

REGULARITIES AND SPECIAL FEATURES OF FILTRATION OF MICROBUBBLE GAS-LIQUID SOLUTIONS IN POROUS MEDIA

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Results of investigations of filtration of gas-liquid solutions at pressures higher than the equilibrium saturation pressure, including ones with additions of surfactants and polymers, are reported. Experimental data on displacement of oil from porous media by the indicated solutions are discussed.

A microbubble gas-liquid solution is a solution in which at pressures higher than the equilibrium saturation pressure there are gas microbubbles (MiBs). Their characteristic dimensions are 10^{-9} – 10^{-8} m. Such MiBs are often called "solid" – they are weakly deformed by external pressure and thermodynamically are not predisposed to coalescence. The equilibrium saturation state is not determined by the presence of MiBs in the solution but is stably diagnosed only starting with macrobubbles (MaBs) of size 10^{-7} – 10^{-6} m; such MaBs are rather easily deformed and join together, thus providing a minimum of the interface and its energy.

MiB gas objects always exist in large amounts in media with an elevated concentration of active centers, e.g., in unrefined technical and natural liquids, on container walls, in porous media of natural oil-and-gas reservoirs, and in this sense technical and natural liquids differ from standard pure laboratory mixtures (methane-decane, etc.). In principle, this is related to the character of evolution of MiB objects into MaBs of a gas as saturation is approached. With expansion of "standard" solutions (near saturation), classical states of metastable supersaturation appear, followed by a jump (an extremum) of formation of gas MaBs [1]; as for unrefined solutions, they are more likely to demonstrate opposite features associated with monotonic evolution of "solid" MiBs, initially present in the solution, into MaBs. The present knowledge of gas MiBs in solutions is given in [2, 3].

Below we present results of experiments that detect gas MiBs in unrefined solutions of technical and natural liquids by their influence on the filtration characteristics of the solutions in the region above equilibrium saturation. Some of these investigations have been published [4-6], and the others are reported and generalized here for the first time.

1. Hydrodynamic Features of Vertical Filtration of MiB Solutions. It is known from hydrodynamics that if in a liquid flow in a tube macroparticles with a density differing from that of the liquid (sand, gas bubbles) rise or descend, hydrodynamic forces appear that tend to divert these particles to the center or the periphery of the flow. This effect for tubes is known as the Segre–Silberberg effect; it is used, for instance, in [7]. Similar hydrodynamic phenomena occur in aerosol flows [8] and in a gas flow with a dropwise condensate [9].

We carried out experiments on filtration of gas-liquid solutions in porous media at a pressure higher than the saturation pressure, the results of which point to the aforementioned hydrodynamic effects similar to the Serge–Silberberg effect.

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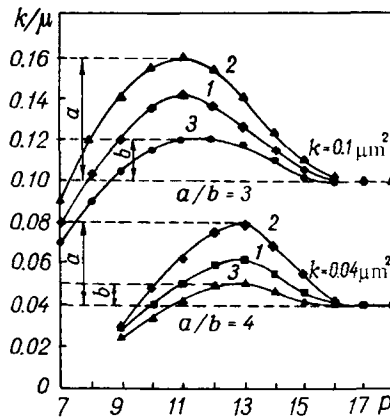


Fig. 1. Mobility of an MiB solution (water + CH₄, 2 m³/m³; 293 K) for different filtration directions: 1) horizontal; 2, 3) vertical. P , MPa.

The initial mixture consisting of unpurified potable tap water and methane with an equilibrium gas-water ratio of 2 m³/m³ was mixed and compressed in a high-pressure bomb at a temperature of 293 K to an equilibrium pressure of 16 MPa, which significantly exceeded the equilibrium saturation of the water-gas solution in the PVT bomb, equal to 9 MPa.

Two filtration columns, each with a length of 0.5 m and an inside diameter of 0.03 m, were used, in which a porous medium was prepared from finely granular quartz sand. Next, the medium was subjected to maximum saturation with water accompanied by vacuum suction of air at the opposite end of the column until a water permeability of 0.03 μm² in one case and 0.08 μm² in the other was attained. Then the pressure was increased to 16 MPa, and at minimum pressure drop water filtration was carried out until a new steady water permeability of 0.04 and 0.1 μm², respectively, was attained (the result of dissolving and removing residual air by water from the column). After this the filtration was stopped; one of the columns with a pressure of 16 MPa was connected to a bomb with the gas-liquid solution at the same pressure, and with minimum pressure drop one void volume of the solution was pumped through the column with the aid of a piston press, which forced the solution out of the bomb at a fixed constant flow rate into the column at a filtration rate of ~10⁻⁵ m/sec. At the column outlet the flow rate of degassed water (Q) and the pressure drop between the inlet and the outlet (ΔP) were measured. Three series of experiments were successively carried out with each column: 1) in the horizontal position, 2) in the vertical position with an ascending flow, and 3) in the vertical position with a descending solution flow. We did not interchange the inlet and outlet, and the solution was supplied to the column inlet at the same rate, which was constant with time and provided maximum pressure drops of $\Delta P \sim 10^{-6}$ MPa, which is much less than the pressures at the inlet (P_1) and outlet (P_2) and the mean pressure in the column $P = (P_1 + P_2)/2$.

