр}$, определенные по лабораторным исследованиям керна, объединены в единую статистическую выборку для возможности разработки методики, которая будет направлена на описание $K_{пр}$ при помощи комплексного использования лабораторных исследований, а именно добавлением в анализ ρ породы.

В результате статистического анализа установлено, что проницаемость в интервалах с низкими коллекторскими свойствами контролируется с одинаковой степенью значимости как пористостью, так и плотностью пород для всех литологических разностей. В то же время отмечается наличие высокопроницаемых коллекторов для песчаников и практически отсутствие их для алевролита. Для всех литологических разностей установлены связи коэффициента проницаемости не только с пористостью, но и с их плотностью. Разработка методики построения статистических моделей для вычисления проницаемости по значениям пористости и плотности пород реализована раздельно для месторождений выборки восточной и западной частей Бабкинской седловины.

Описываемый подход учета влияния плотности пород на проницаемость позволил определить дифференцированное влияние литотипов на фильтрационные характеристики пласта.

При моделировании коллектора необходимо перейти от линейности к нелинейности и принять во внимание, что решаемая задача распределения проницаемости в залежи несколько сложнее: на различных участках порой проницаемость не контролируется пористостью в принципе, а где-то преобладает только этот параметр.

Методический подход рекомендуется использовать при трехмерном моделировании. Выявление связей между параметрами наиболее значимо при разработке методики настройки модели в межскважинном пространстве. Разработка достоверной оценки проницаемости для подавляющего большинства скважин позволит значительно повысить эффективность гидродинамического моделирования. При этом необходимо комплексно учитывать выявленные связи между петрофизическими характеристиками эксплуатационных объектов. Использование подхода по анализу петрофизических характеристик позволит получить более достоверную и менее субъективную гидродинамическую модель пласта.

Aleksey Yu. Vishnyakov (Author ID in Scopus: 56979040900) – Leading Specialist of the Production Optimization Department (tel.: +007 950 444 54 90, e-mail: Aleksej.Vishnyakov@pnn.lukoil.com).

Вишняков Алексей Юрьевич – ведущий инженер управления оптимизации добычи (тел.: +007 950 444 54 90, e-mail: Aleksej.Vishnyakov@pnn.lukoil.com).

Please cite this article in English as:
Vishnyakov A.Yu. Studying the Influence of Changing Sandstone and Aleurolite Reservoir Properties on Quality of Geological Modeling. *Perm Journal of Petroleum and Mining Engineering*, 2021, vol.21, no.3, pp.117-122. DOI: 10.15593/2712-8008/2021.3.3

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Вишняков А.Ю. Исследование влияния изменения коллекторских свойств песчаника и алевролита на качество геологического меделирования // Недропользование. – 2021. – Т.21, №3. – С.117–122. DOI: 10.15593/2712-8008/2021.3.3

Introduction

The construction of geological and hydrodynamic models (HDM) is associated with a high degree of uncertainty of initial information, especially when it comes to reservoir distribution of parameters in the interwell space. A geological model containing a reliable estimation of initial reservoir porosity and permeability properties (RPP) is a basis of quality hydrodynamic models. According to many specialists, the main factor of the quality matching of HDM lies in a reliable estimation of permeability values (K_{perm}) [1–3].

A hydrodynamic model is to accurately describe filtration, physical and chemical processes, which are characteristic for a real reservoir [4–8]. To get a reliable prediction at the design stage and during construction of hydrodynamic models of deposits developed at early stages, it is necessary to have a deep analysis of the initial data.

So far, according to the regulations [9], the modeling of permeability is up to a model's author. In real practice, K_{perm} is taken from hydrodynamic studies of wells (HSW) or from data about the petrophysical function on porosity (K_p): $K_{perm} = f(K_p)$ [10]. Both methods have negative and positive features. The use of HSW allows permeability evaluation oriented on the real extraction, however, the model itself, in general, turns out to be quite uniform due to both insufficiency of number of determined HSW and estimation of the extraction interval (perforation) without differentiation of K_{perm} values for sublayers. The main problem of using petrophysical dependences $K_{perm} = f(K_p)$ is their weak correlation. In general, if we use both approaches, the convergence of comparing the real and project indicators of the extraction does not always comply with necessary requirements. Many authors in their researches write about a need to increase quality of determining filtration parameters of facilities [11–14].

By considering the aforementioned, we analyzed the laboratory core data of the pay zone of the Tula reservoir for a number of deposits of one of major tectonic units of Perm Kray, i.e. the Babkinskaya anticline (BA). Also, we studied the influence of both porosity and rock density (ρ) on permeability.

Research and Analysis of Permeability Coefficient Based on Petrophysical Parameters of Rocks

The main commercial oil content of the Babkinskaya anticline deposits is related to Visean (C1v) terrigenous deposits of the Carboniferous system. Visean deposits consist of interlaminated sandstones and aleurolites. In the section of the terrigenous strata of BA of most oil fields, there are two main reservoirs: in the Bobrikovsky horizon (Bh) and in the Tula horizon (Th).

As part of the work performed, four deposits were identified within the tectonic block. For the Visean terrigenous formation of Th of all four oil fields of the Babkinskaya anticline, the analysis of laboratory core data was carried out (492 samples, 81 wells), of which 155 samples are aleurolite and 337 samples are sandstone.

Taking into account the remoteness of one, the largest of the sample fields (west of BA) relative to three others (east of BA), the distribution of the parameters K_p and K_{perm} for the studied lithological differences is considered separately.

For the formations represented by aleurolite in the western part of the field, there are two peaks in the ranges of 0.1–0.12 and 0.18–0.2, for the eastern part of the fields in the sample, a close to uniform distribution is typical. In case of sandstone for the deposit in the west of the BA, a uniform distribution of K_p is observed, while the presence of two modes in the ranges of 0.1–0.12 and 0.16–0.18 is observed in three deposits of the eastern part (Table 1).

