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Interpretation of NMR data in the complex of laboratory work on the study of core (on the example of terrigenous deposits of the Timano-Pechora oil and gas province)

Alexandr V. Raznitsyn

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

Интерпретация данных исследований методом ядерного магнитного резонанса в комплексе лабораторных работ по изучению керна (на примере терригенных отложений Тимано-Печорской нефтегазоносной провинции)

А.В. Разницын

Филиал ООО «ЛУКОЙЛ-Инжиниринг» «ПермНИПИнефть» в г. Перми (Россия, 614015, г. Пермь, ул. Пермская, 3а)

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The petrophysical characteristics of the productive deposits in one Timan-Pechora oil and gas province fields were determined by interpreting the data of the nuclear magnetic resonance (NMR) method in the complex of laboratory core studies.
NMR studies were carried out on 38 core samples of a standard size (30×30 mm) with full and partial (residual) saturation of the reservoir water model. For a comprehensive interpretation of the data obtained, the results of standard (determination of porosity, absolute gas permeability, etc.), special (capillarimetric studies, determination of wettability) and lithological-petrographic (macro-description of the core, description of thin sections) core studies were involved. All studies were carried out on modern verified equipment in accordance with approved state, industry and production measurement methods in an accredited testing center. When interpreting NMR data, both well-established and generally accepted methods were used, and new possible approaches were proposed to obtain additional information about the petrophysical characteristics of rocks.
Using the indicated methods, the following results were obtained: the coefficients of porosity and residual water saturation were determined, the values of the boundary cutoffs of the transverse relaxation times T_{2bound} separating free water from bound water were studied, the distribution of residual water in the void space of the samples was studied, pore size distributions were constructed, the size of the pore channels connecting them, the influence of the wettability of the pore surface on the results of NMR studies (in the "gas - water" system) was studied.
The conducted studies showed the effectiveness of using the NMR method in the complex of laboratory studies of the core of hydrocarbon fields. The proposed approaches to the interpretation of experimental data make it possible to obtain additional information about the features of the structure of the void space of rocks and, undoubtedly, require further testing and development. The information obtained could be used for petrophysical support of geological and hydrodynamic modeling of a hydrocarbon deposit.

Ключевые слова:
ядерный магнитный резонанс (ЯМР), коэффициент пористости, структура пустотного пространства, коэффициент остаточной водонасыщенности, лабораторные исследования керна, терригенный коллектор, радиус поровых каналов, релаксационная активность, радиус пор, удельная поверхность, смачиваемость, пленка воды, капиллярно-удерживаемая вода, время поперечной релаксации, уравнение Козени-Кармана.

Осуществлено определение петрофизических характеристик продуктивных отложений одного из месторождений Тимано-Печорской нефтегазоносной провинции путем интерпретации данных метода ядерного магнитного резонанса (ЯМР) в комплексе лабораторных исследований керна.
ЯМР-исследования проведены на 38 образцах керна стандартного размера (30×30 мм) при полном и частичном (остаточном) насыщении моделью пластовой воды. Для комплексной интерпретации полученных данных привлечены результаты стандартных (определение пористости, абсолютной газопроницаемости и т.д.), специальных (капилляриметрические исследования, определение смачиваемости) и литолого-петрографических (макроописание керна, описание шлифов) исследований керна. Все исследования проведены на современном поверенном оборудовании в соответствии с утвержденными государственными, отраслевыми и производственными методиками измерений в аккредитованном испытательном центре. При интерпретации данных ЯМР применены как хорошо зарекомендовавшие себя и общепринятые методы, так и предложены новые возможные подходы к получению дополнительной информации о петрофизических характеристиках горных пород.
С помощью обозначенных методов получены следующие результаты: определены коэффициенты пористости и остаточной водонасыщенности, значения граничных отсечек времен поперечной релаксации $T_{2гр}$, отделяющие свободную воду от связанной, изучен характер распределения остаточной воды в пустотном пространстве образцов, построены распределения пор по размерам, установлена связь размера пор с размером соединяющих их поровых каналов, изучено влияние смачиваемости поровой поверхности на результаты ЯМР-исследований (в системе «газ – вода»).
Проведенные исследования показывают эффективность применения метода ЯМР в комплексе лабораторных исследований керна углеводородных месторождений. Предложенные подходы к интерпретации экспериментальных данных позволяют получить дополнительные сведения об особенностях строения пустотного пространства горных пород и, несомненно, требуют дальнейших апробации и развития. Полученная информация может быть использована для петрофизического обеспечения геологического и гидродинамического моделирования углеводородной залежи.

