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Mixed Wettability and Its Share in the Total Amount of Productive Strata Wetting Pore Channels

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Abstract

Reservoir wettability is one of the main factors controlling fluids distribution and flow in the reservoir, since it is caused by the molecular adhesion forces and viscous friction manifestation. The laws of the fluids motion in the formation and their displacement from the porous medium are determined not only by the rock and liquids properties, but also by the processes occurring at the fluids-filtration channels surface contact zones.

Many researchers note that the reservoir rocks filtration channels surface wettability has a direct effect on the virtually all technologies used to intensify the oil recovery development and enhancement efficiency.

In the proposed work the influence of the nature of wettability of the pore channels surface in the curves of capillary pressure was studied. It justifies the distribution of wettability in the hollow space of the productive strata. The maximum inefficient oil-saturated reservoir pore channels are hydrophilic and usually filled with water. The most efficient thin pore channels (capillaries) that are filled with water in the process of natural saturation of the sample are completely hydrophilic. These capillaries residual water surface is covered with film, and in the central part there is mobile oil.

The main part of the void space is represented by alternating long and interporous channels. According to the author's opinion the capillaries are completely hydrophilic and contain a film on the surface of the residual water and makrokapillyary (pores) - are almost completely hydrophobic. This part of the hollow space is filled with water only after additional compulsory flooding. Large pore channels are usually hydrophobized under the influence of high molecular compounds. This is confirmed by the fact that they are filled during the spontaneous infiltration model oil (kerosene).

When mixed (microstructural) wettability of pore channels presented long chain hydrophobized and hydrophilic interporous restrictions.

In our view, when lab definition does not take into account the contribution of hydrophilic microvessel (interporous restrictions) on the value of the indicator of wettability.

The work carried out microvessel quantification of the contribution of the value of the wettability index on the basis of "dumbbell" model of the void space reservoirs. In the authors' opinion, as a result of laboratory wettability determinations, it is necessary to make a correction for the hydrophilic interporal narrowings' contribution the general core samples from productive layers wettability.

Keywords: capillary pressure, water saturation, mixed wettability, identified an oil saturated reservoir formation, index of wettability, dumbbell model.

It is known that the liquid hydrocarbon resource efficiency is largely determined by the influence of the environmental conditions of field development [5, 8, 9, 11, 14, 20, 23, 28]. Among these key factors of the field development optimization by waterflooding, as well as of selecting the enhanced oil recovery methods, is a reservoir wettability [10, 15].

In the vast majority of cases, natural oil and gas reservoirs are represented by sedimentary rocks. As a rule, the void surface of such reservoirs is initially hydrophilic, i.e. it is better wetted by reservoir water than by hydrocarbons [2, 3, 19, 27].

Hydrophobic minerals in sedimentary rocks are practically absent, they are peculiar only to metamorphic rocks. Sedimentary rocks can be hydrophobic only if they are oil source rocks.

In the process of reservoir formation during water displacement from the reservoir, the productive strata, more or less, is capable of be hydrophobizated due to adsorption of asphaltic-resinous oil components by the rock's void surface [16, 17, 25, 26].

Thus, depending on the deposit development history, the active reservoirs may remain hydrophilic or become more or less hydrophobic.

Wettability of the productive strata is the overarching factor controlling the distribution and flow of fluid in the reservoir, because it is caused by occurrence of molecular far-acting forces and viscous friction [18, 21, 22, 24].

The oil-filled formation is a big accumulation of pores and cracks, the general surface of which is very large. In this regard, the fluid migration laws in the formation and their expulsion from the porous medium are determined not only by the properties of rocks and fluids, but also by the processes proceeding on the contact surface of oil and water with the rock, and, first of all, by the wettability.

Since the fluid distribution on a void surface in the filtration process and also at the end of expulsion is a wettability function, so this parameter has a significant impact on the oil recovery factor.

The analysis of many sources allows to assert that the surface wettability of the reservoir rocks' filtration channels has a direct impact on the efficiency of almost all technologies used in the field development with pressure maintenance by flooding.

The main parameters of the productive strata, directly related to the rock wettability, are:

- waterflood oil recovery factor;
- sweep efficiency;
- volumetric oil and water distribution in the reservoir;
- residual water and oil saturation;
- water and oil relative permeability;
- well intake capacity;
- injection pressure;
- oil and water bank advance speed in the reservoir of invasion of the clay mud filtrate into the reservoir;
- non-invaded reservoir resistivity.

