NOTATION

d, element diameter; d_e, equivalent annular channel diameter; w and w_0, mean flow-rate velocities for liquid and gas; x, distance from holes to vorticizer; ΔP, pressure difference; u_φ, u_z, and u_r, tangential, axial, and radial gas flow velocities; r and R, current radius and element radius; τ, time; q, irrigation density; α, flow coefficient; β, blade inclination; ρ and ρ_ℓ, densities of gas and liquid; μ and μ_ℓ, dynamic viscosities of gas and liquid; $Re_f = 4q/u_\ell$, Reynolds number for liquid film; $Re = wd_e\rho_\ell/\mu_\ell$, Reynolds number for liquid in annular channel; d_0, diameter of holes; d_s, equivalent slot diameter.

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VARIABLE-PRESSURE CAPILLARY IMPREGNATION OF A GAS-SATURATED POROUS MEDIUM

A. N. Shandrygin

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Variable-pressure impregnation of a gas-saturated porous medium differs considerably from the constant-pressure case. The periodic pressure falls and rises have marked effects on the gas content. Pressure cycling can increase the extent to which the gas is displaced.

Tests have been made [1-3] on the effects of cyclic pressure on oil-saturated jointed porous collectors; that treatment raises the performance in capillary displacement.

The effects of cyclic pressure variation on capillary impregnation for a gas-saturated porous medium in experiments on various rocks have been examined. The cylinders were cut from natural sandstones and limestones and also from an artificial porous medium made of cement stone. The diameters were 0.0198-0.0204 m and the lengths 0.02-0.034 m. The permeability coefficients ranged from 0.005 to 8.9 μm^2, while the porosities varied from 49.9 to 30.6%. The water uptake was measured by a volumetric method, which in some cases was checked by weighing.

One-dimensional countercurrent and direct-flow methods were used. The specimens were prepared as in [4], but the residual water saturation was not simulated. In direct flow, the sides of the cylinders were coated with epoxide resin, while in counterflow simulation, one of the ends was also treated with resin. The pressure variation was simulated by evacuating the cylinders. Various values were used for the pressure variation, the cycle time, and the time from the start of impregnation to the start of the cyclic treatment.

Pressure variation influenced the gas displacement, particularly the gas extraction and gas content coefficients. The gas-extraction coefficient was the ratio of the extracted gas volume to the initial gas volume in the specimen. The current gas saturation coefficient was defined as the ratio of the pore volume occupied by the gas to the total. There is a general similarity in the impregnation of low-porous and high-porous cylinders, but the time scales differ.

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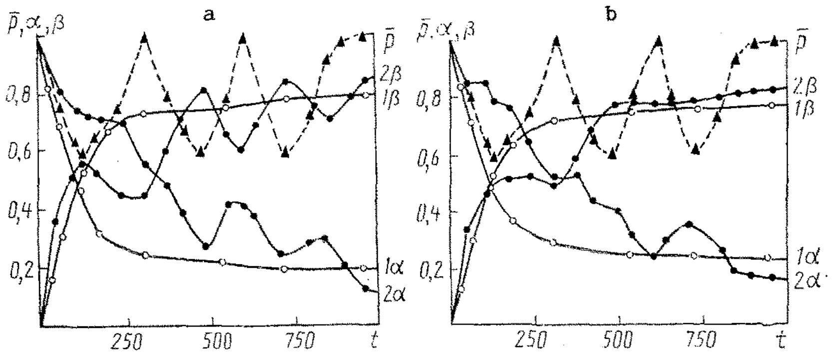

Fig. 1. Time course of gas saturation and gas extraction coefficients for direct flow (a) and counterflow (b) impregnation: 1α, 2α) saturation coefficients for constant and variable pressure; 1β, 2β) extraction coefficients for constant and variable pressure; $\bar{p}$) ratio of current and initial pressures in specimen, t in sec.

