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THE INFLUENCE OF WETTABILITY ON OIL RECOVERY

1. INTRODUCTION

The degree of depletion of oil operated the primary methods using energy reserves is small, and in most cases does not exceed 5% to 30% of the geological resources. The exploitation of these deposits it is more effective when they are methods used to support the extraction (secondary and tertiary methods), allows for additional oil extraction by providing for additional deposits. The application of these methods allows double to increase the oil recovery. The best results are achieved when secondary and tertiary methods are matched to the parameters of oil and field conditions, including petrophysical properties, such as relative permeability, saturation and wettability.

Wettability type of reservoir rocks and its impact on the petrophysical properties are crucial in determining the mechanisms of oil recovery and estimating the efficiency of its production. Numerous studies indicate that wettability is one of the main factors controlling and regulating the spread of oil and water in the reservoir rock. The characterization of the wettability of reservoir rock plays an important role in optimizing oil recovery. Nature wettability (hydrophobic or hydrophilic) affects the behavior of reservoir rock, in particular for the waterflooding of the deposit and in the case of using advanced methods of oil recovery. For example, a wrong assumption, hydrophilic nature of the rocks, where it is hydrophobic can lead to permanent damage deposit and complicate the process of its operation [1].

2. THE WETTABILITY OF RESERVOIR ROCKS

If the liquid is in contact with the solid, the liquid and solid particles interact with each other through adhesion due to the action of van der Waals forces, and ionic bonding. The measure of adhesion is the force or work separation of phases (liquid and solid) per unit area.

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As a result of the forces of adhesion a liquid creates with a solid surface contact angle (θ) (Fig. 1). When the adhesive strength of a liquid to a solid are large in comparison with the forces of cohesion of the liquid (liquid wets the solid surface), the angle is small (θ < 90°). If the adhesive strength is small compared with the forces of cohesion (the liquid does not wet the surface), the contact angle is large (θ > 90°) [19].

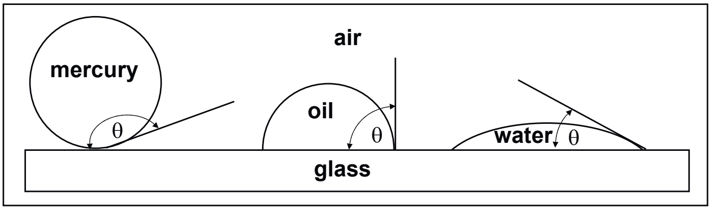

Fig. 1. Nonwetting fluid (mercury, θ > 90°), wetting fluid (water, θ < 90°)

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Wettability is a property of reservoir rocks to spread on or adhere to the surface of the rock one fluid in the presence of a second fluid. A drop of preferential wetting fluid displaces the other fluid from the surface of the solid and distributed all over. Conversely, in the case of non wetting liquid that hitting the solid surface previously coated with a wetting fluid, creates a drop with a minimum contact area with the solid phase [1].

A water-wet rock (hydrophilic) has a greater attraction for water than for oil. In these rocks, water can deal with smaller pores and the majority of the volume of pore space. The oil-wet rocks (hydrophobic) are characterized by a greater attraction for oil than water. The wettability of rock differs greatly from hydrophilic (*very strongly water-wet*) to hydrophobic (*very strongly oil-wet)*, depending on the interaction of oil and water from the surface of the rocks [2]. Wettability depends on: the pore size, the surface roughness adsorbed liquid layer and the adsorptive properties of minerals [15]. Reservoir rocks are characterized by a different mineral composition. Different minerals have different wettability, making it extremely difficult to quantify the overall wettability of the rock. Generally, the main minerals forming the reservoir rocks (quartz, calcite, dolomite) are hydrophilic [19].

The entire surface of the hydrophilic rocks is in contact with water. The water fills the small pores, but oil covers the central part of the large pores. Oil does not contact directly with the surface rocks, because the surface of the large pores covers a thin water film (bound). In the case of hydrophobic rock, oil is in the small pores and covers the surface of the rock; in the center of large pores is water [21]. The concept of fractional wettability, also known as heterogeneous, spotted or dalamation, for the first time suggested Brown and Fatt [6]. Researchers estimate that may occur to alter the wettability of a rock hydrophilic to hydrophobic, while the remainder of the rock is hydrophilic. A variation of fractional wettability is mixed wettability. Oil-wetting surfaces form a continuous migration path through the porous medium. The smallest pores contain water and are wetted by it, while some of the larger pores contain oil and it is moistened. Mixed wettability is different from the fractional wettability of the occurrence hydrophobic zones in a specific location. In the case of mixed wettability, medium typically has very low residual oil saturation and can spontaneously absorb both water and oil [2] (Fig. 2).