The change in the productive strata's wettability occurs due to the oil contact with rock-forming minerals on a void surface during a long geologic time.

The main reservoir hydrophobization factor is the oil viscous properties, namely the content of naphthenic acids, resins and asphaltine components in the oil.

Hydrophobization of the productive strata is provided by the following main factors:

- the content of naphthenic acids, resins and asphaltenes in the oil. As the content of these substances increases, the hydrophobization degree also increases;
- an increase in the oil viscosity leads to a sharp increase in the reservoir hydrophobization;
- the probability of reservoir hydrophobization increases with increase in oil-gas saturation;
- an increase in the formation water salinity causes a loss in the adhesive film thickness, which, in turn, leads to an increase in the reservoir hydrophobization degree;
- a long-term fresh water injection may cause hydrophilization of the initially hydrophobic carbonate reservoir.

Relating to hydrophobization, it should be noted that we can talk only about the surface of oil-filtering pore channels, while the non-effective part of the void surface remains, perhaps, initially hydrophilic. Obviously, this concerns thin pore channels (sub- capillaries), the sizes of which are less than 1 μm, in which the oil didn't get in the course of migration. This is evidenced, for example, by the relatively high residual-water saturation of even such hydrophobic rocks as argillaceous deposits of the Bazhenov Formation of Western Siberia.

Let the oil begin to flow into the natural completely water-saturated reservoir. It occupies the pore's central part, and the pore corners (inter-porous swell) is still occupied by water. In this case, the capillary pressure increases, the water film on the pore surface thins, and the wedging pressure also increases. When a certain critical capillary pressure value is reached, the water film becomes unstable and is subject to thinning and rupture, which leads to hydrophobization of the pore surface. But even so, the inter- porous swells (pore corners) still remain completely filled with water. Thus, we obtain the microstructural (mixed) wettability of the pore channel surface.

Let us assume that the oil, which has flowed during the reservoir formation process, completely hydrophobizes the contact surface with the walls of the pore channels. However, even in this case, the surface of the inter-porous swells remains hydrophilic. This means that the complete (100%) hydrophobization in natural reservoirs is generally impossible. Nevertheless, in the laboratory determination of wettability, the possibility of complete reservoir hydrophobization ($M = 0$) is supposed.

In our opinion, it is necessary to make a correction to the results of laboratory wettability determinations for contribution of hydrophilic inter-porous swells to the general wettability of core samples from the productive strata.

By the wettability, productive strata are divided into hydrophilic, hydrophobic and intermediate wettability. The case of the completely hydrophobic reservoir is possible only in oil-source rocks.

As against to the completely hydrophilic or hydrophobic reservoir, the mixed or micro-structural wettability of the pore channel surface is the most common wettability case.

Let's consider the capillary pressure curves obtained by laboratory measurement of the core wettability (figure).

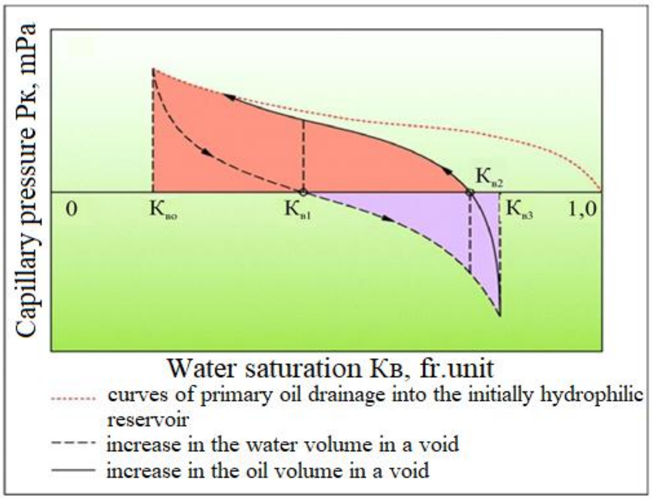

Figure 1. Capillary pressure curves for mixed productive strata wettability

It is a reminder that the capillary pressure curves are diagrams of dependence of capillary pressure on the water saturation factor of the rock's void surface.

The lower branch of the capillary curves corresponds to an increase in the water saturation of the core sample, and the upper branch - to an increase in the oil saturation on a void surface.