Constant-pressure impregnation leaves residual gas consequent on the capillary displacement, so the gas saturation coefficient varies in proportion to the gas extraction one. With variable pressure, the gas is extracted not only by capillary impregnation but also because of the gas volume change in response to the pressure, in which case the response of the gas saturation and extraction will differ. In direct flow, pressure reduction at the start of impregnation produces a larger increase in the gas extraction coefficient but a change in the gas saturation less than with constant pressure because the gas expands in the unimpregnated part of the specimen and also because of the trapped gas behind the impregnation front. The subsequent pressure rise in the first cycle reduces the extraction coefficient somewhat. This was observed in all cases of direct flow and is due to the specimen taking up gas from the surrounding space on account of the pressure rise. The gas injected on pressure rise is distributed in the specimen on account of the volume reduction and does not hinder the water injection by the capillary forces, as is evident from the reduction in the gas saturation in that period.

The behavior of the coefficients in the subsequent cycles is as in the first one, but lower gas saturation coefficients are observed from cycle to cycle at the same pressures and larger gas-extraction ones. The impregnation with pressure cycling continues after the pressure has been restored to the initial level.

Figure 1a shows direct-flow impregnation for a highly permeable specimen with variable and constant pressures. When the pressure falls at the start to 0.6 of the initial value, the extraction coefficient rises to 0.559. The change in saturation coefficient is here from 1.0 to 0.735. At the same instant with constant pressure, those two coefficients are correspondingly 0.532 and 0.468. A rise to the initial value in the first cycle produced a reduction in the extraction coefficient (from 0.559 to 0.440), while the saturation coefficient fell to 0.560. In the second and third cycles, the extraction coefficient increased correspondingly by 1.9 and 2.9%, with the saturation coefficient falling correspondingly.

Mostly, direct-flow impregnation with cyclic pressure increased the final extraction coefficients by 5-12% by comparison with constant pressure. Table 1 gives the performance for that treatment in all the experiments.

Pressure variation also affects countercurrent impregnation. Reducing the pressure causes a considerable increase in the extraction coefficient with a minor change in the saturation one.

Here in most cases the extraction coefficient was not reduced in the rising-pressure phase but instead remained at the level attained at the start of pressure rise. The saturation coefficient fell, which was due to the lack of gas injection from the surrounding space during the rising phase, since the specimen was in contact only with water. In the falling phase, there was considerable increase in the extraction coefficient and a slight increase in the saturation one. The extraction coefficient increased and the saturation one

TABLE 1. Performance from Cyclic-Pressure Impregnation

Specimen type	Ranges		Impregnation	Number of specimens showing increased extraction coefficient in %				
	impermeability coefficient, μm²	porosity coefficient, %		no increase	0—5	6—10	11—15	16—20
Low-permeability	0,005—0,073	4,9—30,6	Direct	2	1	4	2	—
			Countercurrent	1	1	3	3	1
High-permeability	1,21—8,9	23,7—27,9	Direct	—	1	5	2	—
			Countercurrent	1	2	3	2	—

fell from cycle to cycle for given pressures, and the countercurrent impregnation continued after the pressure had been restored to the initial value.

Figure 1b shows countercurrent impregnation for a highly permeable specimen. Reducing the pressure to 0.6 of the initial value increases the extraction coefficient to 0.482 and reduces the saturation one to 0.861 in the initial period. The extraction and saturation coefficients for that time for constant-pressure treatment were 0.468 and 0.532. When the pressure recovers to the initial value in the first cycle, the extraction coefficient increases to 0.478 and the saturation one decreases to 0.522. In the second cycle, the extraction coefficient is 0.778 and the saturation one 0.222 when the pressure reduces the initial value. The changes in those two coefficients in the third cycle were 0.065. That behavior was observed in most of the countercurrent impregnations.

Pressure cycling mostly increases the extraction coefficient. Table 1 shows that on average it exceeded the value without pressure cycling by 5-20%.

Pressure cycling thus increases the extraction coefficient. Improved capillary impregnation with cyclic pressure reduction has two causes. Firstly, pressure reduction in the initial period extracts a certain amount of gas by expansion, while subsequent water infiltration replaces the gas, so the gas volume is smaller. However, a more important factor is that the phases are redistributed in the medium with pressure cycling, which leads to additional impregnation.

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