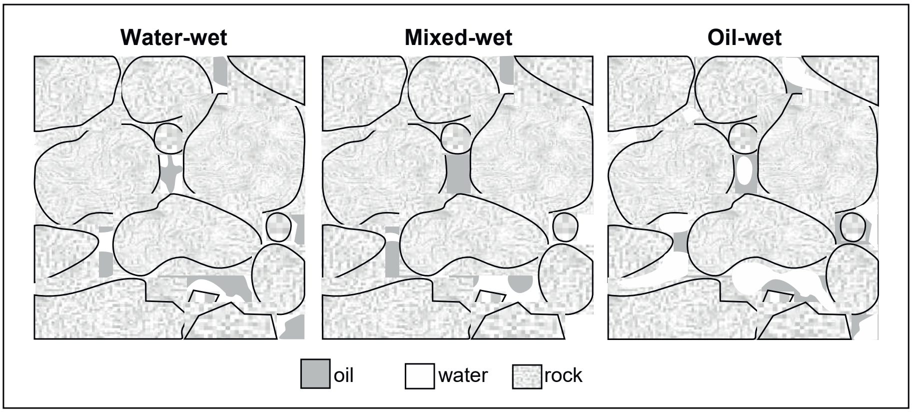

Fig. 2. Wetting in porous medium [1]

3. TEST METHODOLOGY OF THE DETERMINATION OF WETTABILITY

In 1986, Anderson divided wettability measurement methods into direct and indirect. Direct methods involve measurements of the contact angle and capillary pressures, on the basis of which shall be the value of the wettability. Indirect methods include measurements of the relative permeability [3] and capillary pressure [16]. It is also used many other methods, such as flotation or magnetic resonance imaging [7].

The degree of wetting can be determined based on the measurement of the contact angle between the tangent to the liquid at the contact point with the rock material and the surface of the rock. The contact angle depends on the surface energy and surface tension of the liquid and the properties of the solid phase. The high impact of its size is so kind of rocks and chemical composition of the liquid [17, 18]. The contact angle can be determined in several ways: a sitting drop method, an air bubble method or by a Wilhelmy plate method.

The wettability of rocks can also be determined based on the imbibition and drainage curves that are plotted on the basis of capillary pressure. On the basis of these curves is determined the Amott wettability index and USBM wettability index. The Amott index is based on the relative change in saturation, while the rate USBM is a measure of the energy required to force the displacement of the liquid, these two quantities are related, but are independent of wettability indexes [1].

Amott Test

The Amott wettability test allows for the determination ofthe average wettability through the study of spontaneous imbibition and displacement of liquid (water and oil) through the rock samples. In this method, the wetting fluid is imbibed by the sample, displacing the fluid non-wetting. Also apply a centrifuge, which is used to absorb a larger volume of wetting fluid to the pore space in the reservoir rock. Based on the examination the saturation sample is determined the Amott index – the ratio of the volume of liquid spontaneously imbibed to the total volume of imbibed fluid (spontaneously and forced) (Fig. 3).

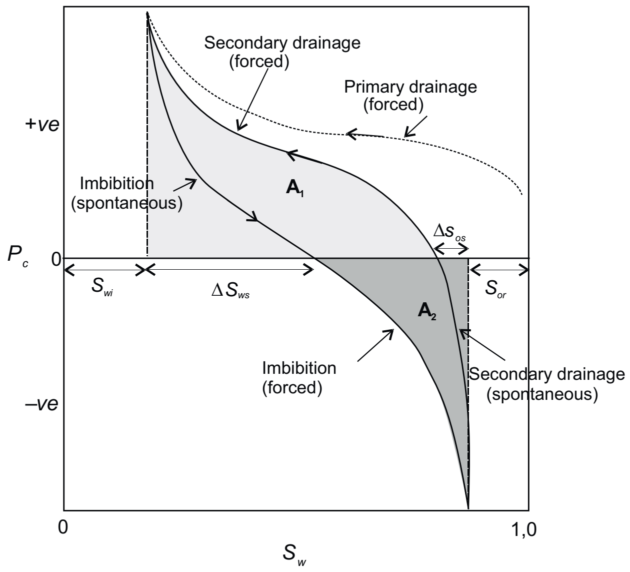

Fig. 3. Capillary pressure diagram used to characterize wettability [15]

