Changes of phase permeability due to micro-processes of water flooding under ultrasound action

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Abstract. Microemulsion always is formed in the real underground flows. Ultrasound action can create microemulsion phase in the system "water + hydrocarbon". The microemulsion appearance in flows changes conventional continuous phase displacement. The laboratory experiments on water-flooding had shown that in this case the cumulative oil recovery increased and the displacement front velocity was moving differently.

The hypothesis is accepted that there is some changes of threshold saturation values and of the phase permeability curvature. Correspondingly the Buckley - Leverett theory is added by the kinetic equation for the threshold saturation.

Here it is found that the decrease of water permeability concavity leads to the growth of front displacement velocity (if the oil permeability curve is fixed) and to the decrease of the water saturation jump at the front. If the oil permeability becomes less concave, the displacement front velocity is decreasing and frontal water saturation is growing (water permeability curve form is fixed). The second possibility does correspond to observed data of laboratory experiments.

The conventional theory of oil recovery is based on the concept [1] of phase permeability $f_i(s)$. The generalized Darcy law has the following form:

$$\vec{w}_i = -\frac{k}{\mu} f_i(s)\ grad\ p_i \qquad (1)$$

where k is absolute permeability, μ is viscosity, $f_i(s)$ the is phase permeability, p_i is the phase pressure.

The goal of this paper is to understand the influence of the form these curves on features of two phase flows. First of all, let mention the difference of phase permeability, created by natural wetting of solid phase (pore channel walls).

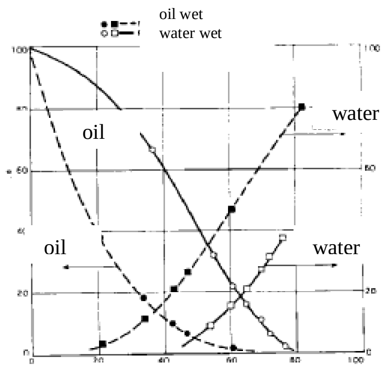

FIGURE 1. Water wetting removes phase permeability curves but changes the of oil curve form only (from concave to convex).

This effect [2] is shown in Fig. 1. One can see that the zero permeability zone exists at saturations less than some s^* (threshold saturation). Correspondingly, the phase permeability depends on saturation as follows:

$$f_i(s_i) = \left[\left(s_i - s_i^+\right)/A_i\right]^{N_i} \qquad (2)$$

Here A_i, N_i are constants, selected by empirical way, s_i^+ is threshold saturation of the i-th phase.

Usually, these curves are given as functions of water saturation s [1]:

$$f_{water}(s) = \left[\frac{s-0{,}2}{0{,}8}\right]^{N_{water}} \quad f_{oil}(s) = \left[\frac{0{,}85-s}{0{,}85}\right]^{N_{oil}} \qquad (3)$$

The example, shown in Fig. 1, may be understood as more fast motion of oil drops along porous channels, wetted by less viscous water. Therefore the oil curve becomes convex.

Experiments with miccelar solutions [3] had shown also that the effective phase permeabilities can change their form (they turn out to be convex) and this effect was explained the presence of an emulsion.

Ultrasound can lead to strong emulsification of the water-hydrocarbon system. If a small amount of gas is present, this will further facilitate emulsification [4]. But the ultrasound can also change wetness (the difference in acceleration of matrix and fluid is thought to be a real reason for degrading of adsorbed films). This effect is important in practice when reservoir ultrasound is intensified by vibroseismic action on the reservoir [5] owing to the strong nonlinearity of the rocks.

If one assume that phase pressures are equal, the Buckley - Leverett theory is valid in its simple form. That is, under assumption that phases are incompressible and the total rate through the sample (or formation) is constant, the effective equation for oil displacement by water becomes hyperbolic one:

$$\frac{\partial s}{\partial t} + \frac{U}{m} F_s'(s) \frac{\partial s}{\partial x} = 0 \; ; \; F(s) = \frac{f_{water}(s)}{\left[f_{water}(s) + \mu^* f_{oil}(s)\right]} \qquad (4)$$

Here s – water saturation (of displacing phase); $F(s)$ is phase flux distribution function; μ^* is the viscosity ratio (= μ_{water} / μ_{oil}); U is the total filter velocity; m is porosity.

Plots of $F'(s)$ and water saturation profiles, that were also calculated by equation (4), are shown in Fig. 2, 3. Water viscosity was μ_{water} = 1 centipoise and oil viscosity μ_{oil} = 3· centipoise.