This observation indicates the heterogeneity of geological conditions and the complexity of the formation process within the lithological differences. Based on the results, it can be assumed that there is a difference in the formation of the void space between the western and eastern parts of the BA reservoirs of the same age.

Similarly, for the objects under consideration, the distribution of K_{perm} was constructed (Table 2).

Based on the distribution density of K_{perm} and K_p for sandstones and aleurolites, the ratio of frequencies up to 10 % (K_p) and $0.110 \cdot 10^3 \cdot \mu m^2$ (K_{perm}) is insignificant, which indicates similar sedimentation processes for all considered reservoir rocks in this interval. When considering the density distribution K_{perm} of more than $0.110 \cdot 10^3 \cdot \mu m^2$ for aleurolite and sandstone, we can indicate the confirmation of differentiation during formation of reservoir properties of these deposits.

The permeability value formation both for lithological differences and in general depends on many factors [15–19]; in our case, we will consider the K_p and ρ of the rock. In this case, the considered connections will be not linear, but complex.

Statistical Estimation

For two lithological differences (aleurolite and sandstone), a single interval has been identified according to the value of the permeability coefficient (K_{perm}) 0.000026–0.500 μm², where a larger amount of joint data (K_{perm}, K_p and ρ) is presented. Based on the available data, a statistical analysis of the values of the geological and physical characteristics of the Tula reservoir rocks was carried out (Tables 3–4) [20–30].

The obtained *t*-criterion values indicate the presence of statistically significant differences between aleurolite and sandstone in all parameters for the group of fields in the eastern part of the BA and K_{perm} of the field in the western part. In addition, the greatest difference belongs to parameter K_{perm}, then K_p and ρ. The statistically significant values of the *t*-criterion for parameter ρ for aleurolite and sandstone allow using ρ as an additional characteristic in estimating K_{perm} of reservoir rocks.

When assessing permeability through the petrophysical relationship $K_{perm} = f(K_p)$, there are often objective problems associated with a not enough relationship between these parameters. With an exponential dependence, it is not possible to substantiate different ratios between K_{perm} and K_p in different ranges of K_p values. When considering the standard set of reservoir properties (K_p, K_{perm}), a detailed account of the structure of the void space does not always take place, which depends on the mineralogical and lithological composition of deposits, the way of packing particles, diagenetic and catagenetic conditions (leading to compaction and decompaction of rocks). Therefore, to improve the quality of predictive models of reservoir properties, it is necessary to use additional characteristics that take into account the composition and properties of the rock [31–35].

For a more detailed study of the permeable part of the reservoir rocks, let us add ρ of the rock to the study. The need is caused by the previously described differences between the parameters of aleurolite and sandstone. Features of the described lithological differences in the lithological structure lead to different mutual correlations between K_p, ρ and K_{perm}.

Building 3D Models, Analysis of Petrophysical Relations

Research and analysis of the joint influence of K_p and ρ will allow us to clarify the method for predicting K_{perm} and the distribution of the indicator values in the deposit area.

Table 1

Comparing frequencies of K_p for aleurolite and sandstone

Interval K_p, fr.unit	Frequency (aleurolite), fr.unit		Frequency (sandstone), fr.unit	
	West of BA	East of BA	West of BA	East of BA
0.00–0.02	0	0	0	0
0.02–0.04	0	0.03	0.01	0.02
0.04–0.06	0.03	0.06	0.05	0.01
0.06–0.08	0	0.06	0.02	0.03
0.08–0.10	0.13	0.1	0.09	0.09
0.10–0.12	0.25	0.16	0.09	0.13
0.12–0.14	0.13	0.2	9	0.09
0.14–0.16	0.06	0.15	0.17	0.23
0.16–0.18	0.09	0.15	0.17	0.28
0.18–0.20	0.16	0.08	0.2	0.11
0.20–0.22	0.09	0.02	0.06	0.01
0.22–0.24	0.06	0	0.05	0
0.24–0.26	0	0	0.01	0
0.26–0.28	0	0	0.01	0

Table 2

Comparing frequencies of K_{perm} for aleurolite and sandstone

Interval K_p, fr.unit	Frequency (aleurolite), fr.unit		Frequency (sandstone), fr.unit	
	West of BA	East of BA	West of BA	East of BA
0.000–0.010	0.59	0.54	0.25	0.22
0.010–0.110	0.38	0.39	0.31	0.32
0.110–0.210	0.03	0.03	0.25	0.16
0.210–0.310	0	0.02	0.13	0.17
0.310–0.410	0	0.01	0.03	0.06
0.410–0.510	0	0	0.04	0.07

Table 3

Comparing mean values according to *t*-criterion of rocks of reservoir rocks of Th deposit in the west of BA

Indicator	Mean values of indicators		*t – criterion* Level of importance
	Aleurolite $n = 32$	Sandstone $n = 176$	
	Mean values ± CO min – max	Mean values ± CO min – max	t_{1-2} p_{1-2}
K_p, fr.unit	0.15 ± 0.05	0.16 ± 0.05	0.737887
	0.05–0.22	0.03–0.26	0.461423
Bulk density of the rock, ρ, g/cm³	2.29 ± 0.12	2.27 ± 0.15	-0.626928
	2.15–2.68	2.03–2.6	0.531878
K_{perm}, μm²	0.026 ± 0.042	0.116 ± 0.122	3.899526
	0.000007–0.193	0.00006–0.495	0.000134

Table 4

Comparing mean values using *t*-criterion of reservoir rocks of Th in the east of BA

Indicator	Mean values of indicators		*t – criterion* Level of importance
	Aleurolite $n = 123$	Sandstone $n = 161$	
	Mean values ± CO min – max	Mean values ± CO min – max	t_{1-2} p_{1-2}
K_p, fr.unit	0.12 ± 0.04	0.14 ± 0.04	3.559429
	0.03–0.21	0.02–0.21	0.000436
Bulk density of the rock, ρ, g/cm³	2.30 ± 0.13	2.26 ± 0.13	-2.777854
	2.02–2.64	1.9–2.91	0.005840
K_{perm}, μm²	0.031 ± 0.057	0.114 ± 0.137	8.579863
	0.000005–0.312	0.0001–0.494	0.000000

Moreover, when using parameter ρ of rocks, when predicting K_{perm}, we take into account additional structural features of the void space of rocks of the same age.