In each experimental series the mean pressures in the column were successively decreased from 16 MPa to a level close to saturation with a step of (0.5–1) MPa. At each step the filtration coefficient, more exactly, the coefficient of filtrational mobility of the solution (the ratio of the permeability of the medium to the solution viscosity k/μ), was determined for the time of pumping 0.1–0.2 void volume of the solution, and the mean value of the mobility was taken. Next, the column pressure was increased to the initial level of 16 MPa, and the column was shut off 2–3 h, after which its new position was set (the column was turned upside down) and filtration of the solution was resumed.

In Fig. 1 the family of the upper three curves (series) corresponds to the column with a higher initial permeability, and the lower family corresponds to the column with a lower permeability. In each family the upper curve corresponds to filtration from bottom to top, the lower curve to that from top to bottom, and the middle curve to horizontal flow.

It will be recalled that a gas microbubble in the solution moving from bottom to top is acted upon by forces that divert it toward the periphery (wall) of the pore channel. Conversely, when the solution moves from

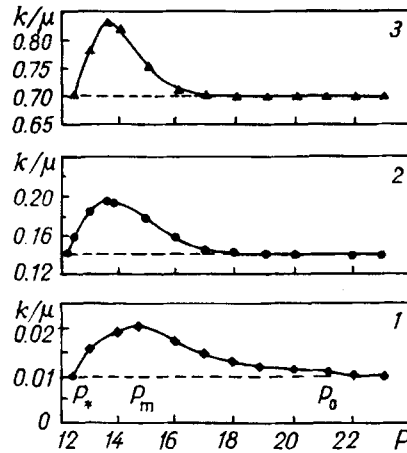


Fig. 2. Mobility of an MiB solution (water + CO₂, 20 m³/m³; 313 K) in media with dissimilar permeabilities: 1) 0.01 μm²; 2) 0.14; 3) 0.70.

top to bottom MiBs are diverted to the center of the pore channel. In the experiments, the ratio of the mean size of the MiBs to the mean diameter of the pore channel was $10^{-8}/4\sqrt{2k/m} = (2-4) \cdot 10^{-3}$ (here $m = 0.2$), which corresponds to Segre-Silberberg experiments in tubes with a diameter of about 0.1 m with sand and with gas bubbles of size 0.5–1 mm.

In each family of curves the liquid mobility is seen to increase with decrease in the mean pressure, and the mobility is at its maximum for filtration from bottom to top, when the gas MiBs are forced against the wall of the pore channels, on which the active centers of the rock are concentrated at their maximum. In this case, in essence, they are sorbed on active centers of the rock surface, thus forming a distinctive kind of "gas-lubricant" layer. Conversely, when the solution flow moves from top to bottom, MiBs of the gas are concentrated at the center of the pore channels; contact of MiBs with active centers on the rock walls and their influence on the gas MiBs are minimum. Nevertheless, in this case, some increase in the solution mobility is also observed, since "solid" MiBs of the gas in the flow volume act as "gaseous roller bearings." The horizontal position of the column provides simultaneous implementation of both mechanisms.

We would like to call attention to the predominant contribution of the active centers on the porous surface of the medium that create the "gas-lubrication" effect, exceeding by a factor of 3–4 the efficiency of the "gaseous bearings" in the solution volume (the ratio a/b in Fig. 1), to the increase in the filtrational mobility of the solution. At a pressure higher than 16 MPa the effect of the MiBs of the gas on the solution flow is insignificant due to the low concentration (volume) of gas MiBs in the solution. After the maximum on the curves of k/μ we observe a relative decrease in the filtrational mobility, leading to its decrease below the initial level because of the accumulation of "soft" MaBs of the gas in the solution and their coalescence (as usually occurs in a solution in the saturation state) and, as a result, to blocking of the solution flow in some pore channels.

