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Abstract

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ON PHASE PERMEABILITIES IN THE FILTRATION OF TWO-PHASE SYSTEMS THROUGH A POROUS MEDIUM

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At the present time, the generally accepted view, based on Leverett' s experiments, is that the relative phase permeabilities in the filtration of two-phase mixtures are practically single-valued functions of the saturation of the porous medium with the given phase and, depending on it, may vary from zero to unity ([1]). Recently, however, papers have appeared in which attempts are made to substantiate, theoretically and experimentally, the possibility of obtaining, under certain conditions, a relative phase permeability exceeding unity ([2], [3]). In particular, it is asserted ([3]) that this phenomenon was observed when water was displaced from a hydrophilic porous medium by viscous mineral oils, owing to the formation on the rock surface of a "lubricating" water adhesion film. However, the experiments confirming this conclusion were conducted unsatisfactorily. The small length of the samples (less than 3.5 cm) and the high interfacial surface tension lead to a violation of all the requirements of the theory of modeling ([4]). In addition, the "end effect" must have significantly distorted the results of determining the residual water saturation, obtained by the method of measuring electrical conductivity.

In order to test the fundamental possibility of obtaining a phase permeability exceeding unity, two series of experiments were carried out in the hydrodynamics laboratory of the Moscow Institute of the Petrochemical and Gas Industry named after I. M. Gubkin. In the first of them, set up under conditions analogous to those described earlier ([3]), the porous media were hydrophilic bodies —porcelain, artificially cemented sand, and extracted hydrophilic samples from the Tuymazy field with a permeability of about 300 millidarcies.

The results of experiments on the displacement of water by mineral oils of different viscosity at different pressure drops, but with the linear law of filtration observed (the values of Re were certainly below the critical ones), showed that in some cases, during filtration through porcelain samples, the relative phase permeability may exceed unity somewhat; however, no clear regularity was observed.

In the second series of experiments, all the requirements of the theory of approximate modeling of displacement processes were observed ([4]).

The reservoir model was a thick-walled steel tube 2 m long and 50 mm in diameter, with artificially roughened walls, filled with compaction by ground quartz of a narrow fraction. Along the length of the tube, at equal distances from it, two-liquid capillary manometers were connected, making it possible to follow the advance of the displacement front and to determine the pressure drops over selected sections. Between the points of connection of the manometers there were "windows" for taking samples of the porous medium. Mineral oil was supplied to the "reservoir" under a pressure of 8 atm, and the filtered liquid was collected in a measuring vessel with a device preventing its evaporation.*

* The experiment with the most viscous liquid lasted about 4 months.

To prevent the formation of mixtures arising as a result of capillary redistribution of liquids in the porous medium and worsening the phase permeabilities, the "reservoir" was preliminarily saturated with a 2% aqueous solution of the hydrophilizing surfactant OP-7, followed by pumping it through the model until the rock could fully adsorb the surfactant.

Both the main and the auxiliary experiments, carried out under the same conditions, showed that after the front of the displacing liquid had passed, the phase permeability for it first increased rapidly, and then stabilized and subsequently remained practically constant*.

After oil breakthrough, no water production was observed. The water saturation of samples taken both along the flow axis and perpendicular to it from various depths was practically the same and coincided with the water saturation calculated from the material-balance equation for the entire "reservoir" **. The phase permeability for oil, determined from Darcy' s equation both from the readings of intermediate manometers and from the total pressure drop, also coincided with a sufficient degree of accuracy.

Table 1 gives the results of the main experiments in this series.

Table 1

Permeability to water K_w, darcies	Porosity m, %	Relative viscosity of oil $\frac{\mu_o}{\mu_w}$	Interfacial tension σ, dyn/cm	Relative phase permeability $\frac{K_o}{K_w}$	Residual water saturation, %
14.0	31.2	145	4	4.78	8.2
14.9	30.9	68.2	3	2.05	9.8
15.6	31.4	25.3	3	1.71	10.6

Since the residual water saturation is small and the rock is hydrophilic, it may be assumed that water is retained in it only in the form of a film, the thickness of which, for example, in the second experiment, should be[5]

$$\delta = 2.91 \cdot 10^{-2}\ \mu.$$

Control experiments carried out with the same liquids, but with a "reservoir" permeability of 2.1 darcies, gave results analogous to those obtained by Leverett; moreover, the relative phase permeability for oil did not exceed 0.76.

Consequently, it may be concluded that in low-permeability porous media, when a low-viscosity liquid is displaced by a more viscous liquid that preferentially wets the rock, the phase permeability for the displacing liquid may be higher than its absolute value. This phenomenon is evidently associated with a change in the boundary conditions favorable for filtration—the occurrence of slip when the liquid/solid boundary is replaced by a liquid/liquid-film boundary. The effect is intensified with increasing relative viscosity of the displacing liquid, which is simultaneously accompanied by a decrease in the thickness of the adhesion film of the displaced phase.

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* In the auxiliary experiments, sampling for determining the residual water saturation was carried out during the course of the experiment, and in the main experiments—after its completion.

** This, in particular, indicates the absence of oil breakthrough along the walls of the model.

Note: Figure translations are in progress. See original paper for figures.