In order to find more significant relationships between the petrophysical characteristics of the Th formation, we analyzed 388 values (taking into account ρ data of the rock) of determining sandstone core samples, with 246 samples of sandstone and 142 samples of aleurolite. The values of parameters K_p, ρ and K_{perm}, determined from laboratory studies of the core, are combined into a single statistical sample.

Fig. 1–2 show the correlation fields in general for all deposits between K_{perm} and K_p, K_{perm} and ρ, K_p and ρ.

The analysis of the correlation fields between the K_{perm} and K_p values for aleurolite and sandstone shows that statistically significant linear relationships are present between the parameters in both cases, which is further used as the main approach in modeling reservoir properties for hydrodynamic models [34–39].

The interval relationship between sandstone and aleurolite is also confirmed in the correlation fields, that is, the presence of weak reservoirs in the left zone (or non-reservoir rocks). It is worth noting the presence of highly permeable reservoirs for sandstones and their minority for aleurolite. Differentiation of the interval distribution of K_{perm} and K_p parameters for aleurolite and sandstone indicates different conditions of their formations. The ratio of K_{perm} and K_p shows that the influence of K_p on the formation of permeability in different intervals is accompanied by a difference in geological conditions.

The influence of K_p on K_{perm} for aleurolites and sandstones is characterized by a high degree of nonlinearity; in addition, the form of these nonlinearities differs at different ranges of parameter variations.

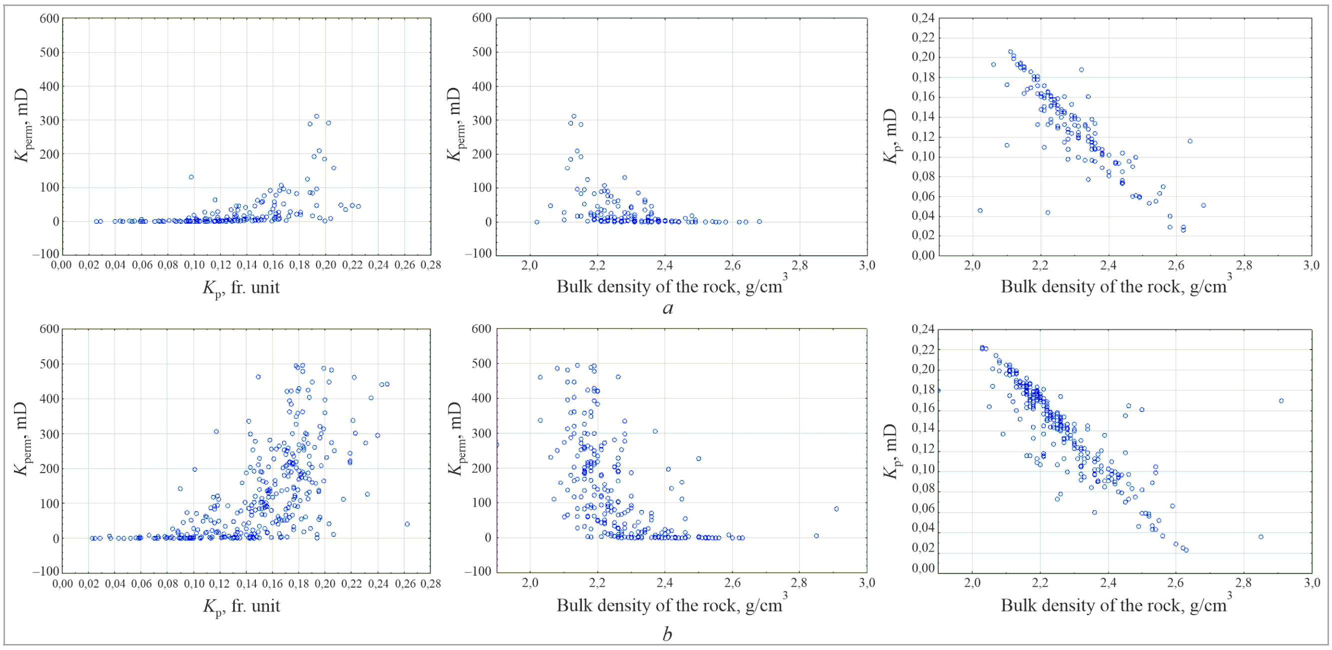


Fig. 1. The correlation fields between parameters: *a*) for aleurolite, *b*) for sandstone