© **Alexandr V. Raznitsyn** (Author ID in Scopus: 57219358238) – PhD in Engineering, 1st category Engineer, Department of Petrophysical Research (tel.: +007 (342) 717 01 87, e-mail: alexandrraznitsyn@gmail.com).

© **Разницын Александр Вячеславович** – кандидат технических наук, инженер первой категории, отдел петрофизических исследований (тел.: +007 (342) 717 01 87, e-mail: alexandrraznitsyn@gmail.com).

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Introduction

After its discovery in 1946 the phenomenon of nuclear magnetic resonance (NMR) has found wide application in various fields of science and practice including oil and gas geology in the study of the petrophysical productive sediments characteristics. The physical foundations of the method are described detailed in this paper [1].

NMR is a non-destructive method for studying rocks which makes it possible to determine various petrophysical characteristics of productive deposits: porosity, residual water saturation, void space structure, wettability and others [1–12]. Its use in a complex of laboratory core studies makes it possible to obtain additional, and sometimes unique, information about the rocks properties.

Using the core of terrigenous sediments from one of the Timan-Pechora oil and gas province fields the work shows the interpretation of NMR data within the framework of petrophysical studies: the coefficients of porosity and residual water saturation are determined, approaches are proposed for assessing the nature of the distributing residual water in the void space determining pore sizes, as well as the influence of wettability on the NMR studies results was studied.

Characteristics of the study object. Used data

The study object is a core of Eifelian D_2ef and Stary Oskol D_2st productive sediments selected from wells from one of the the Timan-Pechora oil and gas province fields (Komi Republic). The deposits are represented by quartz fine-, medium-fine-, coarse-medium- and inequigranular sandstones, predominantly weakly clayey and quartz inequigranular siltstones.

NMR studies were carried out on 38 standard-sized core samples. Before the studies the samples were extracted and dried according to all-Union State Standart (GOST) 26450.0-85 [13]. As a result of the studies distributions of NMR porosity were obtained by transverse relaxation times T_2 on samples completely saturated with the synthetic brine and at residual water saturation, which was created by displacing water with gas in a group capillarimeter according to all-Union Standart (OST) 39-204-86 [14]. In addition, a standard set of core studies (the coefficients of open porosity and absolute gas permeability were determined) and capillarimetric studies in the gas-water system were carried out on the samples as well as the wettability of the pore surface was determined on some of the samples in accordance with all-Union Standart (OST) 39-180-85 [15]. Also microdescription data of petrographic thin sections selected from the sites where samples were cut and lithological macro-description of the core were selected for analysis.

The coefficient of open porosity from the studied rocks varies from 9.16 to 27.92 %, averaging 20.09 %, the coefficient of absolute gas permeability varied from 0.567 to 7427.000 mD, the geometric mean is 289.183 mD. In terms of their permeability and porosity (RQ) the studied sediments belong to pore-type reservoirs (Fig. 1).

Determination of porosity coefficient using NMR method

Determining the porosity coefficient is one of the main tasks during NMR studies [16]. It is believed that the NMR method makes it possible to estimate the total porosity of rocks, which the results do not depend on the lithological features of the deposits [17]. However, while conducting NMR studies, it is necessary to take into account the value of the hydrogen index of the liquid saturating the rock [18].

In Figure 2 it is shown a comparison of porosity coefficients determined by NMR and liquid saturation methods (according to all-Union State Standart (GOST) 26450.1-85 [19]). Good convergence of the obtained data is observed. The results of lithological and petrographic studies show that the studied sediments are mostly characterized by a minimum content of the clay fraction, and therefore the data for determining porosity by the two methods are comparable. Experience in studying