This test is usually carried out in five steps [3, 13]:

1. The test begins at the residual oil saturation; therefore, the fluids are reduced to S_{or} (S_{or} – residual oil saturation) by forced displacement of the oil.
2. The core is immersed in oil for 20 hours, and the amount of water displaced by the spontaneous imbibition of oil.
3. The water is displaced to the residual water saturation (S_{iw}) with oil, and the total amount of water displaced (by the imbibition of oil and by forced displacement).
4. The core is immersed in brine for 20 hours, and the volume of oil displaced, if any, by spontaneous the imbibition of water.
5. The oil remaining in the core is displaced by water to S_{or} and the total amount of oil displaced (by the imbibition of water and by forced displacement).

The Amott index for water and oil can be determined from the following formulas [15]:

$$I_o = \frac{\Delta S_{os}}{1 - S_{wi} - S_{or}} \tag{1}$$

$$I_w = \frac{\Delta S_{ws}}{1 - S_{wi} - S_{or}} \tag{2}$$

where:

I_o – the displacement-by-oil ratio,
I_w – the displacement-by-water ratio,
Δs_{os} – the volume of water displaced by the spontaneous imbibition of oil,
Δs_{ws} – the volume of oil displaced by the spontaneous imbibition of water,
s_{wi} – irreducible water saturation,
s_{or} – residual oil saturation.

The Amott method shows a significant correlation between rock wettability and the process of imbibition. It is interpreted for measuring the wettability between one for the hydrophilic rocks to −1 for hydrophobic. Cuiec in the studies of wettability index, said that the rock is hydrophilic when $I_w \leq 0.3 \leq 1.0$; neutral rock wettability, respectively ($-0.3 \leq I_w \leq 0.3$) and hydrophobic rock, where $-1 \leq I_w \leq -0.3$ [8].

The $I_w = 0$ is usually observed in the case of cores with a neutral wettability, which indicates a lack of spontaneous imbibition of both oil and brine or equal amounts of the two liquids to be imbibed spontaneously.

United States Bureau of Mines (USBM) Wettability Index

Donaldson and his team developed a method for evaluating wettability on the basis of forced displacement of liquid from the rock [11]. In this method the calculated area under the curve resulting capillary pressure during displacement. Wettability (N_W) is determined by comparing the surface area associated with an increase in water saturation (A_1) to the field associated with increasing oil saturation (A_2) (Fig. 3) [11, 15]:

$$N_w = \log\left(\frac{A_1}{A_2}\right) \tag{3}$$

The range of the wettability is from +∞ for the hydrophilic material to −∞ for the hydrophobic material. Rock wettability index values are in the range of from −1.5 to +1.0 [15]. Sharma and Wunderlich, presented in the research that USBM index is greater than 1.0 for rock hydrophilic [24].

4. INFLUENCE OF WETTABILITY ON OIL RECOVERY

Wettability is the most important parameter that affects the flow and distribution of reservoir fluids in the rock. The effectiveness of oil recovery depends on the wettability of reservoir rocks. In the hydrophilic rocks (which are mostly reservoir rocks) oil, which is a non wetting liquid, located mainly in large pores of the rock matrix. During primary oil recovery methods under the influence of a pressure drop in the wellbore oil has a relatively high mobility and easily moving in its direction. In the case of hydrophobic rock, oil is in small pores, of which the harder it is to extract only by the influence of a pressure difference.

The relative permeability is a key feature of decisive about the possibility of movement of the individual phases in the pore space of reservoir rocks. This parameter is a function of wettability, pore geometry, distribution of fluids in the rock and the history of saturation. Hydrophilic rocks have a higher water permeability than oil, where rock is hydrophobic is vice versa. Extraction of oil from hydrophilic reservoir rocks is greater due to higher relative permeability [3].

When three reservoir fluids are present in the rock, two non-wetting liquids compete with each aiming and fill the larger pores, disrupting the flow of each other. Gas, occurring in hydrophilic rocks lowers the relative permeability to oil. In the hydrophobic rocks the presence of gas reduces the relative permeability to water. In both cases, the relative permeability to the non-wetting fluid does not change. It was observed that the relative permeability of the rock for the wetting fluid is a function of the wetting phase saturation. While the relative permeability of rocks for non-wetting liquids is a function of the fluid saturation distribution of non-wetting phase [12].