Note that as the water saturation factor K_s increases from the residual water saturation K_{rs} to the value corresponding to the residual oil saturation (K_{s3}), the average filtration radius of the pore channels gradually increases from zero to a certain maximum value.

In the figure, the dashed line corresponds to the primary drainage, i.e. simulates the process of oil ingress into the primary hydrophilic reservoir.

If the maximally oil saturated core sample is placed in a vessel with water for a long time, then the spontaneous water impregnation occurs with the simultaneous oil displacement from the sample. As a result of spontaneous impregnation, the sample's water saturation changes from the initial value K_{rs} to the value K_{s1} corresponding to zero capillary pressure.

There are many mathematic models approximating the capillary curves of the primary drainage. However, the most popular one is the Brooks-Corey model allowing to obtain the best comparability with the laboratory data:

$$K_s = K_{rs} + (1-K_{rs})\cdot\left(\frac{P_{ic}}{P_c}\right)^{\alpha}, \qquad (1)$$

where K_s – a water saturation; K_{rs} – a residual water saturation; P_c – a capillary pressure; P_{ic} – an initial (upstream) capillary pressure; α – a capillary curve factor.

If the oil wetting angle and surface tension in a drainage are considered as invariable, then we can replace the capillary pressure ratio by the inverse ratio of the corresponding pore channel radii in the formula (1). The result will be the following:

$$K_s = K_{rs} + (1-K_{rs})\cdot\left(\frac{r}{r_{max}}\right)^{\alpha}, \qquad (2)$$

where r – the capillary radius corresponding to the capillary pressure P_c; r_{max} – the maximum capillary radius corresponding to $K_s = 1,0$.

We express the filtration capillary radius through the water saturation of the rock sample in terms of the formula (2):

$$r_{\phi} = r_{max}\cdot\left(\frac{K_s-K_{rs}}{1-K_{rs}}\right)^{1/\alpha}. \qquad (3)$$

As a result, when $K_s = K_{rs}$, the average effective radius of the capillaries is equal to zero, and as the water saturation increases, the average radii of the capillaries increases gradually. When $K_s = 1.0$, the radii of the capillaries reach the maximum value.

It is follows from the above that in case of spontaneous impregnation, the pore channels of the smallest size are filled with water, the radii of which change from zero to the value:

$$r = r_{max}\cdot\left(\frac{K_{s1}-K_{rs}}{1-K_{rs}}\right)^{1/\alpha}. \qquad (4)$$

Therefore, the part of the lower branch of the capillary curves, collected in the water-saturation range K_{rs}-K_{s1} (dashed line), corresponds to the hydrophilic pore channels of the minimum-size rock sample.

If the maximum oil-saturated sample is forcibly saturated with water additionally (for example, by centrifugal process) after spontaneous impregnation, then the final water saturation K_{s3} will be determined by the residual oil saturation K_{ros} of the sample, and:

$$K_{s3} = 1 - K_{ros}. \qquad (5)$$

It is obvious that the part of the lower branch of the capillary curves, which is in the water-saturation range K_{s1}-K_{s3} (dashed line), corresponds, partially or completely, to hydrophobic pore channels, whose sizes increase steadily to the value r_{mo} corresponding to the water saturation K_{s3}. The r_{mo} value depends on the residual oil saturation and displacement coefficient:

$$r_{mo} = r_{max}\cdot\left(\frac{K_{s3}-K_{rs}}{1-K_{rs}}\right)^{1/\alpha} = r_{max}\cdot\left(\frac{1-K_{rs}-K_{ros}}{1-K_{rs}}\right)^{1/\alpha} = r_{max}\cdot K_{dis}^{\ 1/\alpha}, \qquad (6)$$

where K_{dis} – a waterflood displacement efficiency.

If the water-saturated sample is placed in kerosene (oil model), then, after spontaneous impregnation, the sample's water saturation decreases and becomes equal to K_{s2}. Thus, the upper branch of the capillary curves in the range K_{s2}-K_{s3} corresponds to completely hydrophobic pore channels. And these pore channels are characterized by the maximum sizes.

Further, after additional forced saturation with the oil model (kerosene), for example, by centrifugal process, we return from the water saturation K_{s2} to the residual water saturation K_{rs} again. Since the oil saturation in this case is forced, the core sample behaves as a hydrophilic.