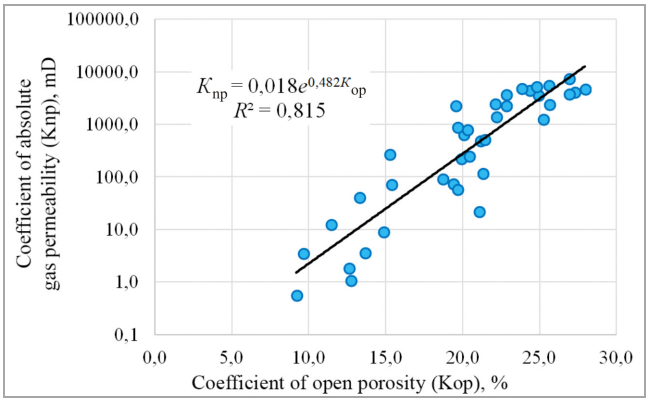

Fig. 1. Dependence between the coefficient of absolute gas permeability and the coefficient of open porosity

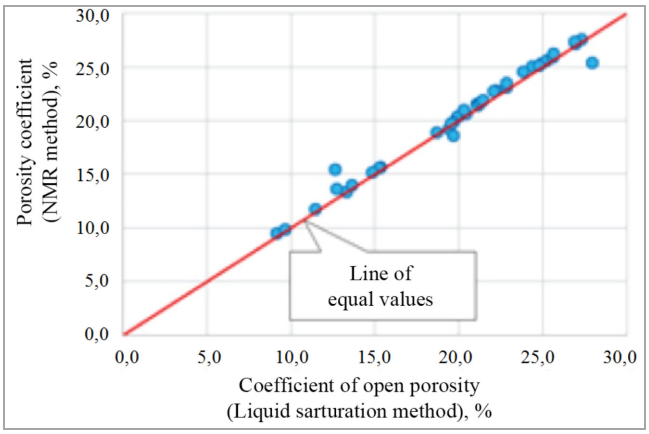

Fig. 2. Comparison of porosity coefficients determined by NMR and liquid saturation methods

terrigenous rocks shows that increasing porosity values determined by the NMR method exceed those obtained by the liquid saturation method was obtained for samples with a high content of pelitic particles, which is connected with the presence of clay-bound water not removed during drying [20, 21].

Estimating the size of the pores composing void space

The NMR method is one for studying the structure of the void rocks space. While performing NMR studies, normally the T_2 transverse relaxation times are measured due to the reduction in time costs. In the case of complete filling a core sample with one fluid and the absence of a magnetic field gradient the transverse relaxation time of an individual pore is determined by the equation [16]:

$$\frac{1}{T_2} = \rho_2 \frac{S}{V} + \frac{1}{T_{2св}}, \quad (1)$$

where T_2 is the observed relaxation time, ms; ρ_2 is a relaxation rock activity for transverse relaxation, μm/ms; S/V is ratio of pore area to its volume (specific surface area), $μm^2/μm^3$; $T_{2св}$ is time of transverse relaxation of the fluid saturating the rock in the free volume, ms. The second term on the right side of the above equation is usually neglected due to the fact that its contribution is insignificant [16, 22, 23].

The relaxation rock activity is a parameter that characterizes the ability of the pore rock surface to influence the relaxation of the fluid saturating the void space and depends on the mineralogical rock composition and the type of fluid [24, 25]. The difference in estimating this parameter is quite large: D. Chang et al. [26] suggest using a value of 0.005 μm/ms for carbonate rocks and 0.015 μm/ms for sandstones; V.A. Murtsovkin obtained relaxation activity values in the range of 0.0076–0.083 μm/ms [27] based on a multilattice capillary

model for sandstones of productive deposits in Western Siberia; according to M.Y. Shumskaite [23] the values of relaxation activity vary in the range from 0.004 to 0.059 μm/ms for terrigenous rocks of Western Siberia; A.S. Denisenko [22] gives the following ranges of variation of this characteristic: 0.05–0.3 and 0.01–0.05 μm/ms, respectively, for terrigenous and carbonate rocks.

Estimating the magnitude of relaxation activity is associated with the difficulty of determining the specific surface rock area. There are several "direct" methods for measuring specific surface area [28], where the most common is the vapor adsorption isotherm method (calculation using the Brunauer, Emmett and Teller (BET) method). It is also possible to estimate the specific surface area based on capillarimetric studies, image analysis of petrographic thin sections and granulometric analysis using simplified models of the void rocks space structure. B. Basan et al. [29] note that the value of relaxation activity significantly depends on the method used to determine the specific surface rock area: thus, differences in the values of relaxation activity can reach three orders of magnitude while comparing image analysis and BET methods.