At the beginning of oil production by primary methods, relative permeability to oil is high, water permeability is small. The value of permeability for oil decreases, as the decline in oil saturation and increasedsaturation of rocks with water. Water saturation is increased mainly as a result of filling out its smaller pores. During oil exploitation from the reservoir rock, the water gradually occupies pores, which previously were filled with oil. A single pore or a group of pores containing oil may be surrounded by water and isolated from the rest of the pore space occupied by oil [1]. Oil is then immobilized in the form of drops in the middle of the larger pore or in the form of large spots surrounded by water in the pores [12].

Secondary oil recovery methods (especially waterflooding) allow for the running part of trapped oil in the pores. By waterflooding the two liquids (oil and water) are the phases moving.

During the injection of water into the oil reservoir (during its watreflooding) oil is displaced from the rocks in different ways. In the hydrophilic rocks oil is displaced as the front before the injection of water (Fig. 4), and each of the fluid flows through pores of a different size. Small drops of oil remain as a residual oil.

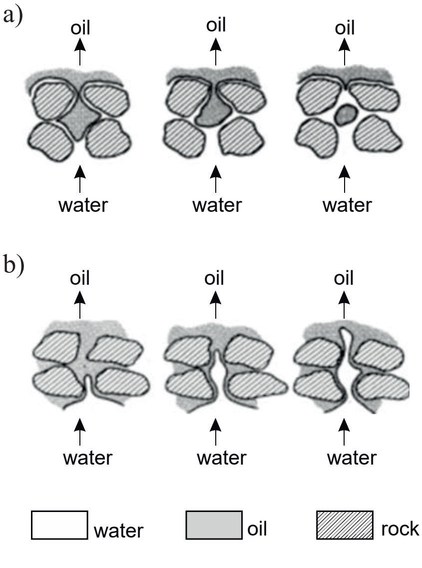

Fig. 4. Water displaced oil from a pore during waterflood:
a) strongly water-wet rock; b) strongly oil-wet rock [3]

The efficiency of water flooding (the amount of additional extracted oil) is dependent on the amount of injected water and the type of rock wettability. In the hydrophobic rocks case oil recovery does not exceed 30% of the geological resources (Fig. 5). Water flooding of hydrophilic rock allows for a much larger amount of additional oil (oil recovery can be up to about 70%).

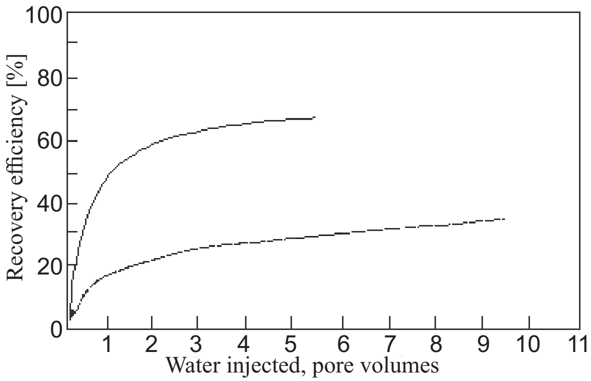

Fig. 5. Recovery efficiency for water
1 – to oil-wet, 2 – reservoir rock

The amount of oil, that can be obtained by flooding hydrophilic and hydrophobic rocks varies. In the case of hydrophobic rock waterflooding, it is less efficient than for hydrophilic rock [12].

Laboratory tests have shown that the amount of oil extracted decreases with decreasing humidity rocks. The conducted tests also showed that higher oil production can be obtained from the rocks weakness and medium moistened with water. Rathmell et al. in their study on sandstone samples [20] showed that oil production increased as the cores become less wetted with water or the wettability changed in the direction of the intermediate wettability [14].

In the mixed wettability rock, with increasing water saturation, it migrates to the largest pores first, remaining inside them (because the surfaces of these pores are hydrophobic). This results in a decrease in the relative permeability to oil, because the most permeable voids are filled with water. For these kinds of rocks, even when the water breaks down into the borehole, oil production lasts a long time, although the water cut increases [1].

As mentioned earlier the oil recovery efficiency from the deposits is dependent on the wettability of reservoir rocks. Reservoir rocks are usually wetted with both water and oil, and therefore water injection (even to hydrophilic rocks) is not as effective as would be expected. Advanced methods (tertiary) allow for oil production, which can not be achieved by primary and secondary methods. Oil is present in the form of isolated droplets trapped in the pores or in the form of the film around the grains of rock. Tertiary-effective process methods should start dispersed oil droplets and create a zone saturated with oil, which can migrate to the production well [22]. For this purpose are used different methods of modifying wettability – chemical and thermal. They allow for changing the wettability of the deposit with the hydrophilic to hydrophobic.

