EXPERIMENTAL STUDY OF THE EFFECT OF RELATIVE VISCOSITIES ON THE RATE OF COUNTER-CURRENT CAPILLARY IMPREGNATION OF POROUS MEDIA

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Countercurrent impregnation in this context means simultaneous movement (in opposite directions) of water and petroleum (oil) in a porous bed under the influence of capillary forces [1, 2]. This phenomenon plays a substantial part in the mechanism of displacement of oil by water. Countercurrent impregnation is practically the only means of recovery of oil from small "pockets" surrounded by water.

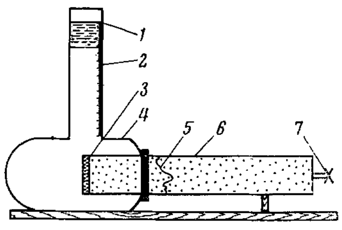

Fig. 1

Pockets of this kind are formed during unstable displacement of oil [3] and when oil is displaced from heterogeneous and fractured strata [4-6]. For estimating the extraction of oil in the case of the formation of oil pockets (i. e., under conditions of unstable movement of the front) it is important to know the dependence of the rate of countercurrent impregnation on the oil/water viscosity ratio. This paper describes a series of experiments carried out to study this dependence.

The experiments were carried out in glass tubes (37 cm long, 4.7 cm diam) filled with glass powder. The permeability of these models varied within the limits 1.0-1.5 darcy. Both ends of each tube were closed with filters (7-9 mm thick) made from sintered glass powder and attached to the tube with the aid of an epoxy resin putty. To make the surface of the porous medium hydrophilic, the tubes were washed before each experiment with ether, methyl alcohol, and a 30% HCl solution. The washing was done in the following order: methyl alcohol-ether-acid-water-methyl alcohol. The tube was mounted in an apparatus shown schematically in Fig. 1. The tube 6 was attached to the chamber 4 (with an epoxy putty) in such a way that the filter 3 was placed opposite the measuring cylinder 2. A plug 7 was fitted to the other end of the tube.

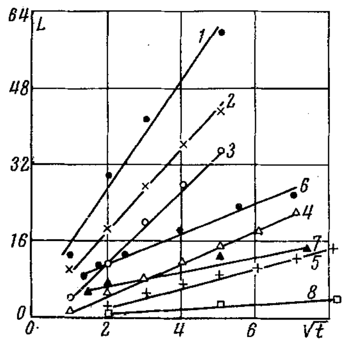

Fig. 2

After filling the tube with a mixture simulating oil, the chamber and the measuring cylinder were filled with distilled water. The oil coming out of the model rose to the top of the liquid column in the measuring cylinder while water penetrated into the tube. In this way it was possible to measure the quantity of oil displaced from the tube and the distance traversed by the front (the tube length was graduated).

In most experiments petroleum oil was simulated by a mixture of purified kerosene and vaseline oil.

The surface tension of mixtures of this kind at the water/mixture interface did not significantly vary, ranging from 37 to 40 dynes/cm. In a few experiments we used a mixture of Arlansk petroleum, kerosene and vaseline oil (one part of petroleum and three parts of the nonpolar liquid). Various oil/water viscosity ratios ($M = \mu_2/\mu_1 = 2-20$) were used in the experiment.

The average results of each series of experiments were plotted in the form of curves representing the dependence of the distance L traversed by the advancing water front on the square root of time $t^{1/2}$. This way of plotting the results was chosen because, according to the results of a theoretical study [2], before the advancing front reaches the closed end of the tube the process in question is described by the following relation: $L = ct^{1/2}$, where c is a constant depending on the properties of the porous medium and liquids used. All the experimental curves obtained are reproduced in Fig. 2, where t is measured in days.

Curves 1-5 relate to experiments in which M was equal to 2.5, 5.3, 8.0, 14, and 19, respectively. Combined water was not modeled. Figure 2 shows that the relation studied is fairly accurately represented by a straight line for all the values of M tested. The rate of capillary impregnation at equal values of M is substantially reduced if petroleum is added to the liquid being displaced (compare curve 6 at M = 2.5 and curve 8 at M = 19 with curves 1 and 5).

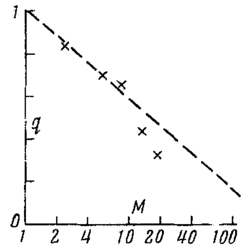

Fig. 3

The variation in the oil/water viscosity ratio did not substantially affect the total recovery of oil (equal to the ultimate water saturation) which varied between 69 and 72%. The average saturation in the mixture zone did not vary much either. And so, irrespective of the water/oil viscosity ratio, L was proportional to the volume of water that had penetrated into the specimen.

