SovietRxiv

Soviet-era science, translated into English

D. A. EFROS

1960

SovietRxiv

View the original and related papers at https://sovietrxiv.org/items/ru-196001.33885

Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.

SovietRxiv

Abstract

Full Text

HYDROMECHANICS

D. A. EFROS

PERMEABILITY OF POROUS MEDIA DURING FILTRATION OF A GAS-SATURATED LIQUID

(Presented by Academician L. I. Sedov on 4 I 1960)

The hydrodynamic theory of filtration of a gas-saturated liquid and of gas–liquid mixtures uses empirical relations for permeability, determining the permeabilities from the ratios $k_{\mathrm{g}} = \dfrac{v_{\mathrm{g}}\mu_{\mathrm{g}}}{\partial P/\partial x}$, $k_{\mathrm{l}} = \dfrac{v_{\mathrm{l}}\mu_{\mathrm{l}}}{\partial P/\partial x}$, where v_{g} and v_{l} are the phase velocities; $\mu_{\mathrm{g}}, \mu_{\mathrm{l}}$ are the viscosities; and $\partial p/\partial x$ is the pressure gradient.

Numerous experimental data ([12], [14]) make it possible to assume that, in the filtration of mixtures, i.e., for flows in which gas is not liberated from the liquid but is introduced from outside,

$$k_{\mathrm{g}}/k \simeq F_{\mathrm{g}}(\rho), \qquad k_{\mathrm{l}}/k \simeq F_{\mathrm{l}}(\rho), \tag{1}$$

where k is the initial permeability and ρ is the saturation.

The dependences (1) are also used in theoretical studies of flows of a gas-saturated, i.e., gas-saturated, liquid. At the same time, the physical processes occurring in a flow accompanied by liberation from solution and in the motion of a mixture are different. In the flow of a gas-saturated liquid, the system of parameters determining the phenomenon must contain the diffusion coefficient, the pressure, and the solubility. These quantities are, obviously, immaterial for flows in which no gas liberation occurs.

The admissibility of applying, to the flow of a gas-saturated liquid, dependences found in experiments on the flow of mixtures does not follow from the nature of the phenomenon and requires special verification.

1. **Permeability of external gas and of gas liberated from solution.** In investigations in which a change in saturation could be achieved both by changing the gas factor and by changing the pressure ([16]), an extremely large scatter of experimental data was observed.* We carried out special experiments aimed at establishing whether the dependences determining permeability in steady motion coincide for a mixture and for the flow of a

SovietRxiv

Fig. 1. Dependences $F(F)$ for external gas and gas liberated from solution. Uncemented sand, $k = 1.0$-3.5 darcy. $P^* = 1$ –external gas; $\lambda = 1$ –gas liberated from solution.

Figure 1: Fig. 1. Dependences $F(F)$ for external gas and gas liberated from solution. Uncemented sand, $k = 1.0$-3.5 darcy. $P^* = 1$ –external gas; $\lambda = 1$ – gas liberated from solution.

gas-saturated liquid without the introduction of external gas. Characteristic results of the experiments are presented in Fig. 1. In calculating the gas permeability, it was assumed that thermodynamic equilibrium exists between the liquid and the gas. Since in reality the liquid is supersaturated with gas ([11], [7]), the true gas permeabilities are somewhat smaller than the calculated ones. The experimental data establish that the functions F_g (F_l) for a gas-saturated liquid and for a mixture are different. A comparison of flows having equal gas factors shows that in

---

* In later works it is indicated that reproducibility of the results can be achieved only when using a gas practically insoluble in the liquid ([14]).

at points of equal pressures, i.e., for $F/F = \psi =$ const, the permeabilities for the mixture prove to be greater (Fig. 1).

If an external gas is introduced into the specimen together with the liquid, then F assumes intermediate values between F for the mixture and the gas permeability of a flow in which all the gas has separated from the solution. The difference between $F(F)$ for the mixture and for the gasified liquid increases as the viscosity ratio μ/μ decreases (Fig. 1). The conditional nature of the calculation of the gas permeability reduces the true difference between the dependences $F(F)$.

Fig. 1. Dependences $F(F)$ for external gas and gas liberated from solution. Uncemented sand, $k = 1.0$-3.5 darcy. $P^* = 1$ –external gas; $\lambda = 1$ –gas liberated from solution.