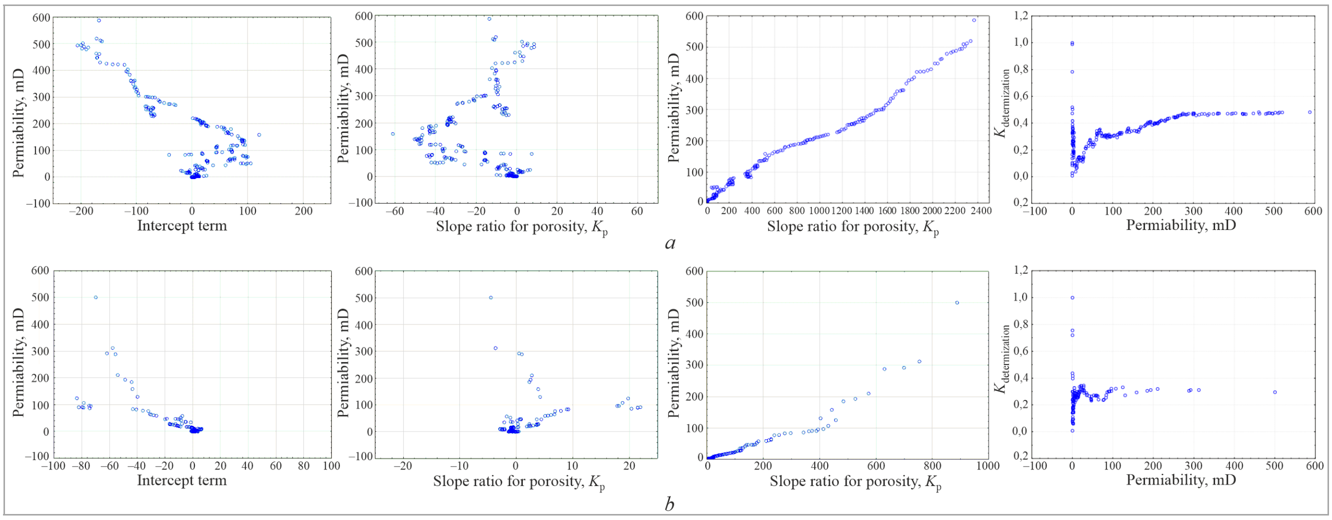


Fig. 2. The correlation fields of parameters of the regression equation: *a*) for sandstone, *b*) for aleurolite

Formation of a relation between K_p and ρ for aleurolite and sandstone is represented by two components that characterize the process of compaction and decompaction: one of them is significant correlationally , the second one is from points that fall out of the general relationship. When K_p is less than 20–22 %, a decrease in the indicator is observed with an increase in density, which is possibly associated with the presence of denser minerals in the pore space or with the rearrangement of crystal lattices into denser ones with a decrease in pore volume. Thus, a close, directly proportional relationship is noted, an increase in bulk density leads to an increase in K_{perm}.

To predict the values of K_{perm}, multidimensional regression equations were constructed, and a step-by-step regression analysis was carried out [40, 41]. Fig. 2 shows the correlation fields of the parameters of the regression equations.

In the obtained models for predicting the K_{perm} of sandstone and aleurolite, positive coefficients at K_p indicate a directly proportional dependence of K_{perm} on K_p, while it is possible to distinguish the multidirectional behavior of the permeability values at different intervals, which indicates a differentiated influence of K_p parameter in these parts. At the same time, for sandstone, the threshold value of the dependence is 150 mD, for aleurolite it is 100 mD. The correlation dependence on ρ for both sandstone and aleurolite has a linear trend. This indicates that the formation of K_{perm} value in the combination of K_p and ρ is of a differentiated nature, and ρ index is able to increase the filtration characteristic of rocks. Differences of multidimensional models for predicting K_{perm} for sandstone and aleurolite is associated with the nature of their formation processes.

This is an important factor in the formation of K_{perm}, as it changes the classical (based on the Geological and Mining Information System) logarithmic dependence of K_{perm} on K_p. In this case, when distributing K_{perm} in the three-dimensional space of oil and gas deposit, it is possible to use a refined interpolation of the indicator.

The change of the correlation coefficient *R* for sandstone and aleurolite is characterized by a significant difference depending on the considered range of K_{perm} change, which indicates a selective influence of the parameters on each other over the entire range of values.

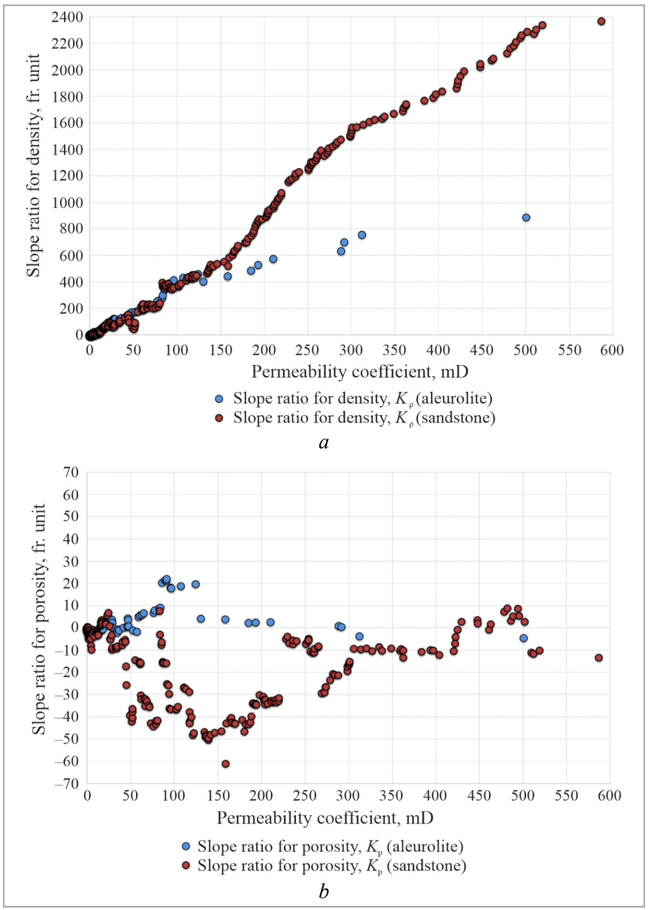
It should be noted that up to permeability value of 150 mD, the influence as per parameter ρ for sandstone and aleurolite is comparable; if it is above 150 mD, the dependence is stronger for sandstone than for aleurolite

(Fig. 3, a). That is, until a certain point, sandstones and aleurolites behave in the same way, then other kinds of sedimentation processes begin, and there is a mismatch in the degree of influence on the filtration properties. The dependence of permeability at the slope of porosity is shown in Fig. 3, b.

For porosity, the influence for aleurolite and sandstone at different intervals of permeability has a differentiated nature. While the maximum degree of mismatch stays within the permeability value of 150 mD.

The influence of porosity and density of rocks on permeability is different and is formed differently at different intervals of permeability, given that permeability is a function of density and porosity, it is possible to determine when they work together, and when separately. When it comes to prospects of further modeling of permeability, in addition to porosity and density, one should also take into account the lithological component of the reservoir rock, judging by the graphs, sandstone is characterized by a greater dispersion.

