Improving the reliability of determining physical properties of heterogeneous clay reservoir rocks using a set of techniques

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Abstract. Oil-water-saturated formations of Western Siberian fields represented by polymictic sandstones are often characterized by strong granulometric heterogeneity. This is the reason for an incorrect assessment of the physicochemical properties of reservoirs, including wettability. On the example of the BS9 - BS11 formations of two fields of Surgut oil and gas region, the distribution of wettability of core samples was analyzed. An analysis of the modeling results for the hydrocarbon phase displacement by oil-saturated reservoir water was carried out using the Tulbovich method. To assess reliability of the wettability values, it was proposed to correlate the difference in the masses of water and kerosene displaced during capillary impregnation and centrifugation with differences in the mass of water and kerosene in water- and kerosene-saturated samples. The method was used to plot the distribution of porosity, permeability and relative clay content on the wettability parameter by capillary impregnation and centrifugal displacement. The results obtained were compared with similar dependences of the reservoir properties and clay content on the general wettability parameter. The type of wettability of core samples with good reservoir properties is validated in complex, low-permeability reservoirs with a high content of clay material. It is recommended to use the results of modeling the displacement by capillary impregnation and centrifugation with differences in the mass of water and kerosene.

1. Introduction

For the fields of Western Siberia, whose oil-saturated formations are characterized by high lithological variability and heterogeneity, in order to identify the causes of residual oil formation during the reservoir development, it is necessary to study reservoirs at the micro level. The reliability of the
conclusions depends on the correct use of the research methods. The research methods have to be chosen when studying the physical properties of reservoir rocks. This problem has been studied by scientists and specialists, but due to the complexity of reservoir rocks and various values of their parameters and properties, it becomes necessary to integrate and improve methods for specific geological and physical conditions.

When studying the dependence of the filtration-capacitive properties (reservoir properties) of core samples from the BS group of formations (BS9, BS10, BS11) taken in Surgut oil and gas bearing region on the type of wettability and content of clay materials analyzed in [1, 2], the dependence of the wettability and filtration-capacitive properties of core samples on the content of clay materials. According to the data in [3, 4], it was noted that during the migration of oil from oil source rocks to the reservoir rocks, the type of wettability of the latter depends on the number and size of pores, and their permeability. During migration, oil fills and hydrophobizes large pores of the hydrophilic rock, displacing water into smaller ones. Consequently, those areas of the reservoir rock that have high values of porosity and permeability become hydrophobic, and with an increase in the content of clay in the rock and a decrease in the volume and size of the pore space and permeability, an increase in the degree of hydrophilicity of the mineral skeleton can be observed [5–12].

Thus, there is a dependence of kern filtration and storage properties, namely porosity and permeability, on the content of clay material.

In [2], the influence of clay content in the BS formations on their filtration and storage properties was studied at two fields of Surgut oil and gas region (OGR), where in the formations in the first field, located closer to the source of demolition of clastic material, in the eastern part of the oil and gas region, the content of clay minerals was lower than in the second one, located in the western part of the oil and gas region, at a greater distance from the source of clastic materials. By the distribution of points of the dependence of porosity and permeability of the core samples on the value of their relative clay content, we can assume that the points corresponding to the samples of the first field are characterized by higher porosity and low clay content, and the points corresponding to the second field are characterized by low porosity and high content. The area of intersection of points of both fields is in the central part of the graph.

Based on the filling of the initially water-saturated reservoir with oil described in [3], a similar distribution of points of the dependence of wettability (M) values on the relative clay content of the core samples could be expected. However, in this case, the nature of distribution differs from the two previous ones: the change in the values of the wettability parameter for core samples from both fields change in the range of its measurement - from 0 to 1, the average value of M for samples from the first field is 0.68 with the standard deviation (RMS) equal to 0.29; for the second one, it is 0.7 with RMS equal to 0.28. In this case, the average value of relative clay content in the core samples of the first field is 0.18 at an RMS of 0.07, and for the second one it is 0.39 at RMS of 0.16.

The value of average reservoir properties for the first field is higher than that of the second one. The scatter of porosity values for the first field is lower, and higher in permeability than for the second one. The amount of clay material, as well as the scatter relative to the average value, in the samples of the second deposit is higher than that of the first one.

The average values of the wettability parameter, as well as the degree of scatter of its values, are similar for both fields, which, taking into account the mechanisms of formation of hydrophobic wettability of the initially water-saturated reservoir at both fields during oil migration described in [1], could occur provided that the oil pressure when filling the reservoir at the second field was higher than at the first one.

