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TRANSFER PROCESSES IN RHEOLOGICAL MEDIA

RHEOLOGICAL FEATURES OF WATER FLOW IN MICROCRACKS

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Rheophysical phenomena during the flow of a viscous fluid (water) in differently opened flat microcracks have been studied. The role of the electrokinetic factor in the manifestation of the nonlinear rheological effect in a water flow in a microchannel model — the transformation of a Newtonian fluid into a non-Newtonian one — is examined experimentally. Water flow curves were recorded and, based on the Bingham model, its rheological parameters were assessed for differently opened microcracks. It has been established that the non-Newtonian nature of water in microcracks is determined mainly by the value of the electrokinetic potential of the flow, and by reducing it, using antistatic additives, the nonlinear nature of the flow can be weakened significantly.

Keywords: *microcrak, microcrack opening, flow curves, double electric layer, streaming potential, antistatic additives, ultimate shear stress, structural viscosity.*

At the present time, the development and operation of low-permeability hydrocarbon reservoirs is becoming an increasingly urgent task, and therefore the study of the laws governing the movement of fluids in subcapillary pores and microcracks is an urgent scientific and technical problem. In real fractured formations, most of the oil, located in microctacks, does not flow with the displacement gradients of the developed formation and, as a result, even with the modern level of development of science and technology, a significant amount of geological reserves of oil resources remains unextracted from rocks. Of course, one of the main reasons of such low oil recovery efficiency is the insufficient knowledge of the characteristic features of fluid movement in low-permeability reservoirs.

Despite the large number of experimental and theoretical works, there are some fundamental problems in this area that require further study. According to the results of a number of experimental studies, a viscous fluid, when flowing in low-permeability reservoirs, exhibits an anomalous non-Newtonian character accompanied by violation of the linearity of the filtration process and, accordingly, of the Darcy law [4–8]. In studying the flow of Newtonian fluids in microcracks [9], it was established that, when water or viscous oil flows in microcracks, the flow becomes non-Newtonian with a decrease in the opening of cracks, starting from a certain critical size, with manifestation of an initial pressure gradient and blocking of the flow. However, today opinion varies as to the mechanism of these phenomena although there are various approaches to explain the anomalous hydrodynamic behavior of liquids flowing in a low-permeability porous medium and microcracks.

Work [10] is one of the first studies on the influence of flow electrization on the hydraulic characteristics of real liquid systems, in which it was found that various thermohydrodynamic effects in heterogeneous liquid systems are largely determined by the value of the electrokinetic factor, the regulation of which can significantly change the rheophysical state of the system.

As is known, according to Koehn's rule [11], two substances with different dielectric constants that are in contact are charged along the contact surface. In accordance with this rule, upon contact of a liquid with a solid body, an electric double layer with a certain electrokinetic potential is formed on the boundary surface. The boundary of this double layer is quite smeared and its thickness, with account for the diffusion layer, can be on the order of several microns. The electrostatic field caused by the electric double layer imposes a certain influence on the nature of the flow in the boundary zone. For channels (pipes) of sufficiently large dimensions, transverse to the flow, this effect is insignificant. However, for narrow cracks and small diameter pipes, in which the transverse dimensions become commensurate with the dimensions of the

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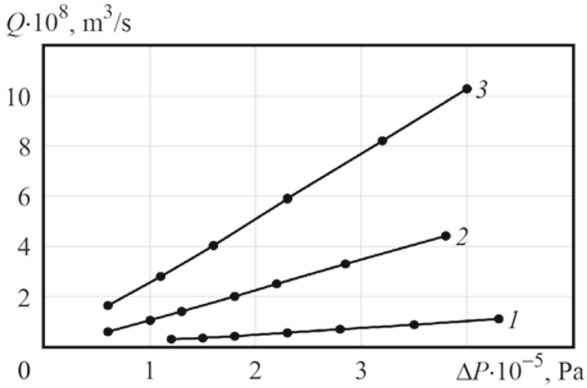


Fig. 1. Flow curves for water at different values of crack opening h: 1) h = 15 μm; 2) 10; 3) 25.

electric double layer, the situation differs fundamentally — the electrostatic field of the electric double layer becomes an additional factor of hydraulic resistance.

