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New normalization index for spontaneous imbibition

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ABSTRACT

Spontaneous imbibition is of special importance in oil recovery from fractured reservoirs. Laboratory measurements of volume of liquid imbibed versus time are often used in the prediction of oil recovery. Laboratory results of oil recovery through spontaneous imbibition are commonly scaled-up to forecast oil recovery at the reservoir scale. Numerous questions arise with respect to the theory of spontaneous imbibition and the valid scaling of laboratory imbibition data. The factors involved in the scaling equation are rock properties, liquids viscosities, interfacial tensions, core geometry and wettability. Some previous developments in scaling were based on oil recovery from very strongly water-wet rocks. In this paper, sequential developments in the mathematical analysis of scaling equations for imbibition recovery are reviewed to the latest one. Previous scaling equations do not fit the imbibition data with different wettabilities in cores. To show this fact, two series of experiments are done on water wet and oil wet cores. Oil wet cores are obtained by means of aging process. The effect of interfacial tension is considered using a new type of surfactant. Imbibition data is compared with different scaling equations that are available in the literature for providing a physical explanation of the new index. The results reveal the inconsistency between scaling equations. Previous methods did not consider the effects of all parameters on determining the Wettability Index. A new procedure is introduced in order to obtain the Normalization Index from the imbibition data using all the parameters affecting the imbibition rate, including wettability. This index, which could be considered as a substitute for the Wettability Index, is then used to modify previous scaling equations and called the Normalization Index. The improved correlation is shown to perform better than the existing equations available in the literature as it gives the closest fit to the experimental data.

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1. Introduction

Capillary (or spontaneous) imbibition refers to the simultaneous capillary suction of water and expulsion of the oil by the rock matrix. Examples include oil and natural gas reservoirs, aquifers, geothermal reservoirs, and subsurface reservoirs used for waste material disposal. This phenomenon is one of the recovery mechanisms in fractured oil reservoirs. The primary conditions necessary for this mechanism to take place are a water-wet matrix rock and the existence of enough water in the fractures in contact with the rock matrix. Many factors such as wettability, matrix boundary conditions causing co- or counter-current transfer, matrix size and permeability, viscosity of the phases, interfacial tension, and temperature are critical to this process and the clarifications of these factors are needed for the assessment of engineering and environmental projects. Oil recovery from naturally fractured reservoirs (NFR) is a challenging task if the matrix is dominating it and unfavorable conditions such as oil-wet rock, high oil viscosity, or low matrix permeability exist. Matrix fracture interaction needs to be accelerated using different enhanced oil recovery techniques. If the matrix is water wet and an immiscible wetting phase exists in the fracture, the interaction occurs due to spontaneous imbibition. (Babadagli, 2002; Babadagli and Boluk, 2005; Hatiboglu and Babadagli, 2010).

The rate and extent of spontaneous imbibition provide a measure of wettability which is inherently dependent on surface energy. However, the mechanism of imbibition is highly complex and many factors, besides wettability, affect the rate of spontaneous imbibition and the displacement efficiency. Different approaches were used in recent years for interpreting the imbibition mechanism and producing a universal curve to be used in an actual situation. Mattax and Kyte (1962), considered imbibition to be driven by capillary forces and showed that the appropriate dimensionless time scale for flow is:

$$t_{D-Pc} = \sqrt{\frac{K}{\phi}}\frac{\sigma}{\mu_w \cdot L^2}t \tag{1}$$

Where t_{D-Pc} is dimensionless time, K is permeability, ϕ is matrix porosity, σ is interfacial tension, μ_w is water viscosity, L is block length, and t is imbibition time. They argued that, for a given rock

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type (K, ϕ), block dimension (L), and fluid properties (μ,σ), the imbibition process at different times (t) in which the values of t_{D-Pc} are equal should show the same oil recovery.

On the other hand, the oil viscosity is not included in Eq. (1). However, the change in the oil viscosity would substantially affect the imbibition rate. Cuiec et al. (1994) proposed a modified form of the Mattax and Kyte's dimensionless group by replacing the water viscosity with oil viscosity:

$$t_{D-Pc} = \sqrt{\frac{K}{\phi}}\frac{\sigma}{\mu_o \cdot L^2}t. \tag{2}$$

Zhang et al. (1996) combined oil and water viscosities as the geometric mean of the viscosity of both phases and modified Eq. (2) as follows:

$$t_{D-Pc} = \sqrt{\frac{K}{\phi}}\frac{\sigma}{\mu_{gm} \cdot L^2}t. \tag{3}$$

Where μ_{gm} is defined as $\sqrt{\mu_w \mu_o}$.