Thermal methods (injection of steam or hot water) change the wettability of rocks in the hydrophilic direction [12]. This is confirmed by numerous wettability studies made on various types of lithological reservoir rocks. Tang and Morrow conducted a study on sandstone, showing that with increasing temperature the nature of rock wettability changed towards a more hydrophilic [25]. Changing the character of wettability allows for a greater degree of exhaustion of oil resources. Similar results were obtained by Dangerfield and Brown, who studied the dependence of wettability since the temperature of carbonate rocks [9]. The study rock was originally hydrophilic, oil deposited on the surface of the rock changed its wettability on hydrophobic. Changing the wettability was due to the adsorption of ionic compounds (asphaltenes) of crude oil. At high temperatures, ionic compounds disengage from the surface of the rocks as a result, the wettability of the rock changed again hydrophilic. The temperature also affects the relative permeability. Relative permeability increases with increasing temperature, whereas decreasing residual oil saturation [10].

The same as thermal methods, chemical methods, eg. injection of the surfactant can change the wettability of rocks, thereby increasing the degree of oil production from the reservoir. Among the various types of surfactants: anionic, nonionic and cationic, the first two are used for EOR methods, because of their good solubility in brine. The surfactants are composed of hydrophilic parts, soluble in water or polar liquids and a hydrophobic portion, soluble in oils and non-polar liquids.

Surfactants reduce the viscosity and surface tension between the injection fluid and oil. This results in a change in the wettability and increase in oil production [5]. These changes are due to the adsorption of the hydrophobic portion of the surfactant molecule on the oil droplets, which moves ionic compounds (asphaltenes) of positive and negative charges. The reduced capillary pressure allows for combining the particles into larger oil droplets (coalescence), which are in contact with each other and form a zone of saturated oil (oil bank), that may migrate to the production well [12] (Fig. 6).

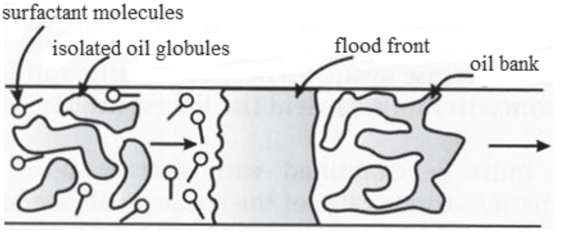

Fig. 6. A surfactant in injected water [12]

The key problem, when using chemical methods is to determine the type of rock wettability. Incorrect determination of rock wettability type may lead to the use of an improper surfactant and do not get a sufficiently large extraction. Surfactants should be selected depending on initial rock wettability [14].

The selection of an appropriate surfactant has been studied by numerous authors. Wang et al. studied the changes in the wettability of calcite surface using alkali / anionic surfactants [26]. They obtained changing the wettability of the originally oil wetted to water wetted. Seethepall and al. used anionic surfactants to injecting limestone, obtaining 50% oil recovery [23]. Austad et al. conducted a series of studies on the effects of different surfactants on the oil production from carbonate rocks (chalk) [4]. In the case of cationic surfactant, trimethylammonium bromide, production of oil increased to 70%. For oil wetted cores anionic surfactant allow for obtaining larger quantities of oil for a longer period of time than cationic [14].

5. CONCLUSIONS

In the case where the reservoir rock is saturated more fluids, it is important to recognize the type of the rock wettability. Determination of whether we are dealing with the hydrophilic or hydrophobic rock is essential for planning the extraction of crude oil. The quantity of oil production is a function of rock wettability, properties of the pore space and reservoir fluids. Studies of numerous authors have shown that in the case of hydrophobic rock, both the primary method, as well as waterflooding, the oil recovery is less than for hydrophilic rock. Also, weakness and medium water wetted rocks allow for obtaining larger quantities of oil during exploitation than from the hydrophobic rocks.

The use of tertiary oil recovery methods can increase oil production by changing the wettability. In particular, chemical methods, injection water with a surfactant allow for changing the wettability from hydrophobic to hydrophilic.

Specifying the type of reservoir rock wettability is crucial for estimating the oil recovery efficiency. The reduction of wettability, which is obtained through EOR methods, is still a complex area of research in secondary and tertiary oil recovery methods.

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