PERCOLATION OF NON-NEWTONIAN SYSTEMS

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Results of an experimental investigation of percolation of non-Newtonian systems are presented. Various approximate models and factors affecting the characteristic constants of these models are considered.

Considerable attention has recently been given to the problem of non-Newtonian fluids in connection with the use of polymer materials in engineering and development of oil and gas deposits.

Percolation of non-Newtonian systems was studied in [1-5, et al.], where it was described by a modified Darcy's law for a viscoplastic medium, first written by Mirzadzhanzade [1] in the form

$$\bar{v} = -\frac{k_0}{\eta_0}\left(1 - \frac{P_0}{(\operatorname{grad} P)}\right)\operatorname{grad} P. \tag{1}$$

The results of an experimental confirmation of Eq. (1) for the example of a model fluid – a mixture of vapor lubricating oil and bright stock oil – are presented in [2], where the following expression was obtained for P_0

$$P_0 = \alpha_0\tau_0/\sqrt{k}. \tag{2}$$

Percolation in the presence of an initial pressure gradient related with the particular behavior of percolating fluids in a porous medium (e.g., water in clay) was investigated by Puzyrevskaya, Florin, et al., and even earlier – at the end of the last century – by King [6-9]. We note that an initial pressure gradient occurs also in the case of percolation of gas through clay containing a comparatively large quantity of residual water.

The investigations of percolation carried out for various non-Newtonian systems at the Azizbekov Institute of Petroleum and Chemistry in Azerbaidzhan showed that in a number of cases, especially at pressure gradients less than P_0, Eq. (1) cannot be used.

Here we present the results of an experimental investigation of the percolation of non-Newtonian systems for which we used model fluids – mixtures of vapor and bright stock oils, two-phase foam (seawater + air + surfactant), and tarry oils from a number of deposits in Azerbaidzhan. A column, 625 mm long and 42 mm inside diameter, was filled with purified quartz sand and then tamped with a vibrator. The experiments were carried out under isothermal conditions.

Percolation of the fluid occurred at a given pressure gradient. The latter was maintained by gas delivered from a high-pressure cylinder to a tank with a valve which prevented an inrush of the gas into the core holder. The flow rate of the fluid was changed by adjusting the pressure gradient, which was recorded by standard pressure gauges, and was determined by the weight method.

Assuming that, other conditions being equal, the value of ΔP changes in direct proportion to the change l, for the pressure gradient we can write the following physical equation:

$$\frac{\Delta P}{l} = f(v,\ k,\ k',\ n',\ \rho). \tag{3}$$

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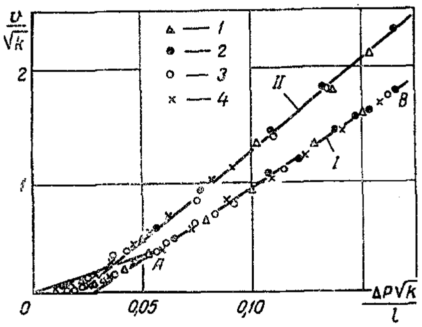

Fig. 1. Graph of $v/\sqrt{k}$ (sec^{-1}) vs $\Delta P\sqrt{k}/l$ (g/cm^2) for a mixture of vapor (75%) and bright stock (25%) at various air permeabilities, darcys: 1) 75; 2) 12; 3) 5.1; 4) 1.4 and temperatures, °C: I) 27; II) 29.

On the basis of analyzing the dimensionalities we obtain a dependence in the form:

$$\frac{\Delta P\sqrt{k}}{l\left(\frac{v}{\sqrt{k}}\right)^{n'}k'} = f(n',\ \mathrm{Re}),\qquad \mathrm{Re} = \left(\sqrt{k}\right)^{n'} v^{2-n'}\rho/k'. \tag{4}$$

From the experimental data we constructed graphs of $v/\sqrt{k}$ as a function of $\Delta P\sqrt{k}/l$. The values of the indicated quantities calculated for different values of air permeability fitted onto one common curve passing through the origin of the coordinates. Figure 1 shows such curves for a mixture of vapor and bright stock oils for different temperature values, and Fig. 2 for two-phase foam with a 1.0% concentration of PO-I surfactant in water.

Treatment of the experimental data showed that the dependence $f(n', \mathrm{Re})$ for the experiments can be represented in the form $f(n')$, which is presented in Fig. 3. It follows from this figure than when $n' \to 1$, $f(1) \to 1$.