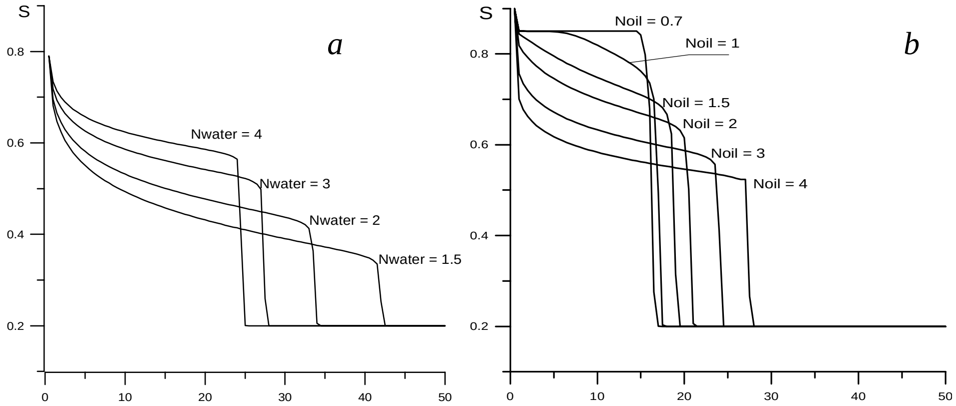

FIGURE 2. The less concavity means faster waterfront motion during the displacement regime (*a*). The convex oil permeability curve means more slow water front motion and higher oil recovery (*b*).

The decrease of water permeability concavity (of N_{water} up to one) leads, see Fig. 2[a], to the growth of front velocity (if the oil permeability curve is fixed: $N_{\text{oil}} = 3.5$) and to the decrease of the frontal water saturation down to the threshold value s^+ (at $N_{\text{water}} \to 1$ asymptotically)[1].

If the oil permeability becomes less concave (the power N_{oil} is decreasing), the displacement front velocity is decreasing (Fig. 2[b]) and frontal water saturation is growing (water curve is fixed: $N_{\text{water}} = 3{,}5$). The limit water saturation reached was $s_f = 1 - s_{oil}^+$. The frontal discontinuity does exist always (even in the case of convex phase permeability: $N_{oil} \geq 1$).

The same result can be reached also by the following arguments. If water permeability curve is concave ($N_{\text{water}} > 1$), the function $F'(s)$ is not monotonous (Fig. 3[a]). Therefore, at one moment the saturation profile becomes multi-valued. This means the necessity to introduce the moving discontinuity, that is, the displacement front.

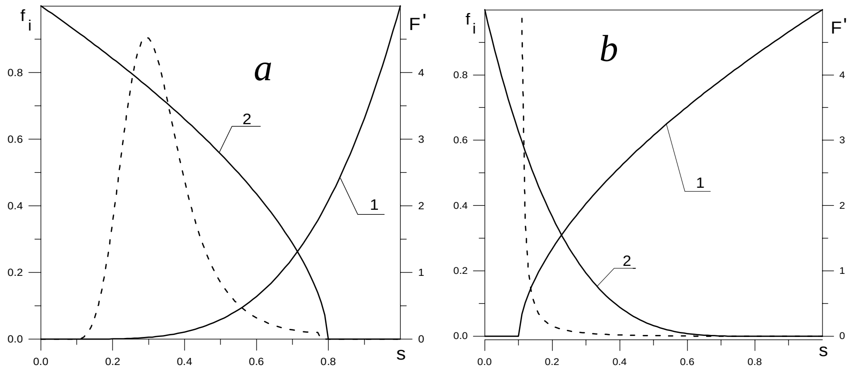

FIGURE 3. The phase permeability curves (continuous curves) and the graph of the function F'(s) (broken curve). Curves 1 and 2 correspond to the displacing and displaced phases.

[1] Water saturation s_f cannot be less than s^+. Really, if $N_{\text{water}} \leq 1$ (when water permeability would be convex), the discontinuity at the front disappears.

However, if the water permeability is convex ($N_{\text{water}} \leq 1$), the function $F'(s)$ is decreasing monotonously (Fig. 3^b) and the multi-value profiles do not appear (less saturation will move faster than bigger one). In this case the discontinuity is absent.

Our results (Fig. 2^b) could be possible explanation of tests [4]. In these experiments were found that under ultrasound action (1 MHz) the displacement front was moving slower than without sounding and oil recovery at water breakthrough was bigger. It is possible that ultrasound transforms the oil phase permeability to some convex form.

Earlier we have noted that in many cases of the displacement of oil by water an microemulsion is formed. Emulsion droplet capture in the fluid and pore system is not absolute (for example, an increase of velocity of the coexisting phase or acoustical action can restore their mobility). So, the threshold saturation s^* could be considered to be a dynamic parameter which only asymptotically reaches the constant (down to zero). This reflects the mobility of part of the residual oil (or bound water).

Therefore let's assume that s_i^* (phase "i") varies with time and only asymptotically reaches the threshold saturation s_i^+ measured in steady-state experiments. The relaxation time should be assumed to be inversely proportional to velocity of coexisting phase w_j (d_i is the effective size of oil drops [6]):

$$\frac{\partial s_i^*}{\partial t} = \frac{w_j(s)}{d_i}(s_i^+ - s_i^*) \qquad (5)$$

The calculation results realized by the system equations (4) and (6), indicate that taking into account for the effects with the dynamics of the threshold saturations leads to change of the front velocity as well as of saturation distribution. Corresponding calculations were published [6]. Generally, owing to the threshold saturation dynamics the displacement front becomes steeper and residual oil saturation is reached more slowly than in the steady-state case of water-flooding. In such a way we can describe the increase of cumulative oil recovery at increase of displacement velocity or under ultrasound action [4].

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