Consequently, the initial reservoir pressure at the second field should be higher, which has not been observed - the difference in reservoir pressure between the second and first fields does not exceed 1.5 MPa. Thus, it can be assumed that the results obtained by the method used for determining the wettability parameter is incorrect.
2. Materials and methods
Initially, the value of M for both fields was determined by the capillary impregnation method when modeling residual water (the modified Tulbovich method):
1) oil-water-saturated samples were extracted from oil, washed from salts and dried to constant weight;
2) the samples were saturated with a model of formation water to determine the porosity and pore volume, weight $P_0$;
3) residual water was saturated in the samples using the centrifugation method;
4) the pore volume freed from mobile water during centrifugation was saturated with purified kerosene $P_1$;
5) water-kerosene-saturated samples were placed in water for 20 hours and after spontaneous capillary impregnation with $P_2$, the samples were centrifuged in water for 20 minutes at a speed of 3500 rpm to displace kerosene $P_3$.

After each operation, the samples are weighed to determine the amount of displaced kerosene during the spontaneous water absorption and subsequent centrifugation.

The wettability parameter $M$ was calculated by formula:

$$M = \frac{P_2 - P_1}{P_3 - P_1},$$

where $P_1$ – mass of the initial water-kerosene-saturated sample; $P_2$ – mass of the sample after spontaneous absorption of water and displacement of kerosene after 20 hours of holding the sample in water; $P_3$ – sample weight after centrifugation.

The Tulbovich approach simulates the displacement of a hydrocarbon phase by water from the oil-saturated reservoir. At the first stage, it occurs due to the capillary displacement of oil by water; at the second - due to the creation of a pressure drop in the core samples during centrifugation. At the same time, when calculating the wettability parameter, the total mass of kerosene displaced at step 5 was used as a reference value. As described in [8, 13], depending on the reservoir properties of the core samples, the centrifugation modes should be different. In the original version of the Tulbovich method [8], samples with high values of porosity (average value about 20%) and permeability (average value about 100 mD) were used. The use of such centrifugation modes is not able to ensure the displacement of free kerosene by water and, as a consequence, the type of wettability can be incorrect.

In order to assess the reliability of the values of M, it was proposed to correlate the difference in the masses of water and kerosene displaced during capillary impregnation and centrifugation with the difference in the weight of water and kerosene in water-$P_0$ and kerosene-saturated $P_1$ samples. Thus, the parameter of kerosene displacement by water was calculated separately for the processes of capillary impregnation $M_{ci}$ and centrifugal displacement $M_{cd}$:

$$M_{ci} = \frac{P_2 - P_1}{P_0 - P_1},$$

$$M_{cd} = \frac{P_3 - P_1}{P_0 - P_1}.$$ (3)

Parameter $M_{ci}$ depends on the following parameters of the core sample:
1) type of wettability;
2) pore size and permeability.

In case of large pores and a hydrophobic type of wettability with water, kerosene will be displaced from the central part of the capillary, while maintaining kerosene on the walls. In case of small pores with a hydrophobic type of wettability, water will not penetrate into the pores due to the capillary forces. With a hydrophilic type of wettability, water will penetrate into the capillary along the walls. $M_{ci}$ parameter should correlate with the reservoir properties of the samples.

Parameter $M_{cd}$ depends on the value of the pressure drop, determined by the speed of rotation of the centrifuge, and the centrifugation time required to displace free kerosene with water at a given speed. In this case, the degree of displacement of kerosene by water will also depend on the reservoir
properties of the sample and the type of its wettability, but provided that the pressure drop created by the rotation of the centrifuge exceeds the value of capillary pressure inside the pores of the core sample. Otherwise, the displacement of kerosene by water during the centrifugation will be insignificant and, as a consequence, the mass of the sample will slightly change relative to the reference value. Because the value of the capillary pressure is equal, according to formula (4) [8], the capillary pressure in samples with a high content of clay material will be higher, and, therefore, the displacement of kerosene at a given centrifuge speed can be difficult:

\[ P_r = \frac{2\sigma \cos\theta}{r} \]

where \( \sigma \) – coefficient of surface tension at the water-oil interface; \( \theta \) – contact angle at the interface between two phases of liquid and rock; \( r \) – capillary radius.