2. Distribution of phases in pores and permeability. Consideration of flow in pores makes it possible to explain the difference between the permeabilities of the mixture and of the gasified liquid. For filtration of mixtures, experimental dependences close to $F(\rho)$ and $F(\rho)$ can be found if it is assumed that the phases occupy different pores ([10,17,6]). In filtration accompanied by liberation from solution, on the contrary, it should be assumed that in many pores liquid and bubbles of the liberated gas are simultaneously present. Permeability calculations based on this assumption agree satisfactorily with experiment for flow without introduction of external gas in the region of ρ close to unity.

The distribution of phases in pores depends on the complex

SovietRxiv

$$\pi_D^* = \frac{DP}{k\,dP/dt}$$

where P is the saturation pressure, D is the diffusion coefficient, t is time, and

$$\frac{dP}{dt} = \frac{\partial P}{\partial t} + \left(\frac{\mathbf{v}}{m\rho}\nabla P\right).$$

At large values of dP/dt, gas liberation leads to continuous formation of bubbles in the pores, i.e., to low permeability. With a very slow pressure decrease, the gas diffuses into bubbles formed in the initial period. The expanding bubbles displace the liquid and form a mixture analogous to external gas. As a result, the average-reservoir function $\Psi(\rho)$, found in field investigations ([9,13,1]) and in depletion experiments ([7,2]), is usually sufficiently close to $\Psi(\rho)$ of the mixture*. At the same time, the permeabilities of the near-wellbore region prove to be considerably smaller than the permeabilities for the mixture ([3–5]).

3. Quantities determining permeability in steady flow. The characteristics of linear flows of a weightless gasified liquid in the general case, when gasified liquid and external gas simultaneously enter the specimen at the inlet, are determined by specifying the dimensionless complexes

$$k/l^2 = \pi_k, \qquad P_1\sqrt{k}/\sigma = \pi_\sigma, \qquad D\mu\,/kP_1 = \pi_D,$$

where l is the linear dimension, P_1 is the outlet pressure, and σ is the surface tension. In addition, the gas

* For porous media having dead-end pores and cavities, the difference between the functions $\Psi(\rho)$ for a gasified liquid and for a mixture may persist even with a very slow pressure decrease ([15]).

factor Γ^*, or, more conveniently, the quantity $\lambda = \Gamma^*/S(P_1)$, and also dimensionless quantities and functions characterizing the physical properties of the system. The outlet pressure $P_2^* = P_2/P_1$ is not a determining quantity, since the flow at some P_2^* can be regarded as the initial portion of a flow having a smaller P_2^*. A difference in P_2^* for these flows is equivalent to a change in the complex π_k. If π, π_D, λ, and the physical properties of the system are fixed, then a series of experiments carried out at some $P_2^* = P_{20}^* = \text{const}$ for different π_k includes all linear flows for the given π_k with $1 > P_2^* > P_{20}^*$. The arguments will also include local quantities—the saturation ρ and the dimensionless pressure $P^* = P/P_1$. For a given porous medium, liquid, and gas with given physical properties, when the complexes π are constant, the arguments may be ρ, P^*, and λ. Here only any two variables are independent, since in steady flow

$$\lambda = P^*\left[\frac{\beta(P^*)\mu_\ell(P^*)}{\mu_{\mathrm{g}}S(P^*)}\,\psi + 1\right] = \text{const}. \tag{2}$$

SovietRxiv

Fig. 2. Pressure distribution along a linear specimen. Uncemented sand, $k = 3.5$ darcies. 1—$\lambda = 2.6$; 4.5; 7; 11.8; 18; 0.378; 2—$\lambda = 1.25$; 3—$\lambda = 1.16$. The curves $\lambda = 1.25$ and $\lambda = 1.16$ are shifted to the right by 0.2 and 0.4, respectively.

The indeterminacy of the gas permeability, specified as a function of ρ or F_ℓ, is removed by introducing one more independent variable.

The permeability under steady filtration of a gas-saturated liquid is determined by relations of the form

$$F_{\mathrm{g}} = F_{\mathrm{g}}(\rho, P^*),$$

$$F_{\mathrm{g}} = F_{\mathrm{g}}(\rho, \lambda)$$

or

$$F_{\mathrm{g}} = F_{\mathrm{g}}(P^*, \lambda).$$

In this case, as experiment shows, it may be assumed that

$$F_\ell \cong F_\ell(\rho). \tag{3}$$

It follows from these relations that the function

$$F_\ell = F_\ell(P^*, \lambda) \tag{4}$$

can be obtained.