The capillary impregnation rate can be characterized by a value $c = Lt^{-1/2}$ or $Q = Qt^{-1/2}$, where Q is the volume of water penetrated into the specimen in time t. The dependence of Q on M was determined theoretically on the basis of a self-similar solution of the problem of countercurrent capillary impregnation cited in [2]. It was shown there that the saturation distribution s(x, t) in a linear specimen (before its closed end is reached by the "impregnation front") can be found by solving a boundary problem for the ordinary differential equation of the second order which relates s to a value

$$\xi = \frac{x}{at^{0.5}} \qquad \left(a = \left(\frac{\sigma\cos\theta}{\mu_1}\right)^{0.5}\left(\frac{k}{m}\right)^{0.25}\right)$$

Here σ is the interfacial tension at the oil/water interface, θ is the contact angle, k denotes permeability, and m is the porosity of the medium. Curves s (ξ) were calculated for various values M.* The ultimate saturation at $\xi = 0$ (i.e., $t \to \infty$ or $x = 0$) was assumed in these

*The calculations were carried out in the Computer Center AS USSR under the supervision of Ya. I. Alikhashkin.

calculations to be 0.7, and the same permeability and capillary pressure curves as those used in [2] were employed. From curves $s(\xi)$ it is possible to find the quantity of water absorbed by a specimen in a time t, which is $Q = q\alpha t^{1/2}$, where $q = q(M)$. We determined q for M equal to 1, 2, 10, and 100. All the values of q were calculated for one and the same value of the initial water saturation $s_0 = 0.2$.

The determination of q was done accurate only to a constant factor since calculated (instead of experimental) capillary pressure curves were used and because the magnitude of dynamic contact angle θ was not known. The dependence of q on log M in Fig. 3 is therefore plotted so that at M = 1 we have q = 1. It will be seen that this dependence in the range studied is represented by a practically straight line. The experimental values of q for the case of the displacement of nonpolar mixtures of kerosene and vaseline oil are plotted in Fig. 3 also to an arbitrary scale so that the theoretical and experimental values of q at M = 2.5 coincide. Comparison shows that the experimental curve q (log M) at $M < 10$ is less inclined than the theoretical curve, being steeper at $10 < M < 20$. On the average, however, the slopes of the theoretical and experimental curves are quite close. Of course, this is only a qualitative comparison since there was no residual water in the experiments, i.e., $s_0 = 0$, while the theoretical calculations were carried out for $s_0 = 0.2$. It should also be pointed out that in plotting the experimental curve q(M) no account was taken of certain differences in the permeability of the models, since the variation in permeability was small (1–1.5 darcy) and because $k^{0.25}$ appears in the expression for α.

In one experiment (curve 7 in Fig. 2) a mixture of Arlansk petroleum and nonpolar liquids was displaced in the presence of residual water occupying 24% of the interstitial volume of the tube; in this experiment M = 19. It will be seen that the presence of residual water accelerated capillary absorption. However, even in this case the rate of capillary impregnation at a high M was considerably slower than in the case of nonpolar liquids with the same viscosity.

The course of countercurrent impregnation at low M is noticeably affected by capillary instability observed in [3] in the case of petroleum being displaced by water at slow speeds. In some experiments the influence of capillary forces led to the appearance of large zones in which "tongues" of water were formed. At the same time, no marked spreading of the advancing water front due to capillary instability was observed when small diameter (2.5 cm) tubes were used in the experiments.

To carry out a more detailed study of capillary instability, we conducted a series of experiments on countercurrent capillary impregnation using a flat model of a porous bed measuring 47 × 26 × 1.3 cm; the permeability of the model was 5.3 darcy, and M = 2.5. The experimental technique differed slightly from that used in experiments with tube specimens. In one side of the model a box was mounted through which distilled water was flowing. Oil displaced from the model found its way to the box from which it was carried away by the water current.

The character of the movement of the water/oil interface in one of these experiments is shown in Fig. 4 where the impermeable walls of the model are indicated by cross-hatching. It will be seen that in the initial stages of the process the advancing front was quite stable (line 1). Later, as the impregnation rate decreased, water "tongues" protruding into the oil part of the zone began to form at the advancing front (line 2). As a result, an oil pocket (line 4) was left behind and subsequently encircled by water as a result of countercurrent capillary impregnation. At the moment when water reached the opposite wall of the model, three oil pockets were left behind the advancing front (line 5). Their disappearance was a very slow process: It took as long a time as the time taken by water to traverse the length of the model.

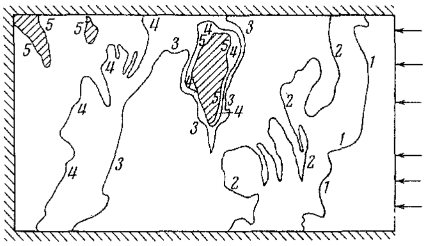

Fig. 4

This slowing down of the process is due to the fact that the degree of water saturation at the oil pocket boundary is low and much lower than at the point of entry into the model. It is possible that under real conditions at slow impregnation rates this specific feature of the process in question may play a substantial part.

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