Obviously, the construction of a predictive dependence of permeability estimate for the objectives set is not so important for low permeability values as there are no oil reserves in them. Wells with high permeability (over 500 mD) are important in estimating reservoir properties for describing processes such as premature flooding, water breakthroughs, or high values of fluid and oil flow rates in single wells [42]. For the studied area, their share in porous reservoirs is less than 3 % [43].



a

b

Fig. 3. The relation for sandstones and aleurolite: *a*) slope ratio during bulk density of the rock and K_{perm}; *b*) slope ratio with porosity and K_{perm}

Conclusions

Finding relationships between parameters K_{perm}, K_{p} and ρ of the rock is of particular importance when developing a methodology for model matching in the interwell space. It also follows from the study results that taking into account the lithological component will allow differentiating the distribution of parameters, thereby clarifying the reservoir properties for a reservoir. When modeling a reservoir, it is necessary to switch from linearity to nonlinearity and take into account that the problem of permeability distribution in a reservoir being solved is more complicated. In different areas, sometimes permeability is not controlled by porosity, in principle, and in some areas only this parameter prevails. A reliable estimation taking into account the relationship between reservoir properties and the range of the most probable changes in K_{perm} values, will significantly increase efficiency of both geological and hydrodynamic modeling.

References

1. Khalimov E.M. Detal'nye geologicheskie modeli i trekhmernoe modelirovanie [Detailed geological models and three-dimensional simulation]. *Neftegazovaia tekhnologiia. Teoriia i praktika*, 2012, vol. 7, no. 3.
2. Rezvanov R.A., Smirnov O.A. Tipizatsiia kollektorov kak sredstvo povysheniia tochnosti opredeleniia pronitsaemosti [Reservoirs typification as a means of improving the permeability determining accuracy]. *Neftianoe khoziaistvo*, 2013, no. 2, pp. 42-45.
3. Koshovkin I.N., Belozerov V.B. Otobrazhenie neodnorodnostei terrigennykh kollektorov pri postroenii geologicheskikh modelei neftianykh mestorozhdenii [Display of heterogeneities of terrigenous reservoirs in the construction of geological models of oil fields]. *Izvestiia Tomskogo politekhnicheskogo universiteta*, 2007, vol. 310, no. 2, pp. 26-32.
4. Kozyrev N.D., Vishniakov A.Iu., Putilov I.S. Otsenka vliianiia parametrov neopredelennosti na prognozirovanie pokazatelei razrabotki [Assessment of the Uncertainty Parameters Influence on the Development Indicators Forecasting]. *Nedropol'zovanie*, 2020, vol. 20, no. 4, pp. 356-368. DOI: 10.15593/2712-8008/2020.4.5
5. Gavura V.E. Geologiia i razrabotka neftianykh i gazoneftianykh mestorozhdenii [Geology and development of oil and gas-oil fields]. Moscow: VNIIOENG, 1995.
6. Aziz Kh., Settari E. Matematicheskoe modelirovanie plastovykh sistem [Mathematical modeling of reservoir systems]. Moscow: Nedra, 1982.
7. Krichlou G.B. Sovremennaia razrabotka neftianykh mestorozhdenii - problemy modelirovaniia [Modern Oilfield Development – Modeling Problems]. Moscow: Nedra, 1979.
8. Nasybullin A.V., Antonov O.G. Postoianno deistvuiushchaia geologo-tekhnologicheskaia model' 3-go bloka Berezovskoi ploshchadi [Permanent geological and technological model of the 3rd block of the Berezovskaya area]. *Sbornik nauchnykh trudov TatNIPIneft'*. Moscow: VNIIOENG, 2012, iss. 80, pp. 91-95.
9. Reglament po sozdaniiu postoianno deistvuiushchikh geologo-tekhnologicheskikh modelei neftianykh i gazoneftianykh mestorozhdenii. RD 153-39.0-047-00 [Regulation on the creation of permanent geological and technological models of oil and gas-oil fields. GD 153-39.0-047-00]. Moscow: Ministerstvo topliva i energetiki Rossiiskoi Federatsii, 2000.
10. Boganik V.N., Medvedev A.I., Medvedeva A.Iu., Pestrikova N.A., Pestov V.V., Reznichenko V.A., Iarmetov V.L. Metodika perekhoda ot srednei kernovoi pronitsaemosti k "istinoi" [Technique of transition from average core permeability to "true"]. *Tekhnologii TEK. Neft' i kapital*, 2005, no. 1.
11. Mangazeev V.P., Belozerov V.B., Koshovkin I.N., Riazanov A.V. Metodika otobrazheniia v tsifrovoi geologicheskoi modeli litologo-fatsial'nykh osobennostei terrigennogo kollektora [Methods for displaying lithological-facies features of a terrigenous reservoir in a digital geological model]. *Neftianoe khoziaistvo*, 2006, no. 5.
12. Bobrov S.E., Evdoshchuk A.A., Rozbaeva G.L. Povyshenie tochnosti prognoza pronitsaemosti na osnove vydeleniia klassov kollektorov i ikh izucheniia v ob"eme plasta Hx-I Suzunskogo mestorozhdeniia [Improvement of the geological model forecast accuracy based on identification of reservoir classes and study of the same in Nh-I reservoir of Suzunkoye field]. *Neftianoe khoziaistvo*, 2013, no. 2, pp. 46-49.
13. Hovadik J.M., Larue D.K. Static characterization of reservoirs: refining the concepts of connectivity and continuity. *Petroleum Geoscience*, 2007, vol. 13, pp. 195-211. DOI:10.1144/1354-079305-697
14. Deriushev A.B. O neobkhodimosti sopostavleniia geologicheskikh i gidrodinamicheskikh kharakteristik zalezhei po dannym trekhmernogo modelirovaniia na primere produktivnogo plasta Tl2-b Nozhovskogo mestorozhdeniia nefti [On the need to compare geological and hydrodynamic characteristics of a deposit using 3D modelling as exemplified by the Tl_2-b pay bed of the Nozhovskoie oil field]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2014, no. 13, pp. 15-25. DOI: 10.15593/2224-9923/2014.13.2
15. Barskii M.G., Konoplev A.V., Khronusov V.V., Krivoshchekov S.N. Novyi instrument prostranstvennogo analiza geologo-geofizicheskoi informatsii – Template Analyst [New tool for spatial analysis of geological and geophysical information – Template Analyst]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2008, no. 8, pp. 17-20.
16. Vistelius A.V. Osnovy matematicheskoi geologii [Fundamentals of Mathematical Geology]. Leningrad: Nedra, 1980, 389 p.
17. Galkin V.I., Khizhniak G.P. O vliianii litologii na koeffitsient vytesneniia nefti vodoi [On the influence of lithology on the water-oil displacement efficiency]. *Neftianoe khoziaistvo*, 2012, no. 3, pp. 70-73.
18. Vinnikovskii C.A. et al. Geologicheskoe stroenie Kamsko-Kinel'skoi vpadiny v sviazi s neftegazonosnost'iu i uglenosnost'iu Permskoi oblasti [Geological structure of the Kamsko-Kinelskaya depression in connection with the oil and gas content and coal content of the Perm region]. *Geologiia i neftegazonosnost' Kamsko-Kinel'skikh progibov*. Kazan': Kazanskii universitet, 1970.
19. Vendel'shtein B.Iu., Zoloeva G.M., Tsareva N.V. et al. Geofizicheskie metody izucheniia podschetnykh parametrov pri opredelenii zapasov nefti i gaza [Geophysical methods for studying calculation parameters in determining oil and gas reserves]. Moscow: Nedra, 1985, 248 p.