To "set up" the NMR method (determining relaxation activity), normally the results of capillarimetric studies or image analysis of thin sections are used [22, 30]. At the same time, many researchers note that NMR allows one to estimate the size of pores [22, 31–33] and not the pore channels connecting them, which size determination is the task of capillarimetric studies. Accordingly, it is not always correct to adjust NMR data based on the results of capillarimetric studies.

To estimate the specific surface area you can use the following equation which is the variant of the Kozeny–Karman equation [34]:

$$S_{уд} = \frac{K_п\sqrt{K_п}}{\sqrt{2K_{пр}}}, \quad (2)$$

where $S_{уд}$ – specific surface, m^2/m^3; $K_п$ – porosity coefficient, fractions of units; $K_{пр}$ – permeability coefficient, m^2. It is worth noting that this equation was derived theoretically for a model of a porous medium with cylindrical pore channels. It is also necessary to point out that the value calculated using this equation is the specific surface area of the filter channels and, with a significant content of clay particles, does not reflect the full specific surface area of the rock due to the fact that the huge surface of small pores located between the pelitic particles does not participate in the filtration process [35]. Since the core samples studied in this work are not clay in their lithological characteristics, the use of this equation for an approximate estimate of the specific surface area is quite legitimate.

As a result of applying equation (2), the specific surface area was calculated for all samples: for sandstones, its value varies from 0.036 to 0.452 $μm^2/μm^3$, and for siltstones – from 0.419 to 1.408 $μm^2/μm^3$.

To estimate the relaxation activity, we will assume that within the sample for all groups of pores its value remains constant. For the i-th group of pores (of the same size) equation (1) takes the following form (without the second term on the right side):

$$\frac{1}{T_{2i}} = \rho_2 \frac{S_i}{V_i}. \quad (3)$$

Rewriting equation (3) with respect to the specific surface area, we obtain:

$$\frac{S_i}{V_i} = \frac{1}{T_{2i}\rho_2}. \quad (4)$$

The total specific surface area can be expressed in terms of NMR porosity as follows:

$$S_{уд} = \frac{1}{K_п}\sum_{i=1}^{n}\frac{S_i K_{пi}}{V_i}, \quad (5)$$

where $K_{пi}$ is the porosity of the i-th pores group, unit fractions; $K_п$ is the sample porosity, unit fractions.

Substituting equation (4) into equation (5) and solving it for relaxation activity, we obtain:

$$\rho_2 = \frac{1}{K_п S_{уд}}\sum_{i=1}^{n}\frac{K_{пi}}{T_{2i}}. \quad (6)$$

In equation (6) the value of the specific surface area is obtained from the data of determining the coefficients of porosity and permeability based on equation (2), the remaining parameters are obtained from the NMR studies results.

As a result of calculations, relaxation activity values were determined for all samples which ranged from 0.033 to 0.635 μm/ms averaging 0.174 μm/ms.

Since while calculating the specific surface, the void space was taken in the form of a capillary tubes bundle (equation (2)), the specific surface can be expressed in terms of the capillary radius, and for the transition from relaxation times to the pore radius, equation (3) can be written in the following form:

$$R_i = 2\rho_2 T_{2i}, \quad (7)$$

where R_i is the radius of pores of the i-th group, μm.

As a result of calculations, pore size distributions were constructed for all samples. The order of pore size is comparable to the data from the petrographic description of thin sections, and their size is larger than the size of the pore channels determined as a result of capillarimetric studies. As an example in Figure 3 it is shown a comparing the distributions of pore channels and pores for one of the samples under study: it is clear that the distributions have a similar form but the radius of the pores is much larger than the radius of the channels connecting them.

Also, as a result of the research, it was established a fairly close relationship between the weighted average radius of pore channels, determined according to capillarimetric studies, and the logarithmic average value of the pore radii (Fig. 4), which is calculated from equation (7) where T_2logmean (logarithmic average value of transverse relaxation times), determined by the formula [36] is substituted for T_{2i}:

$$T_2\text{logmean} = 10^{\frac{\sum K_{пi}\lg(T_{2i})}{\sum K_{пi}}}, \quad (8)$$

where T_2logmean is the logarithmic mean value of transverse relaxation times, ms; Кпi is i-th porosity, unit fractions, corresponding to the i-th value of T_{2i}, ms. The presence of this connection justifies the possibility of using the so-called "dumbbell" model [37] while describing the void space of the studied deposits.