The pore channels (see the figure) corresponding to the water saturation range K_{rs}-K_{s1}, behave as hydrophilic both when saturating with water and when saturating with oil. The pore channels in the range K_{s2}-K_{s3} behave as hydrophobic both when saturating with water and when saturating with oil.

The pore channels in the range K_{s1}-K_{s2} behave as hydrophobic when saturating with water, and as hydrophilic when saturating with oil. Let's consider the cause of this phenomenon. To explain the processes occurring on a void surface during fluid motion, the specialists, as a rule, use the capillary model of a void surface of natural oil reservoirs. When examining the relations between filtration and capacitive properties, the model of parallel capillaries gives satisfactory results.

But it isn't possible to examine the influence of reservoir properties on the process of water-oil displacement using the model of parallel capillaries, because it doesn't take into account changes in sections of the pore channels along the filtration lines.

The complex geometry of the reservoir pores is due to the complexity of the surface of the mineral matrix surrounding this pore.

The main pore volume is usually filled with oil in the process of deposit formation, but the void surfaces in the areas of rock pellet convergence remain unfilled with oil, because the capillary pressure is insufficiently high for penetration of the oil phase into the inter-porous swells.

Therefore, depending on the void surface geometry, one part of the void surface is filled with oil, and the other part - with reservoir water. As a result, there is a mixed (microstructural) wettability: one part of the void surface remains hydrophilic, and the other part - hydrophobic.

Hydrophobization of the intra-porous surface is a process of adsorption of polar oil components on natural-hydrophilic mineral surfaces. Active adsorption centers can serve as surface charges in the corners and ribs of the rock's crystal lattice in the places of chips and swells of the intra-porous surface.

The sandrocks usually have a negative charge and form a weakly acidic surface, while the carbonates have a positive charge and form a weakly basic surface.

The hydrophobization factor characterizes the relative fraction of the intra-porous surface occupied by adsorption hydrocarbons, it quantitatively determines the degree of change in wettability of initially hydrophilic rocks.

In the previous studies we proposed and examined the "dumb-bell" model, according to which each pore channel of the rock is represented by an alternation of macro- and microcapillaries. It is true that each pore canal of a real rock is represented by an alternation of pores and inter-porous channels (narrowings). It is also obvious that the pores determine capacitive properties, and the inter-porous narrowings - the filtration properties of the reservoir. This undeniable fact isn't taken into account in capillary models.

Please note that the filtration radii of the pore channels, represented in the formulas (1) - (3), are close to the radius of microcapillaries (inter-porous narrowings).

Many specialists pay attention to the differences in the wettability of pores and inter-porous channels. In this case, the big pores are more likely to be hydrophobic, and the small pores and void surfaces in the pores surrounding the contact points of the grains are most likely to be hydrophilic.

Therefore, the pore channels that behave as hydrophobic when saturating with water and as hydrophilic when saturating with oil, have a mixed wettability: their pores are hydrophobic, and the inter-porous narrowings are hydrophilic.

The mixed wettability of the part of the pore channels has a significant impact on the fluid filtration process through the rock's void surface and, as a consequence, on the waterflood displacement efficiency value [4, 6, 7, 12, 13].

Information on distribution of the wettability of the reservoir's pore channels should be taken into account when choosing the methods for intensification of the development and increase in the oil recovery of the productive strata.

Let's consider the method for determining wettability of hydrocarbon-bearing rocks in accordance with the industry standard OST 39-180-85. This method is intended for determination, under laboratory conditions, of the parameter expressing the integral wettability characteristics of rocks according to the capillary penetration data in the sample of distilled water and kerosene under atmospheric conditions and in a gravitational field during the centrifugal process.

In accordance with OST 39-180-85, the wettability index M is calculated by the following formula:

$$\mathrm{M} = \frac{P_4 - P_3}{P_5 - P_3}, \tag{7}$$

where P_3 – the sample weight before waterflooding corresponding to the residual water saturation K_{rs} (see the figure); P_4 – the sample weight after the capillary water imbibition, corresponding to the water saturation K_{s1} under zero capillary pressure; P_5 – the sample weight after waterflooding corresponding to the water saturation K_{s3}, and

$$K_{s3} = 1 - K_{ros},$$

where K_{ros} – a residual oil saturation.