20. Galkin V.I., Ponomareva I.N., Repina V.A. Issledovanie protsessa nefteizvlecheniia v kollektorakh razlichnogo tipa pustotnosti s ispol'zovaniem mnogomernogo statisticheskogo analiza [Study of Oil Recovery from Reservoirs of Different Void Types with Use of Multidimensional Statistical Analysis]. *Vestnik Permskogo natsional'nogo issledovatel'skogo politekhnicheskogo universiteta. Geologiia. Neftegazovoe i gornoe delo*, 2016, vol. 15, no. 19, pp. 145-154. DOI: 10.15593/2224-9923/2016.19.5
21. Gmurman V.E. Teoriia veroiatnostei i matematicheskaia statistika [Theory of Probability and Mathematical Statistics]. 10nd ed. Moscow: Vysshaia shkola, 2004, 479 p.
22. Devis Dzh. Statistika i analiz geologicheskikh dannykh [Geological data statistics and analysis]. Moscow: Mir, 1977, 353 p.
23. Devis Dzh.S. Statisticheskii analiz dannykh v geologii [Statistical data analysis in geology]. Moscow: Nedra, 1990, book 1, 319 p.
24. Devis Dzh.S. Statisticheskii analiz dannykh v geologii [Statistical data analysis in geology]. Moscow, 1990, book 2, 426 p.
25. Dement'ev L.F., Zhdanov M.A., Kirsanov A.N. Primenenie matematicheskoi statistiki v neftepromyslovoi geologii [Application of mathematical statistics in oilfield geology]. Moscow: Nedra, 1977. – 255 c.
26. Tiab D. Modern Core Analysis. Vol. 1: Theory, Core Laboratories. Houston, Texas, 1993, 200 p.
27. Warren J.E., Root P.J. The Behavior of Naturally Fractured Reservoirs. *Soc. Petrol. Eng. J*, 1963.
28. Watson G.S. Statistic on spheres. New York: John Wiley and Sons, Inc., 1983, 238 p.
29. Yang Xin-She. Mathematical modeling for Earth Sciences. Dunedin Academic Press ltd, 2008, 310 p.
30. Yarus J.M. Stochastic modeling and geostatistics. *AAPG*. Tulsa, Oklahoma, 1994, 231 p.
31. Repina V.A., Galkin V.I., Galkin S.V. Primenenie kompleksnogo ucheta petrofizicheskikh kharakteristik pri adaptatsii geologo-gidrodinamicheskikh modelei (na primere vizeiskoi zalezhi Gondyrevskogo mestorozhdeniia nefti) [Complex petrophysical correction in the adaptation of geological hydrodynamic models (on the example of Visean pool of Gondyrev oil field)]. *Zapiski Gornogo instituta*, 2018, vol. 231, pp. 268-274. DOI: 10.25515/pmi.2018.3.268
32. Amanat U. Chaudry. Oil well testing handbook. Advanced TWPSON Petroleum Systems Inc. Houston, 2004, 525 p.
33. Yortsos Yannis C., Choi Youngmin, Yang Zhengming, Piyush C. Shah. Analysis and interpretation of the water-oil ratio in waterfloods. *SPE Annual Technical Conference and Exhibition*, 5-8 October. San Antonio, Texas, 1997, pp. 413-434. DOI: 10.2118/38869-MS
34. Anisur Rahman N.M., Bin Akresh S.A., Al-Thawad F.M. Diagnosis and characterization of cross flow behind casing from transient-pressure tests. *SPE Annual Technical Conference and Exhibition*, 28-30 September, Houston, Texas, 2015. DOI: 10.2118/174999-MS
35. Chan K.S. Water control diagnostic plots. Paper SPE 30755. *SPE Annual Technical Conference and Exhibition*, 22-25 October. Dallas, Texas, 1995, pp. 755-763. DOI: 10.2118/30775-MS
36. Gladkov E.A. Geologicheskoe i gidrodinamicheskoe modelirovanie mestorozhdenij nefti i gaza [Geological and hydrodynamic modeling of oil and gas fields]: uchebnoe posobie. – Tomsk: Izd-vo Tomsk. politekhn. un-ta, 2012. – 99 s.
37. Dement'ev L.F. Matematicheskie metody i EVM v neftegazovoi geologii [Mathematical methods and computers in oil and gas geology]. Moscow: Nedra, 1983, 62 p.
38. Dement'ev L.F. Sistemnye issledovaniia v neftegazopromyslovoi geologii [System studies in oil and gas field geology]. Moscow: Nedra, 1988, 204 p.
39. Prisiazhniuk M.A., Vishniakov A.Iu. K voprosu o sopostavlenii znachenii pronitsaemosti v geologicheskoi i gidrodinamicheskoi modeliakh [On the issue of comparing permeability values in geological and hydrodynamic models]. *Problemy razrabotki mestorozhdenii uglevodorodnykh i rudnykh poleznykh iskopaemykh. Materialy XI Vserossiiskoi nauchno-tekhnicheskoi konferentsii*, Perm', 7-9 November 2018. Perm': Permskii natsional'nyi issledovatel'skii politekhnicheskii universitet, 2018, pp. 187-189.
40. Galkin S.V., Poplaukhina T.B., Raspopov A.V., Khizhniak G.P. Otsenka koeffitsientov izvlecheniia nefti dlia mestorozhdenii Permskogo kraia na osnove statisticheskikh modelei [Estimation of oil recovery ratios for Permskiy region fields on the basis of statistical models]. *Neftianoe khoziaistvo*, 2009, no. 4, pp. 38-39.
41. Dreiper N., Smit G. Prikladnoi regressionnyi analiz [Applied regression analysis]. Moscow: Vil'iams, 2007.
42. Nikolaev M.N., Ermilov E.V., Gnilitskii R.A., Sagaidachnaia A.S., Konienko S.A. Kompleksirovanie istoricheskikh dannykh pri obosnovanii prostranstvennogo rasprostraneniia i fil'tratsionnykh svoistv vysokopronitsaemykh intervalov v razreze plastov sherkalinskoi svity Talinskoi ploshchadi [Integration of history data at justification of space distribution and reservoir properties of high permeable intervals of Sherkalinskaya suit, Talinskaya area]. *Neftianoe khoziaistvo*, 2013, no. 3, pp. 28-31.
43. Poplygin V.V., Galkin S.V. Prognoznaia ekspress-otsenka pokazatelei razrabotki neftianykh zalezhei [Forecast quick evaluation of the indices of the development of the oil deposits]. *Neftianoe khoziaistvo*, 2011, no. 3, pp. 112-115.