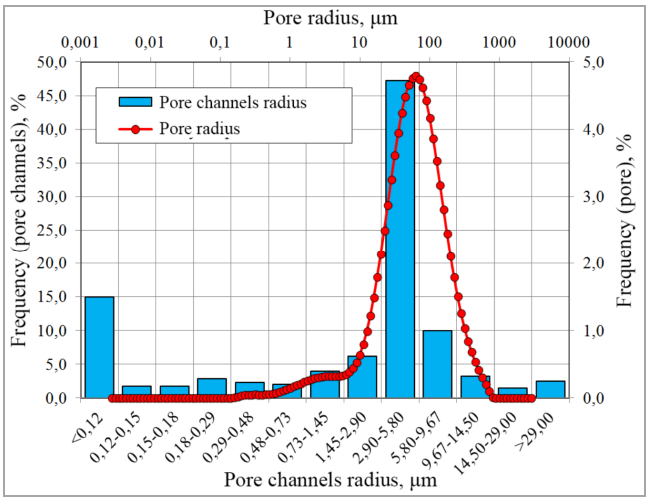

Fig. 3. Comparison of radius distributions pore channels and pores of the core sample

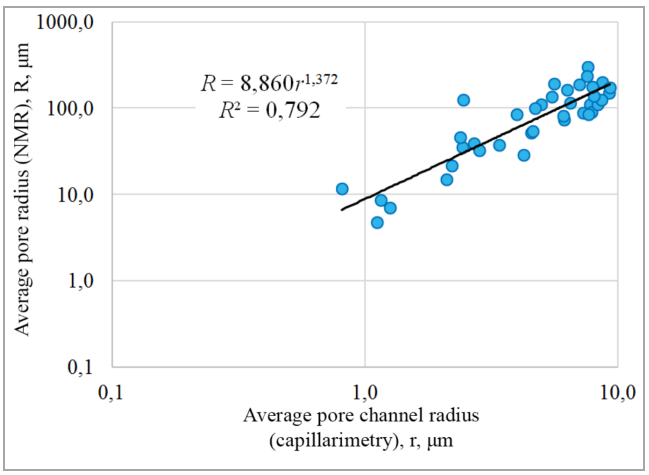

Fig. 4. Relationship between the average pore radius (NMR) and the average radius of pore channels (capillarimetry)

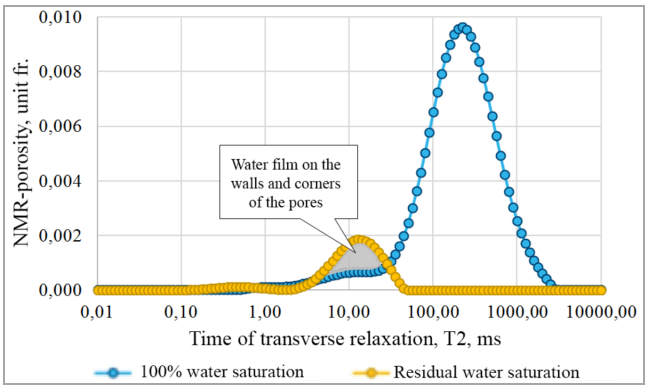

Fig. 5. NMR porosity distributions over time of transverse relaxation T_2 with complete and residual water saturation of the core sample

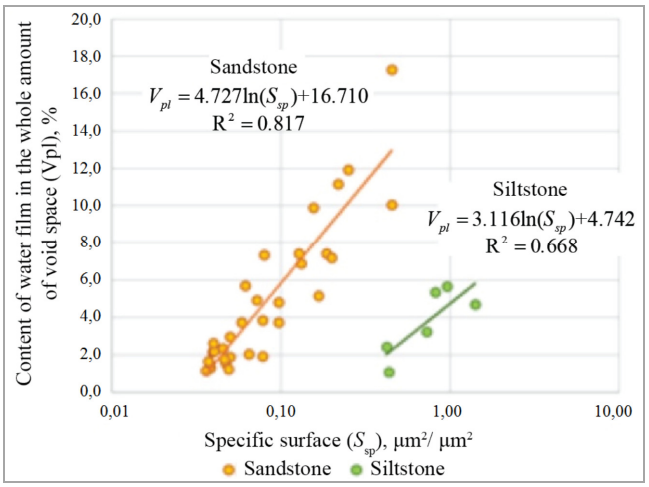

Fig. 6. Dependence of water film content in general void space volume from specific surface