Thus the process of percolation of non-Newtonian fluids at comparatively low velocities can be described by Darcy's law (see Fig. 1, straight line OA) and at high velocities by the modified Darcy's law for a viscoplastic medium (see Fig. 1, line AB) and by an exponential function.

With the use of the exponential function the law of percolation can be formulated so

$$\operatorname{grad} P = -\frac{k'f(n')}{\sqrt{k^{n'+1}}}\ \frac{\bar{v}}{v^{1-n'}}\ . \tag{5}$$

The modified Darcy's law for a viscoplastic medium is written in the form

$$\operatorname{grad} P = -\left(\frac{\eta}{k}\,v + \frac{\alpha}{\sqrt{k}}\right)\frac{\bar{v}}{v}\ . \tag{6}$$

With the use of Caesson's relation, modified in [1], the law of percolation is expressed by the formula

$$\operatorname{grad} P = -\left[\left(\frac{\eta_1 v}{k}\right)^{\frac{1}{n}} + \left(\frac{\alpha_1}{\sqrt{k}}\right)^{\frac{1}{n}}\right]^n \frac{\bar{v}}{v}\ . \tag{7}$$

Equation (6) follows from (7) when $n = 1$ as a particular case. The graphs of $(v/\sqrt{k})^{1/2}$ vs $(\Delta P\sqrt{k})^{1/2}$ are rectilinear and intercept segments $\alpha_1^{1/2}$ on the x axis. The slope of the straight lines is $\eta^{1/2}$.

The approximation constants of these dependences are presented in Table 1.

We note that the selection of one or the other dependence is determined by the conditions of the problem and by the difficulties arising in its solution. For example, when using dependence (6) the region of percolation is tentatively divided into a region of motion, where the relation between the pressure gradient and the velocity of percolation is linear, and a "stagnant" region, where the fluid is stationary. In connection with this, when solving nonsteady-state problems of percolation with the use of Eq. (6) a special feature arises which consists in that there is an unknown moving boundary. This can be said also about Eq. (7). With the use of dependence (5) the equation becomes complicated, but there is no moving boundary. It is necessary to note that the practical use of Eq. (6) for solving problems of oil-field mechanics is broader than Eq. (5).

Let us look at some factors affecting the approximation constants of the models used.

We will evaluate the effect of the quantity of clay and residual water in a porous medium on the magnitude of the initial pressure gradient according to the data of the experiments carried out by Yu. G. Mamedov, Ya. G. Farzane, and M. Abdullakimov on columns filled with purified quartz sand with different air permeabilities at a constant temperature. Saturation of the specimen with water was carried out under a vacuum

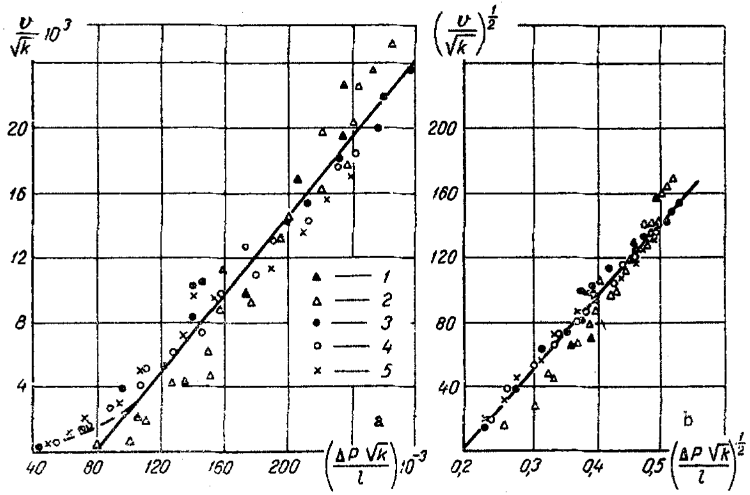

Fig. 2. Graphs of $v/\sqrt{k}$ (sec^{-1}) vs $\Delta P\sqrt{k}/l$ (g/cm^2) (a) and $(v/\sqrt{k})^{1/2}$ vs $(\Delta P\sqrt{k}/l)^{1/2}$ (b) for two-phase foam at different permeabilities, darcys: 1) 25; 2) 39; 3) 79; 4) 111; 5) 133.