This work experimentally examines the role of the electrokinetic factor in the manifestation of nonlinear effects during water flow in microcracks. The experimental setup consisted of a microcrack model, a high-pressure cylinder, and a thermostat. Tap water was used as the working fluid. A model of a microchannel with a length of 30 cm and a width of 4 cm was formed by two parallel steel plates 1.8 cm thick. The plates made of 40Kh steel, after heat treatment with high-frequency currents, had a surface hardness of 40–50 Rockwell units. The inner surface of the plates was processed and polished with a smoothness corresponding to class 10.

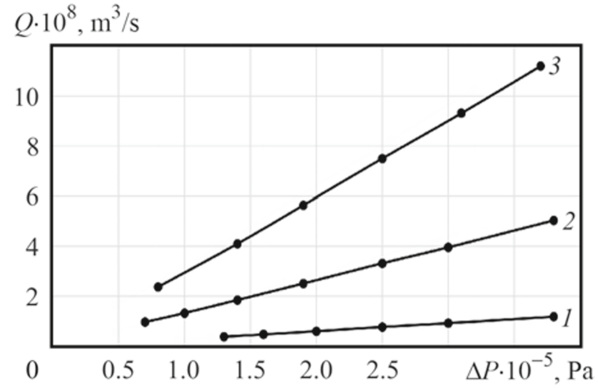
Microcracks of a given opening (h) were obtained by installing nonwetted gaskets of appropriate micron thickness between the plates. Experiments were carried out at various values of h in range 10–25 μm.

To ensure the isothermal nature of the process, the model was placed in a thermal bath connected to an ultrathermostat. To determine the pressure drop at the inlet and outlet of the model, standard pressure gauges with an error of 0.2–0.35% were installed. The mass flow rate of the liquid was determined on an electronic balance with an accuracy of 0.001 mg.

Upon reaching a steady flow regime at different openings of cracks, the flow rate curves $Q = Q(\Delta P)$ were recorded for water at atmospheric pressure at the outlet of the model. Figure 1 shows the flow curves obtained in experiments for three values of crack opening (h = 15, 20, and 25 μm) at the temperature $T = 30^{\circ}$C. As can be seen, with a gap h = 25 the flow curve is linear and corresponds to the Newtonian model. However, at lower values of h the flow becomes nonlinear — the water behaves as a non-Newtonian fluid with some initial pressure gradient ΔP_0 characteristic of Bingham liquids. In this case, with decrease in the opening of the gap, starting from the critical value h_{cr} = 25 μm, the nonlinear nature of water is enhanced, the effect of flow blocking appears, which is maximally manifested at the smallest value of the gap (h = 10 μm) in the considered range. In the observed transformation of a Newtonian system into a non-Newtonian one, an increase in the rheological nonlinearity and hydraulic resistance in thin cracks, the role of the electrokinetic factor is undeniable.

As already noted, in thin cracks the transverse geometric dimensions of the channel become commensurate with the dimensions of the double electric layer, which causes the manifestation of electrophysical effects. So, when water flows through a crack, it carries ions from the diffuse part of the double electric layer at the water–metal surface interface, which generates the so-called streaming potential. The generated potential difference between the ends of the microchannel, in turn, causes the transfer of ions opposite to the flow of liquid, which ultimately leads to the manifestation of additional resistance to movement and a corresponding increase in viscosity — a phenomenon called the electroviscous effect [12], which is reflected significantly in the fluid flow pattern.