Determining size and character of distributing residual water saturation

To determine the values of the residual water saturation coefficient from NMR data, the boundary cutoff method was used, the which essence is to find the boundary value of the transverse relaxation time T2rp separating free water from bound one [16]. To find the boundary cutoff time two measurements of transverse relaxation times are carried out: at full water saturation and at residual water saturation which in this work was achieved by the semipermeable membrane method [14].

The resulting cutoff values range from 19.076 to 631.227 ms, averaging 119.936 ms. The value of the coefficient of residual water saturation for the studied rocks according to NMR data varies from 2.16 to 77.23 %, the average value is 20.67 %.

A joint analysis of porosity distributions over transverse relaxation times T_2 with complete and partial (residual) water saturation of the sample allows us to obtain additional information about the distribution of residual water saturation in the void space of rocks. In capillarimetric studies not displaced by gas water is retained by surface tension forces in thin capillaries, completely filling them, and also in the form of film on the walls and corners of large pores [35]. An increase in NMR porosity values in the region of small relaxation times at residual water saturation compared to values at full saturation indicates the formation of a thin film of residual water on the walls and corners of the pores [38]. As an example in Figure 5 it is shown the distributions of NMR porosity over transverse relaxation times T_2 at complete and residual water saturation in one of the core samples under study: in the range of relaxation times from 5 to 30 ms, a significant excess of NMR porosity at residual water saturation is observed over the values at full water saturation which caused by the formation of water film when it is displaced by air from large pores.

For all samples the volume of water present in the form of film on the walls and in the corners of the pores was calculated. The content of this water type from the total volume of residual water for sandstones varies from 22.23 to 75.27 %, averaging 41.98 %, and for siltstones varies from 1.72 to 8.19 %, the average value is 5.43 %. It can be seen that for siltstones the predominant type of residual water is capillary-retained. The proportion of residual water in the form of a film on the walls and in the corners of the pores in the total volume of the void space was also calculated. It is expected that its content is closely related to the specific pore surface area (Fig. 6), while the data for sandstones and siltstones are approximated by different equations.

Influence of wettability on results Of NMR studies

The influence of pore surface wettability on the results of rocks NMR studies was firstly shown in 1956 in the publication of R.J.S. Brown and I. Fatt [39]. Since then, various researchers have developed a large number of methods and indices for assessing the wettability of productive sediments based on NMR data [40–56].

Let us consider the influence of wettability on the results of determining transverse relaxation times when water is displaced from a sample by air in the process of modeling residual water saturation. In respond to complete saturation of the core sample with water, the transverse relaxation time of a single pore is determined by the following equation:

$$\frac{1}{T_2\left(K_в = 1\right)} = \rho_2 \frac{S_п}{V_п}, \qquad (9)$$

where Sп is pore area, μm²; Vп is pore volume, μm³.

When water is displaced by air and residual water saturation is achieved, the relaxation time will be determined by the equation

$$\frac{1}{T_2\left(K_{ов}\right)} = \rho_2 \frac{S_{ов}}{K_{ов} V_п}, \qquad (10)$$

where Sов is the pore area occupied by residual water, μm²; Kов is a coefficient of residual water saturation, unit fractions.