3. Results and Discussion

According to the proposed method, the dependences of distribution of the values of porosity \( m \), permeability \( K \) and values of relative clay content \( n_{cc} \) on the wettability parameter by capillary impregnation \( M_{ci} \) and centrifugal displacement \( M_{cd} \) were constructed. The results obtained were compared with similar dependences of reservoir properties and clay content on the wettability parameter \( M \).

An analysis of the obtained dependences showed that \( M_{ci} \) has a satisfactory correlation with the reservoir properties of the samples (Figures 1, 4 and 7) - porosity and permeability - which confirms the assumption that \( M_{ci} \) is related to the number of small pores in the core sample (Figure 7). The distribution of points on the graphs has changed, depending on their belonging to the fields: the values of the core samples of the first field are located in the upper left corners of the graphs in Figures 1 and 4, and in the lower left corner of Figure 7. The group of points related to the second field in Figures 1, 4 and 7 is located in the central part, which characterizes the ability of this group of samples to retain absorbed kerosene.

For the first field, the average value of \( M_{ci} \) is 0.25 at RMS of 0.19, for the second one - 0.36 at RMS of 0.16. This also confirms the correlation of the parameter with the clay content in contrast to the distribution of points of \( M \) (Figures 3, 6 and 9), which confirms the conclusions made in [3, 4].

There is a group of points with low values of porosity, permeability and high clay content (the area highlighted in blue in Figures 1-9). In this group of samples, during the capillary impregnation and centrifugal displacement with water, about 30% of the mass of absorbed kerosene was displaced, which allows us to speak of the hydrophobic type of wettability. According to the distribution of values of \( M \), this group of samples is characterized by a significant range of values of the type of wettability (from purely hydrophobic to purely hydrophilic ones).
Figure 1. Dependence of the distribution of porosity values on $M_{ci}$

Figure 2. Dependence of the distribution of porosity values on $tM_{cd}$
Figure 3. Dependence of the distribution of porosity values $m$ on $M$

Figure 4. Dependence of the distribution of permeability values $K$ on $M_{cl}$
Figure 5. Dependence of the distribution of permeability values $K$ on $M_{cd}$

Figure 6. Dependence of the distribution of permeability values $K$ on $M$
Figure 7. Dependence of the distribution of the values of relative clay content $n_{cc}$ on $M_{ci}$

Figure 8. Dependence of the distribution of the relative clay content values of $n_{cc}$ on $M_{cd}$
Figure 9. Dependence of the distribution of the values of relative clay content \( n_c \) on \( M \)

The correlation between \( M_{cd} \) and the reservoir properties of the core samples is weak. It is possible to trace the dependence of an increase in \( M_{cd} \) with an increase in the reservoir properties of the samples and a decrease in \( M_{cd} \) with an increase in the content of clay material.

The dependence of distribution of points depending on their belonging to the field is preserved - the values related to the first field are located in the upper right corner (Figures 2 and 5); in the lower right corner (Figure 8) - for the dependence of the parameter from relative clay content. Samples related to the second deposit are located in the central part of the graphs (Figures 2, 5 and 8). This distribution indicates the effective displacement of kerosene by water during the centrifugation.

The average value of \( M_{cd} \) for the first field is 0.6 at RMS of 0.09; for the second one it is 0.13 at RMS of 0.69. The degree of displacement of kerosene by water increases with a decrease in the content of clay material in the samples, which, as in the case of \( M_{ci} \), confirms the conclusions made in [3, 4].

There is an isolated group of points, but it has a wider range of scatter in \( M_{cd} \). At point 37 its value (field 2) is greater than 1, which may indicate incorrect measurements. According to the \( M_{ci} \) parameter, this point belongs to the partially hydrophobic type, and according to the \( M \) parameter, it belongs to the purely hydrophobic type.

The parameter of wettability \( M \) has a less pronounced correlation with the reservoir properties of the samples and clay content (Figures 3, 6 and 9). There is no dependence of the position of points on the graphs on their belonging to one or another field. There is no separate group of points. A number of points of field 2 are hydrophilic, although the amount of kerosene displaced by water (in total during capillary impregnation and centrifugation) does not exceed 50% of the initially absorbed volume. These samples cannot be considered fully hydrophilic.
4. Conclusion
The analysis of methods for determining the parameter of rock wettability characterized by high heterogeneity and clay content allows for a more objective assessment of the physical properties of the reservoirs. For the BS formations of two fields of Surgut oil and gas region, the type of wettability was identified:
- a separate analysis of the degree of displacement of kerosene by water from core samples during the capillary impregnation and centrifugation relative to the difference in masses absorbed by water and kerosene made it possible to identify groups of core samples with incorrect values of the type of wettability determined by the main method;
- distribution of points of the degree of displacement of kerosene by water during capillary impregnation correlates with distributions of reservoir properties;
- distribution of points of the degree of displacement of kerosene by water during centrifugation correlates with the research data; however, in a joint analysis with , it allows the identification of points with an incorrect type of wettability.