In experiments, the streaming potential Δφ was measured with a microvoltmeter (multimeter CHY 20) using platinum electrodes at the input and output of the model. The measurement error did not exceed 0.8%. It has been established that the value of Δφ depends on the opening h of the gap and increases with a decrease of the latter. So, at h = 25, 20, 15, and 10 and ΔP = 1 atm the average values of Δφ are equal respectively to 2190, 2670, 2970, and 3350 mV and with a decrease of h the streaming potential Δφ increases, reaching its highest value at the smallest gap opening in the considered range. The results obtained indicate that the hydraulic characteristics of water flow in thin cracks depend significantly on the degree of



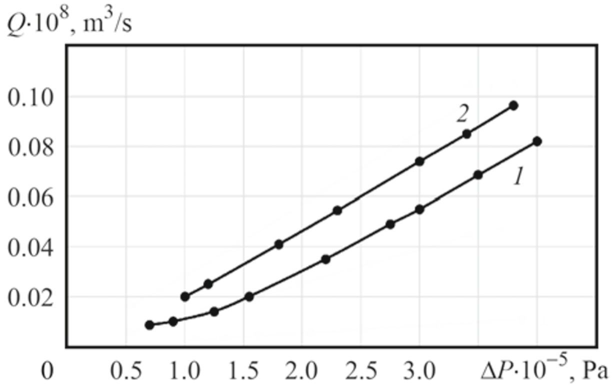
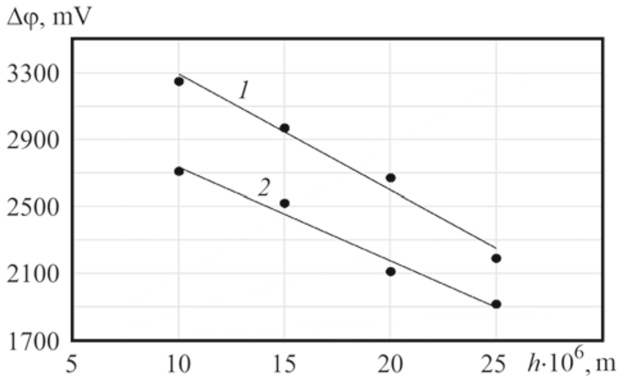


Fig. 2. Curves of water flow in the presence of an antistatic additive at different values of crack opening *h*: 1) *h* = 15 μm; 2) 20; 3) 25.

Fig. 3. Curves of water flow for a crack with *h* = 10 μm in the absence (1) and presence (2) of antistatic additive.



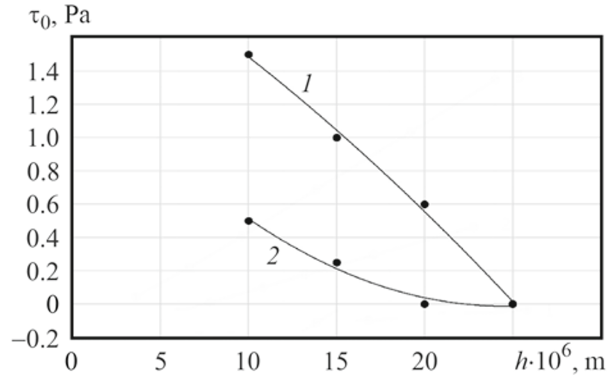


Fig. 4. Dependences of streaming potentials on the microcrack opening in the absence (1) and presence (2) of an antistatic additive.

Fig. 5. Dependence $\tau_0 = \tau_0(h)$ in the absence (1) and presence (2) of an antistatic additive.

flow electrization, and by correspondingly changing the electrokinetic factor, it is possible to change the flow parameters significantly.

To regulate the electrostatic potential of the flow, it was decided to use an antistatic reagent. The ND-12 reagent, usually employed as a demulsifier in oil field conditions, was used as an antistatic agent. Subsequently, the curves of flow through the cracks of the above-mentioned sizes were recorded again, but for water with an antistatic additive. Figure 2 shows the flow curves for water with a very low concentration (0.006%) of the antistatic additive at different values of the gap opening *h*.

From a comparison of the obtained water flow curves in the absence and presence of an antistatic additive, a number of important conclusions can be drawn. Thus, the non-Newtonian character, which manifests itself for water at *h* = 20 μm, practically disappears in the presence of an additive, and the flow becomes Newtonian. But for a gap with *h* = 15 μm, with a decrease in the electrical potential, there is a clear weakening in the non-Newtonian nature of the flow with a significant decrease in the initial pressure gradient and, accordingly, in the hydraulic resistance.