Dividing equations (9) and (10) by one another, we obtain:

$$\frac{T_2\left(K_{ов}\right)}{T_2\left(K_в = 1\right)} = \frac{K_{ов} S_п}{S_{ов}}. \qquad (11)$$

In the case of a hydrophilic surface a film of residual water completely covers the surface of the pore, then Sов = Sп, and equation (11) can be written:

$$\frac{T_2\left(K_{ов}\right)}{T_2\left(K_в = 1\right)} = K_{ов}, \qquad (12)$$

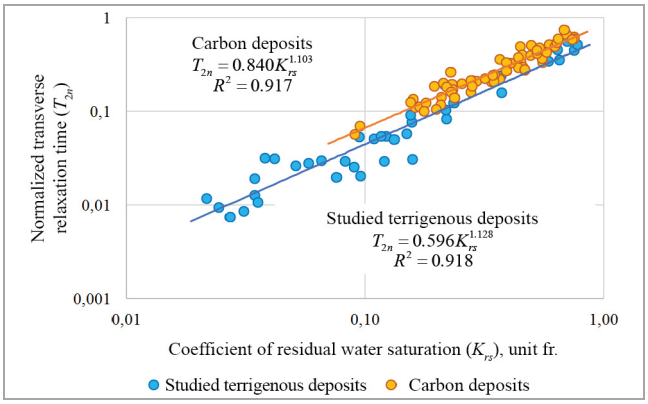

Fig. 7. Dependence of the normalized transverse relaxation time on the coefficient of residual water saturation

The integral characteristic which comprehensively evaluates the distribution of transverse relaxation times, is the average logarithmic value determined by equation (8). Taking into account equation (8), equation (12) takes the form:

$$\frac{T_2\text{logmean}\left(K_{ов}\right)}{T_2\text{logmean}\left(K_{в}=1\right)} = K_{ов}. \qquad (13)$$

Equation (13) was derived theoretically; in practice, experimental data are approximated by the following function (we replace the relation on the left side to T_{2n}) [57]:

$$T_{2n} = aK_{ов}^{\ b}, \qquad (14)$$

where $T_{2п}$ is the normalized transverse relaxation time (dimensionless parameter); a and b are empirical coefficients.

Equation (14) in its form is an analogue of the Dakhnov – Archie equation [35] which relates the electrical resistivity of partially water-saturated rocks to the water saturation coefficient ($T_{2п}$ is an analogue of the saturation parameter $P_н$, b is an analogue of the saturation index n). However, strict parallels between these equations cannot be drawn, since the physical processes underlying them are different.

It is obvious that with the condition of all other things being equal the formation of thin films in a hydrophilic rock will lead to a shift of the average logarithmic value of the transverse relaxation times at residual saturation to lower values (hence, a decrease in the parameter $T_{2п}$) compared to a hydrophobic rock where the displacement of water is not accompanied by the formation of a residual film on pore surfaces. In this case, the value of the exponent b for hydrophilic rocks will be characterized by higher values than for hydrophobic rocks. Of course, the form of function (14) will also be influenced by the structure of the void space, since the transverse relaxation times are proportional to the pore sizes.

In Figure 7 it is shown the dependence of the normalized transverse relaxation time on the coefficient of residual water saturation for the studied terrigenous sediments and carbonate rocks of another field in the Timan-Pechora oil and gas province: fairly close relationships were obtained. The wettability index of he studied terrigenous sediments samples determined according to all-Union Standart (OST) 39-180-85 [15], varies from 0.37 to 0.99, averaging 0.82, which characterizes them for the most part as hydrophilic rocks. While comparing samples with similar values of residual water saturation, samples characterized by higher values of the wettability index are normally located lower (so the $T_{2п}$ value is smaller). For samples of carbonate sediments shown in the graph in Fig. 7, the wettability index varies from 0.03 to 0.92, averaging 0.42, which corresponds to rocks with intermediate wettability. It can be seen that for the most part the experimental data points of carbonate rocks are located above the studied terrigenous sediments; the exponent, although slightly, is lower (1.103 versus 1.128).

Conclusion

As a result of the studies, the coefficients of porosity and residual water saturation were determined for the studied sediments, pore size distributions were constructed, and the nature of the residual water distribution was assessed, and the influence of wettability on the results of NMR studies was shown.

Determining porosity coefficients and residual water saturation (by cutoff method) according to NMR data, in the practice of petrophysical studies of productive sediments, is a long-established and well-developed technology. The approaches proposed by the author in this work to assess the nature of the distribution of residual water, pore size and wettability require testing at other sites and further development.

Carrying out NMR studies and their interpretation in a complex of laboratory work on studying cores shows effectiveness in determining the petrophysical characteristics of productive sediments and provides additional necessary for petrophysical support of geological and hydrodynamic modeling hydrocarbon deposits.information.

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