When determining the type of wettability of core samples with porosity values of more than 10%, permeability above 1 mD and relative clay content of less than 0.5, the main method can be used. When assessing the wettability in complex low-permeability reservoirs with a high content of clay material, it is possible to use additional methods, in particular, the methodological approach proposed in this article. At the same time, it is recommended to observe the uniform parameters for conducting laboratory tests of the core, in particular, the uniform parameters of centrifugation and holding time of samples in water and kerosene for the entire sample under study.

The practical significance of the analytical results obtained in combination with the field research methods will allow us to substantiate the reasons for the formation of residual oil and water cut dynamics in well production.

References
[1] Akhmetov R T, Mukhametshin V V and Kuleshova L S 2019 Simulation of the absolute permeability based on the capillary pressure curves using the dumbbell model J. Phys.: Conf. Ser. 1333(3) 1-8. DOI: 10.1088/1742-6596/1333/3/032001
[2] Malyarenko A M, Bogdan V A, Kotenev Yu A, Mukhametshin V Sh and Umetbaev V G 2019 Wettability and formation conditions of reservoirs IOP Conf. Ser.: Earth Env. Sci. 378(1) 1–6. DOI: 10.1088/1755-1315/378/1/012040
[3] Mikhailov N N, Kuz'min V A, Motorova K A and Sechina L S 2016 The influence of the microstructure of the pore space on the hydrophobization oil and gas reservoirs Moscow University Geology Bull. 5 67–75
[4] Mikhailov N N, Sechina L S and Motorova K A 2012 Role of clay minerals in formation of the adsorption-connected oil in rock-collectors of hydrocarbonic raw materials Georesources, geoenergetics, geopolitics 1(5) 51
[5] Kotenev Yu A, Mukhametshin V Sh and Sultanov Sh Kh 2018 Energy-efficient technology for recovery of oil reserves with gas injection IOP Conf. Ser.: Earth Env. Sci. 194(8) 1–6. DOI: 10.1088/1755-1315/194/8/082019
[6] Nesterenko N Yu 1995 Moisten capacity of reservoir-rocks by bed-fluids Oil & Gas Geology 5 26–35
[7] Al-Yousef H Y, Lichaa P M, Al-Kaabi A U and Alpustun H 1995 Wettability evaluation of a carbonate reservoir rock from core to pore level Middle East Oil Show (11-14 March, Bahrain) pp 461–476 DOI: 10.2118/29885-MS
[8] Akhmetov R T, Kuleshova L S and Mukhametshin V V 2019 Application of the Brooks-Corey model in the conditions of lower cretaceous deposits in terrigenous reservoirs of Western Siberia IOP Conf. Ser.: Mater. Sci. Eng. 560(1) 1-4. DOI: 10.1088/1757-899X/560/1/012004
[9] Akhmetov R T and Mukhametshin V V 2018 Estimation of displacement coefficient with due account for hydrophobization of reservoir using geophysical data of wells IOP Conf. Ser.: Earth
[10] Akhmetov R T, Mukhametshin V V and Andreev A V 2017 A quantitative assessment method of the productive formation wettability indicator according to the data of geophysical surveys *SPE Russian Petroleum Technology Conf. (16-18 October 2017, Moscow)* 12 p. DOI: 10.2118/187907-MS

[11] Kuleshova L S, Mukhametshin V V and Safiullina A R 2019 Applying information technologies in identifying the features of deposit identification under conditions of different oil-and gas provinces *J. Phys.: Conf. Ser.* 1333(7) 1-5. DOI: 10.1088/1742-6596/1333/7/072012

[12] Kuleshova L S and Mukhametshin V V 2019 Elimination of uncertainties in predicting well interaction using indirect geological field information *IOP Conf. Ser.: Earth Env. Sci.* 378(1) 1-8. DOI: 10.1088/1755-1315/378/1/012115

[13] Shishigin S I 1968 *Methods and results of studying reservoir properties of oil and gas horizons of the West Siberian province*, ed A M Volkov (Moscow: Nedra) 135 p