Ma et al. (1997) showed the importance of boundary conditions. A function involving the core sample shape which has been found to correlate with the available data reasonably well is:

$$t_{D-Pc} = \sqrt{\frac{K}{\phi}}\frac{\sigma}{\sqrt{\mu_w \mu_{nw}} \cdot {L_C}^2}t. \tag{4}$$

In this equation, L_C is a characteristic length, K is rock permeability, ϕ is porosity, σ is interfacial tension between the phases, and μ_w and μ_{nw} are the viscosities of the wetting and non-wetting phases. Ma et al. (1997) introduced the following semi-empirical correlation for the general characteristic length L_C:

$$L_C = \sqrt{\frac{V}{\sum_{i=1}^{n} \frac{A_i}{x_i}}}. \tag{5}$$

Where, V is the bulk volume of the matrix, A_i is the area open to imbibition in the *i*th direction, x_i is the distance from A_i to the no flow boundary and n is the number of faces open to imbibition. For linear imbibitions, L_C is simply the length of the core.

These expressions of t_{D-Pc} do not contain any parameter related to the wettability. In fact, the rock sample is expected to represent different wettabilities. Thus, the effect of the wettability that is usually neglected in the scaling formulations must be taken into account. One approach to include the wettability in this formulation is to use the contact angle. This is the most convenient way for the quantification of wettability, but it is difficult to be measured. Another way for the quantification of wettability is to utilize the forced and spontaneous (capillary) displacement data, as introduced by Amott (1959). An easier technique is to use only the spontaneous imbibition data. Handy (1960), Indelman and Katz (1980), Ma et al. (1994) and Morrow (1990) experimentally showed that if the capillary imbibition recovery, R(t), is plotted against the square root of time, t, a straight line can be obtained and the following relationship is valid:

$$R(t) = \frac{2C}{V_p(1 - S_{wi})}.\sqrt{t}. \tag{6}$$

Where C is the slope, V_p is the pore volume, and S_{wi} is the initial water saturation. This approach was used in the quantification of wettability characteristics by Babadagli (1996). The slope, C, is only a function of wettability, if all other parameters related to the recovery are held constant. Babadagli (1996) introduced $f(\theta)$, which is called the Wettability Index and can range between 0 and 1. The highest slope in curves is equal to 1, which represents the strongly water wet condition. Other values of the Wettability Index are determined by dividing to the highest slope. To use the slopes as a wettability indicator, Eq. (4) can be modified as follows (Babadagli, 1996):

$$t_{D-Pc} = \sqrt{\frac{K}{\phi}}\frac{\sigma \cdot f(\theta)}{\sqrt{\mu_w \mu_{nw}} \cdot {L_C}^2}t. \tag{7}$$

Mason et al. (2010) introduced a new dimensionless time for the capillary imbibition mechanism, which is:

$$t_{D-Pc} = \frac{2}{L_C^2}\sqrt{\frac{K}{\phi}}\frac{\sigma}{\mu_w\left(1 + \sqrt{\frac{\mu_{nw}}{\mu_w}}\right)}t. \tag{8}$$

One would expect that, as the viscosity of the non-wetting phase, μ_{nw}, becomes, relatively small (e.g., air) or with a highly viscous wetting phase, the term related to the viscosities would depend mainly on the viscosity of the wetting phase.

This new function incorporates the expected requirement and is $\mu_w + \sqrt{\mu_w \mu_{nw}}$ or, in terms of the viscosity ratio, $\mu_w\left(1 + \sqrt{\frac{\mu_{nw}}{\mu_w}}\right)$. An optional factor of one half can be included in order to make the value numerically equal to the viscosity factor when the viscosity ratio is unity. The new factor thus becomes $\frac{1}{2}\mu_w\left(1 + \sqrt{\frac{\mu_{nw}}{\mu_w}}\right)$ (Mason et al., 2010).

On the other hand, as the IFT is lowered, gravity also becomes effective on the recovery.

A scaling group for gravity-dominated imbibition was defined by Du Prey (1978) as follows:

$$t_{D-G} = \frac{K \cdot \Delta\rho \cdot g}{L \cdot \phi \cdot \mu_w}t \tag{9}$$

Xie and Morrow (2001) stated that when developing scaling laws for imbibition, the effect of gravity can be neglected. If capillary forces are sufficiently small, then the gravity segregation will make a significant contribution to oil recovery. If the gravity is included, the expression for dimensionless time for the imbibition process will have the form:

$$t_{D(C+G)} = \frac{\frac{K}{\phi}}{\sqrt{\mu_o \mu_w} L_C^2}\left[P_{C_i} f(\theta) + \frac{\Delta\rho \cdot g \cdot L_C^2}{L_H}\right]t. \tag{10}$$

Where P_{C_i} represent the imbibition capillary pressure proportional to $\sigma/\sqrt{K/\phi}$, $f(\theta)$ is a Wettability Index and L_H is the vertical height of sample.

In the first part of this paper, the most recently proposed scaling equations for spontaneous imbibition are investigated using the experimental data. Since the Wettability Index introduced by Babadagli (1996) did not consider all of the affecting parameters by assuming all the other parameters are constant, a new index is introduced containing all the parameters affecting the imbibition rate and is called the Normalization Index. This Normalization Index is checked by both the experimental and literature data. It is suggested as a substitution for the Wettability Index in the dimensionless time equations due to its better performance and consistency.

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