Fig. 3. Dependences $F_\ell(\rho^*, \lambda)$. Uncemented sand, $\mu_{\mathrm{g}}/\mu_\ell(P_{\mathrm{n}}) = 0.0077$, $S = 1.11$.

A representation of the form (3), (4), which also makes it possible to construct the flows, contains only quantities accessible to measurement and is not connected with the assumption of thermodynamic equilibrium of the system introduced in calculating F_{g}.

4. Two-parameter dependences. In the experiments, linear flow of a gas-saturated liquid was investigated*. The values of the parameters π remained constant, and at an inlet pressure $P_1 = \mathrm{const}$ a series of steady regimes was carried out, in which

* The experiments were carried out by S. A. Kundin.

the gas factor took values $\Gamma^* \gg S(P_1)$. Examples of the data obtained are shown in Figs. 2, 3, and 4. Measuring the pressure distribution and the flow

SovietRxiv

rate made it possible to find dependences of the form (4) for F. Saturation was not measured in these experiments. To determine ρ, the averaged dependence (3), based on data from previous experiments, was used. By calculation, the dependences for F shown in Fig. 4 were found. In Figs. 3 and 4, the lines $\lambda = 1$ correspond to the motion of a gas-saturated liquid without injection of external gas. The flow of the mixture is represented by the lines $P^* = 1$. Data obtained in linear flow may be used for an approximate calculation of plane-radial flow.

Fig. 4. Averaged dependence $F(\rho)$, dependences $F(\rho, P^*)$ and $F(\rho, \lambda)$. Uncemented sand,
$\mu / \mu(P) = 0.0077,\ S = 1.11$

Calculations of steady-state inflow to a well, based on the use of two-parameter dependences, agree considerably better with field experiments ([3–5]) than calculations based on dependences of the form (1).

Two-parameter dependences are applicable, strictly speaking, only to steady-state flows, but approximate use is also permissible for a number of nonsteady cases.

All-Union Petroleum and Gas
Scientific Research Institute

Received
4 I 1960

CITED LITERATURE

1. L. A. Zinov' eva, *Tr. Vsesoyuzn. neftegaz. n.-i. inst.*, issue 8, 323 (1956).

2. S. A. Kundin, *Tr. Vsesoyuzn. neftegaz. n.-i. inst.*, issue 19, 257 (1959).

3. S. A. Lebedev, V. F. Usenko, *Tr. Ufimsk. neft. n.-i. inst.*, issue 3, 104 (1958).

4. S. A. Lebedev, V. F. Usenko, K. A. Andreev, *Nauchno-tekhn. sborn. Vsesoyuzn. neftegaz. n.-i. inst.*, No. 3, 82 (1959).

5. S. A. Lebedev, V. F. Usenko, M. I. Shvidler, *Izv. AN SSSR, OTN*, No. 7, 56 (1958).

6. E. M. Minskii, *DAN*, 118, No. 2 (1958).

7. D. A. Efros, S. A. Kundin, *Tr. Vsesoyuzn. neftegaz. n.-i. inst.*, issue 10, 318 (1957).

8. D. A. Efros, S. A. Kundin, E. Ya. Solokhin, *Tr. Vsesoyuzn. neftegaz.*

SovietRxiv

n.-i. inst., issue 3, 107 (1953).

9. L. E. Elkins, *Am. Petrol. Inst. Drilling and Production Practice*, 1946, p. 160.

10. J. Fatt, *Trans. AIME*, 207, p. 144, 160, 164 (1956).

11. M. T. Kennedy, Ch. R. Olson, *Trans. AIME*, 195, 271 (1952).

12. M. Muskat, *Physical Principles of Oil Production*, 1949, Ch. 7.

13. E. L. Patton, *Trans. AIME*, 170, 112 (1947).

14. J. Richardson, J. Klever et al., *J. Petrol. Technology*, 4, No. 8, 187 (1952).

15. C. R. Stewart, F. F. Graig, R. A. Mors, *J. Petrol. Technology*, 5, No. 4 (1953).

16. R. D. Wyckoff, H. G. Botset, *Physics*, 7, No. 9 (1936).

17. M. R. J. Wyllie, G. H. F. Gardner, *World Oil*, 146, No. 4, 5 (1958).

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

Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.