Библиографический список

1. Халимов Э.М. Детальные геологические модели и трехмерное моделирование // Нефтегазовая технология. Теория и практика. – 2012. – Т. 7, № 3.
2. Резванов Р.А., Смирнов О.А. Типизация коллекторов как средство повышения точности определения проницаемости // Нефтяное хозяйство. – 2013. – № 2. – С. 42–45.
3. Кошовкин И.Н., Белозеров В.Б. Отображение неоднородностей терригенных коллекторов при построении геологических моделей нефтяных месторождений // Известия Томского политехнического университета. – 2007. – Т. 310, № 2. – С. 26–32.
4. Козырев Н.Д., Вишняков А.Ю., Путилов И.С. Оценка влияния параметров неопределенности на прогнозирование показателей разработки // Недропользование. – 2020. – Т. 20, № 4. – С. 356–368. DOI: 10.15593/2712-8008/2020.4.5
5. Гавура В.Е. Геология и разработка нефтяных и газонефтяных месторождений. – М.: ВНИИОЭНГ, 1995.
6. Азиз Х., Сеттари Э. Математическое моделирование пластовых систем. – М.: Недра, 1982.
7. Кричлоу Г.Б. Современная разработка нефтяных месторождений – проблемы моделирования. – М.: Недра, 1979.
8. Насыбуллин А.В., Антонов О.Г. Постоянно действующая геолого-технологическая модель 3-го блока Березовской площади // Сборник научных трудов ТатНИПИнефть / ОАО «Татнефть». – М.: ВНИИОЭНГ, 2012. – Вып. 80. – С. 91–95.
9. Регламент по созданию постоянно действующих геолого-технологических моделей нефтяных и газонефтяных месторождений. РД 153-39.0-047-00. – М.: Министерство топлива и энергетики Российской Федерации, 2000.
10. Методика перехода от средней керновой проницаемости к «истиной» / В.Н. Боганик, А.И. Медведев, А.Ю. Медведева, Н.А. Пестрикова, В.В. Пестов, В.А. Резниченко, В.Л. Ярметов // Технологии ТЭК. Нефть и капитал. – 2005. – № 1.
11. Методика отображения в цифровой геологической модели литолого-фациальных особенностей терригенного коллектора / В.П. Мангазеев, В.Б. Белозеров, И.Н. Кошовкин, А.В. Рязанов // Нефтяное хозяйство. – 2006. – № 5.
12. Бобров С.Е., Евдощук А.А., Розбаева Г.Л. Повышение точности прогноза проницаемости на основе выделения классов коллекторов и их изучения в объеме пласта Нх-I Сузунского месторождения // Нефтяное хозяйство. – 2013. – № 2. – С. 46–49.
13. Hovadik J.M., Larue D.K. Static characterization of reservoirs: refining the concepts of connectivity and continuity // Petroleum Geoscience. – 2007. – Vol. 13. – P. 195–211. DOI:10.1144/1354-079305-697
14. Дерюшев А.Б. О необходимости сопоставления геологических и гидродинамических характеристик залежей по данным трехмерного моделирования на примере продуктивного пласта Тл2-б Ножовского месторождения нефти // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2014. – № 13. – С. 15–25. DOI: 10.15593/2224-9923/2014.13.2
15. Новый инструмент пространственного анализа геолого-геофизической информации – Template Analyst / М.Г. Барский, А.В. Коноплев, В.В. Хронусов, С.Н. Кривощеков // Геология, геофизика и разработка нефтяных и газовых месторождений. – 2008. – № 8. – С. 17–20.
16. Вистелиус А. В. Основы математической геологии. – Л.: Недра, 1980. – 389 с.
17. Галкин В.И., Хижняк Г.П. О влиянии литологии на коэффициент вытеснения нефти водой // Нефтяное хозяйство. – 2012. – № 3. – С. 70–73.
18. Геологическое строение Камско-Кинельской впадины в связи с нефтегазоносностью и угленосностью Пермского области / С.А. Винниковский [и др.] // Геология и нефтегазоносность Камско-Кинельских прогибов. – Казань: Изд-во Казан. ун-та, 1970.
19. Геофизические методы изучения подсчетных параметров при определении запасов нефти и газа / Б.Ю. Вендельштейн, Г.М. Золоева, Н.В. Царева [и др.]. – М.: Недра, 1985. – 248 с.
20. Галкин В.И., Пономарева И.Н., Репина В.А. Исследование процесса нефтеизвлечения в коллекторах различного типа пустотности с использованием многомерного статистического анализа // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2016. – Т. 15, № 19. – С. 145–154. DOI: 10.15593/2224-9923/2016.19.5