The formula (7) can be rewritten in the following form:

$$M = \frac{K_{s1} - K_{rs}}{1 - K_{rs} - K_{ros}},$$

where (K_{s1} – K_{rs}) – the water volume that got to the sample during spontaneous water impregnation; (1 – K_{rs} – K_{ros}) – the total water volume that got to the sample after waterflooding process (impregnation and centrifugal process).

Small and medium-size pore channels, filled in the process of spontaneous water impregnation, corresponding to the water saturation range K_{rs}-K_{s1}, are completely hydrophilic.

Medium-size pore channels, corresponding to the water saturation range K_{s1}-K_{s2}, behave as hydrophobic when saturating with water and as hydrophilic when saturating with oil. This duality is apparently due to the fact that the surface of these pore channels is partially hydrophobic and partially hydrophilic.

We note that each pore channel of a real rock is represented by a chain of pores and inter-porous narrowings.

In accordance with the dumb-bell model, each pore canal is represented by alternation of large (macrocapillaries) and small-section (microcapillaries) capillaries. Along with this, the large-section capillaries S_l model pores, and the small-section capillaries S_s - inter-porous narrowings.

Now let us imagine that the macrocapillaries in the dumb-bell model are hydrophobic, and the microcapillaries are hydrophilic, and let's estimate the microstructural wettability index for this case.

It is considered in the simple dumb-bell model that all pore channels are similar, with the size of macrocapillaries corresponding to the average pore size, and microcapillaries - to the average size of inter-porous narrowing of the reservoir.

Under these conditions, the microstructural wettability can be estimated as the ratio of the microcapillary surface to the entire channel surface by the following formula:

$$M = \frac{2\pi r_s \rho}{2\pi r_s \rho + 2\pi r_l (1-\rho)}, \qquad (8)$$

where r_s – a microcapillary radius; r_l – a macrocapillary radius; ρ – a linear microcapillary fraction; (1 – ρ) – a linear macrocapillary fraction.

The formula (8) can be rewritten in the following form:

$$M = \frac{1}{1 + \sqrt{\frac{S_l}{S_s}} \left(\frac{1-\rho}{\rho} \right)}, \qquad (9)$$

where S_l/S_s – a ratio of macro- and microcapillary sections.

In accordance with [1], the section ratio is determined by the following formula:

$$\frac{S_l}{S_s} = 1 + \frac{P_{fr} K_{fr} - 1}{\rho(1-\rho)},$$

where P_{fr} – a formation resistivity factor, and $P_{fr} \approx K_{fr}^{-2}$

$$\rho = 1 - \sqrt[3]{K_{fr}}; \qquad 1 - \rho = \sqrt[3]{K_{fr}}.$$

We will plug the expression for the section ratio in the formula (9) and will obtain finally:

$$M = \frac{1}{1 + \frac{1-\rho}{\rho} \sqrt{1 + \frac{P_{fr} K_{fr} - 1}{\rho(1-\rho)}}}. \qquad (10)$$

Using the formula (10), we calculate the values of the wettability index M for reservoirs of different porosity K_{fr}. With the values K_{fr} equal to 0.3; 0.25; 0.20; 0,15; 0.10, the wettability index makes 0.131; 0.136; 0.145; 0.153; 0.159, correspondingly. Therefore, if the pores are hydrophobic and the pore channels are hydrophilic, the average value of the microstructure wettability index is M = 0.14.

When determining the wettability by the method OST 39-180-85, in accordance with the formula (7), the channel volume filled with water in the process of capillary imbibition, i.e. the channels completely wetted by water, is taken into account. But the remaining part of the void surface filled with water during forced waterflooding, automatically changes to a hydrophobic.

Since this part of the void surface actually has microstructural (mixed) wettability, it is necessary to take this fact into account when calculating the wettability by the formula (7).

The wettability, corrected for influence of the microstructural wettability index, can be calculated by the following formula:

$$M_1 = M + 0{,}14(1 - M) = 0{,}86M + 0{,}14, \qquad (11)$$

where M_1 – a wettability, corrected for influence of microstructural wettability; M – a wettability, determined by the formula (7); 0,14 – an average share of microstructural wettability, calculated using the dumb-bell void surface model of the oil and gas reservoirs.

As a result, the mixed (microstructural) wettability increases the reservoir hydrophilicity slightly. The correction for microstructural wettability varies from zero for the hydrophilic (M = 1) to 0.14 for the hydrophobic (M = 0) rocks.

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