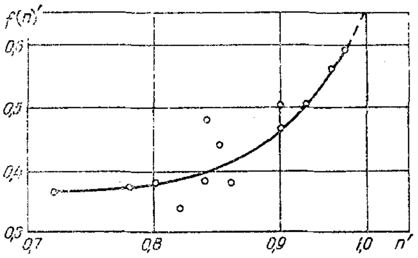

Fig. 3. Graph of f(n') vs n'.

and then it was displaced by air. The quantity of residual water was compared with the value of that for a given permeability according to [11]. Then percolation of non-Newtonian systems, as which we used vapor oil and transformer oil, was carried out and curves of the flow rate plotted against the pressure gradient were constructed. The results of the experiments showed that as the residual water increases the initial pressure gradient decreases, which is explained by its wetting action. The addition of clay to the porous medium, other conditions being equal, leads to an increase of the initial pressure gradient (see Table 2).

Experiments on the determination of the effect of the direction of percolation on the approximation constants were carried out by Ya. G. Farzane and M. Abdullakimov. The integral flow rate versus pressure curves, for example, for a mixture of vapor and bright stock oils, depend on the direction of percolation. These curves are arranged practically symmetrically with respect to the curve obtained in the case of horizontal percolation, namely, the curves obtained for upward percolation is located below the curve for horizontal percolation and the curve obtained for downward percolation is higher (see Table 3). It was also shown that the integral flow rate versus pressure gradient curves obtained on "loading" and

TABLE 1. Results of Experimental Investigations

Experimental system		t, °C	n'	k', $\frac{g\cdot sec^{n'}}{cm^2}$	μ, cP	α, g/cm^2	η, cP	α_1, g/cm^2	η_1, cP
Oil (tar content, %)	82	19	0,72	0,130	4126	0,018	3220	0,0052	1960
		23	0,78	0,080	2607	0,013	2260	—	—
		26	0,80	0,061	2128	0,011	1918	0,0025	1082
		30	0,86	0,040	—	—	—	0,0014	884
	72	18	0,82	0,060	2185	0,020	1830	—	—
		21	0,84	0,041	1776	0,013	1440	—	—
		24	0,85	0,033	—	—	—	—	—
		30	0,89	0,020	—	—	—	—	—
	40	18	0,90	0,034	—	—	—	0,0014	630
		21	0,92	0,025	2397	0,014	986	0,0011	530
		25	0,94	0,014	1387	0,012	684	0,0009	490
		30	0,95	0,010	—	—	—	—	—
Two-phase foam		20	—	—	3,4	0,08	0,8	0,0361	0,48

TABLE 2. Experimental Results

Content, %		ΔP_0, kg/cm^2
clay	water	
10	0	1,1
	14	0,7
	27	0,4
	40	0,2
20	0	2,5
	21	1,6
	40	0,9
30	0	5,6
	20	3,5
	40	1,5

Note: In all experiments the maximum shear stress τ_0 = 96 mg/cm^2 and structural viscosity η = 57 cP.

TABLE 3. Experimental Results

Approximation constants	Horizontal percolation	Vertical percolation	
		upward	downward
α, g/cm^2	0,0018	0,0023	0,0015
η, cP	779	779	746

"unloading" the system have a reversible character and at certain values of the duration of deformation they practically coincide.

We will determine the area of applicability of Darcy's law. It is known that in the literature (see, for example, [12]) the following quantities are used as the linear parameter of the Reynolds number: hydraulic radius of the porous medium, effective diameter of soil particles, "internal scale" of the porous medium, etc., and as the velocity, the average or true velocity of percolation. In conformity with this, different values are obtained for Re.

An analysis of the literature data and experiments carried out by M. A. Melikov with water, isooctane, kerosene, and a 20% solution of glycerin in water showed that, if we take as the linear parameter the diameter of a tube in which the porous medium is located and as the velocity the average velocity, the critical value of Reynolds parameter is equal to 160.

NOTATION

v	is the velocity of percolation;
η_0	is the viscosity of structure;
P_0	is the modulus of pressure gradient for overcoming maximum shear stress;
P	is the pressure;
k_0	is the permeability for a viscoelastic medium;
τ_0	is the maximum shear stress;
k	is the air permeability;
α_0	is a constant coefficient equal to $167 \cdot 10^{-4}$;
k', n'	are the consistency and non-Newtonian behavior indices, respectively;
ρ	is the density;
ΔP	is the pressure loss due to friction;
α, η	are the approximation constants of modified Darcy's law for viscoplastic medium;
μ	is the approximation constant of Darcy's law;
α_1, η_1	are the approximation constants of Caesson's relation;
l	is the length;
t	is the temperature.

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