For comparison, Fig. 3 shows the flow curves for a crack with *h* = 10 μm in the absence and presence of an antistatic additive. As can be seen, in the presence of an additive, due to the decrease in the electrokinetic potential, a significant shift in the flow curves occurs, as well as a corresponding weakening of the non-Newtonian character of the flow.

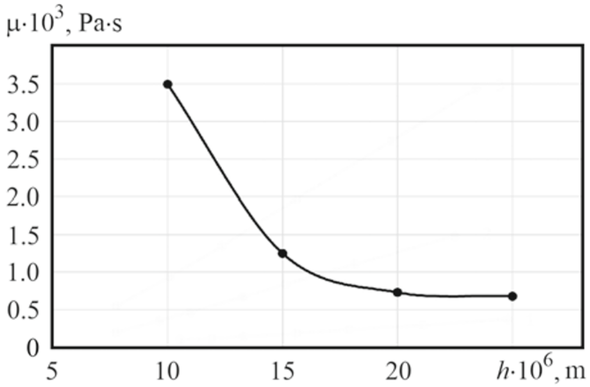


Fig. 6. Dependence of the structural viscosity μ on the crack opening h.

In recording flow curves for each individual case, measurements of the streaming potential $\Delta\varphi$ were carried out simultaneously. The values of $\Delta\varphi$ at $\Delta P = 10^5$ Pa for different values of h in the absence and presence of additives are presented in Fig. 4. As can be seen, in a flow of water containing additives, the value of the streaming potential is significantly lower.

To assess the hydraulic characteristics of the flow in microcracks, the relationships between the tangential shear stress and the average velocity gradient $\gamma = \gamma(\tau)$ are constructed based on the obtained flow curves.

It is known that the volumetric flow rate of liquid in a steady laminar flow between two fixed parallel plates is determined as $Q = bh^3\Delta P/12\mu L$, where b, L, and h, respectively, are the width, length, and opening of a rectangular crack.

The values of γ and τ were defined as $\gamma = 6Q/bh^2$ and $\tau = \Delta Ph/2L$. The curves of the dependence $\gamma = \gamma(\tau)$ were approximated by the Shvedov–Bingham model, on the basis of which the rheological parameters of the liquid — the ultimate shear stress τ_0 and the structural viscosity μ — were estimated.

Figure 5 shows the values of the ultimate shear stress t_0 depending on h. As can be seen, for water without additives $\Delta\tau_0$ begins to manifest itself at values of h less than 25 μm, increases with a decrease in the gap, and reaches its greatest value at $h = 10$ μm. It can also be seen that in the presence of an antistatic additive there is a significant decrease in the critical value of the gap opening h_{cr}. The presence of an antistatic additive in water leads to a significant decrease in the ultimate shear stress $\Delta\tau_0$ manifested at $h < h_{cr}$. Moreover, the smaller the gap, the greater the effect of decreasing $\Delta\tau_0$. Thus, for the gap $h = 10$ μm with additive $\Delta\tau_0$ decreases threefold.

Dependence of the structural viscosity on the opening of the crack $\mu = \mu(h)$ is presented in Fig. 6. As can be seen, the nature of the dependence $\mu = \mu(h)$ is qualitatively similar to that of the dependence $\tau_0 = \tau_0(h)$ — an increase in μ with a decrease in h staring from the critical value of the crack opening h_{cr} (Fig. 6). At $h < h_{cr}$ there is a nonlinear increase in the structural viscosity, which is especially pronounced at $h = 10$ μm. It should be noted that the presence of an antistatic additives has virtually no effect on the nature of the dependence $\mu = \mu(h)$ in the considered range of h values.

NOTATION

h, crack opening, μm (micron); h_{cr}, critical opening, μm; Q, volumetric flow rate, m^3/s; ΔP, pressure difference, Pa; $\Delta\varphi$, streaming potential, mV; μ, structural viscosity, Pa·s; τ, shear stress, Pa; τ_0, ultimate shear stress, Pa.

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