21. Гмурман В.Е. Теория вероятностей и математическая статистика: учебное пособие для вузов. – 10-е изд., стереотип. – М.: Высшая школа, 2004. – 479 с.
22. Девис Дж. Статистика и анализ геологических данных. – М.: Мир, 1977. – 353 с.
23. Девис Дж.С. Статистический анализ данных в геологии. – М.: Недра, 1990. – Кн. 1. – 319 с.
24. Девис Дж.С. Статистический анализ данных в геологии. – М.: Недра, 1990. – Кн. 2. – 426 с.
25. Дементьев Л.Ф., Жданов М.А., Кирсанов А.Н. Применение математической статистики в нефтепромысловой геологии. – М.: Недра, 1977. – 255 с.
26. Tiab D. Modern Core Analysis. Vol. 1: Theory, Core Laboratories. – Houston, Texas, 1993. – 200 p.
27. Warren J.E., Root P.J. The Behavior of Naturally Fractured Reservoirs // Soc. Petrol. Eng. J. – 1963.
28. Watson G.S. Statistic on spheres. – New York: John Wiley and Sons, Inc., 1983. – 238 p.
29. Yang Xin-She. Mathematical modeling for Earth Sciences. – Dunedin Academic Press ltd, 2008. – 310 p.
30. Yarus J.M. Stochastic modeling and geostatistics / AAPG. – Tulsa, Oklahoma, 1994. – 231 p.
31. Репина В.А., Галкин В.И., Галкин С.В. Применение комплексного учета петрофизических характеристик при адаптации геолого-гидродинамических моделей (на примере визейской залежи Гондыревского месторождения нефти) // Записки Горного института. – 2018. – Т. 231. – С. 268–274. DOI: 10.25515/pmi.2018.3.268
32. Amanat U. Chaudry. Oil well testing handbook / Advanced TWPSON Petroleum Systems Inc. – Houston, 2004. – 525 p.
33. Analysis and interpretation of the water-oil ratio in waterfloods / C. Yortsos Yannis, Choi Youngmin, Yang Zhengming, C. Shah. Piyush // SPE Annual Technical Conference and Exhibition, 5–8 October. – San Antonio, Texas, 1997. – P. 413–434. DOI: 10.2118/38869-MS
34. Anisur Rahman N.M., Bin Akresh S.A., Al-Thawad F.M. Diagnosis and characterization of cross flow behind casing from transient-pressure tests // SPE Annual Technical Conference and Exhibition, 28–30 September, Houston, Texas, 2015. DOI: 10.2118/174999-MS
35. Chan K.S. Water control diagnostic plots. Paper SPE 30755 // SPE Annual Technical Conference and Exhibition, 22–25 October. – Dallas, Texas, 1995. – P. 755–763. DOI: 10.2118/30775-MS
36. Гладков Е.А. Геологическое и гидродинамическое моделирование месторождений нефти и газа: учебное пособие. – Томск: Изд-во Томск. политехн. ун-та, 2012. – 99 с.
37. Дементьев Л.Ф. Математические методы и ЭВМ в нефтегазовой геологии: учеб. пособие для вузов. – М.: Недра, 1983. – 62 с.
38. Дементьев Л.Ф. Системные исследования в нефтегазопромысловой геологии: учеб. пособие для вузов. – М.: Недра, 1988. – 204 с.
39. Присяжнюк М.А., Вишняков А.Ю. К вопросу о сопоставлении значений проницаемости в геологической и гидродинамической моделях // Проблемы разработки месторождений углеводородных и рудных полезных ископаемых : материалы XI Всерос. науч.-техн. конф., Пермь, 7–9 нояб. 2018 г / М-во науки и высш. образования Рос. Федерации, Перм. нац. исслед. политехн. ун-т. – Пермь: Изд-во ПНИПУ, 2018. – С. 187–189.
40. Оценка коэффициентов извлечения нефти для месторождений Пермского края на основе статистических моделей / С.В. Галкин, Т.Б. Поплаухина, А.В. Распопов, Г.П. Хижняк // Нефтяное хозяйство. – 2009. – № 4. – С. 38–39.
41. Дрейпер Н., Смит Г. Прикладной регрессионный анализ. – М.: Изд. дом «Вильямс», 2007.
42. Комплексирование исторических данных при обосновании пространственного распространения и фильтрационных свойств высокопроницаемых интервалов в разрезе пластов шеркалинской свиты Талинской площади / М.Н. Николаев, Е.В. Ермилов, Р.А. Гнилицкий, А.С. Сагайдачная, С.А. Кониенко // Нефтяное хозяйство. – 2013. – № 3. – С. 28–31.
43. Поплыгин В.В., Галкин С.В. Прогнозная экспресс-оценка показателей разработки нефтяных залежей // Нефтяное хозяйство. – 2011. – № 3. – С. 112–115.