2. Effects of Filtration of MiB Solutions in Media with Dissimilar Permeabilities. Figure 2 shows characteristic dependences $k/\mu = f(P)$ for a seawater-carbon dioxide mixture (20 m³/m³, 313 K) obtained for a horizontal flow in columns with quartz sand of different initial water permeabilities and a pressure of about 24 MPa.

The experimental results reveal: 1) the pressure (P_0) of the onset of the influence of the gas MiBs on the increase in the filtrational mobility (all other things being equal) depends substantially on the permeability of the medium: for low-permeability media it is higher by approximately a factor of 1.4; 2) the relative increment in the solution mobility in a low-permeability medium is substantially (by a factor of 1.6) higher than in a high-permeability one and is manifested at a higher pressure.

Hence, the following conclusions that are important for the mining of oil-and-gas pools can be drawn.

TABLE 1. Degree of Inhomogeneity of the Columns with Respect to the Mobility Coefficient of the Solutions

Agent filtered at a mean pressure of 12 MPa	Mobility ratio
Water	4.8
Water + 0.02% polymer	4.8
Water + 0.05% polymer	4.2
Water + MiB gas (CH ₄ , 2 m ³ /m ³)	3.8
Water + 0.02% polymer + MiB gas (CH ₄ , 2 m ³ /m ³)	3.6

The first conclusion consists in the fact that in stratified beds, as the bed pressure decreases in productive oil wells and approaches the saturation pressure, intensification of the liquid inflow, first of all, in low-permeability layers must occur. In this connection, it becomes necessary to correlate the sampling rate with the profile of the liquid inflow into the well in order to provide maximum intensification of the liquid inflow in the low-permeability layers and profile leveling.

The second conclusion is related to the possibility of pumping water-gas solutions in the MiB state into injection wells with the purpose of increasing the amount of water injected into low-permeability strata and, as a consequence, leveling the absorption profiles or increasing the flooding of the bed with water through its low-permeability layers.

Finally, the third conclusion is implementation of both solutions with respect to both sampling and pumping simultaneously or in an alternating manner.

3. Comparison of the Leveling Properties of Aqueous Solutions of Polymers and MiB Solutions of a Gas in Aqueous Solutions of Polymers. It is known [10] that in filtration of low-concentration aqueous solutions of polymers in stratified beds the absorption profile of high-permeability layers is leveled somewhat as compared to water injection owing to the viscoelastic properties of the polymer solutions.

Below we present results of a comparison of the leveling properties of weakly concentrated aqueous solutions of polymers and these solutions with MiB additions of a gas dissolved in them.

The solutions were prepared in a high-pressure bomb at a temperature of 293 K under prolonged stirring and compression. Two columns of the same length and inner cross sectional area filled with quartz sand of different permeabilities were saturated with water at a high pressure until permeability was attained. Then two void volumes of the solution from the bomb were pumped through each of them at a high mean pressure. After this the column inlets were joined together and connected to the bomb, and at a prescribed inlet pressure higher than that of saturation of the aqueous solution of the polymer with the gas, the solution was displaced from the bomb (at a prescribed flow rate) into the columns. We measured the liquid flow rate at the outlet (Q) and the pressure drops (ΔP) in each column and calculated the ratio $\delta = (Q/\Delta P)_1 : (Q/\Delta P)_2$, which determines the degree of nonuniformity of the columns with respect to the mobility coefficient of the solutions in them.

The results of the investigations (see Table 1) reveal an improvement in the leveling of the absorption profile in the presence of MiBs of the gas in the solution owing to a combined increase in the elasticity and mobility of the solution in the low-permeability layer of the model.

4. Displacement of Oil by MiB Water-Gas Solutions. Figure 3 shows a characteristic example of displacement of oil from a porous medium by an MiB water-gas solution. The porous medium is quartz sand with a permeability of $0.25 \mu\text{m}^2$ (with respect to air), a porosity of 0.22, an initial oil saturation of 90%, and a water saturation of 10%. The oil is degassed, its viscosity is 0.83 mPa-sec, and the temperature is 353 K.

Experiment 1. The displacement was carried out sequentially at a pressure of 25 MPa: 1) first, by water: the water-free displacement is $\eta = 34\%$, the final displacement is 59% after pumping-through $V = 1.32$ void volumes; 2) next, by an MiB solution of methane in water ($2.5 \text{ m}^3/\text{m}^3$) to a final displacement of 71% after pumping-through an additional 2.7 void volumes; 3) rewashing by an MiB water-gas solution of the same composition with an addition of 0.05% OP-10 surfactant to a final displacement of 79% after pumping-through an additional 0.7 void volume. In all, 4.7 void volumes of displacing liquids was spent.

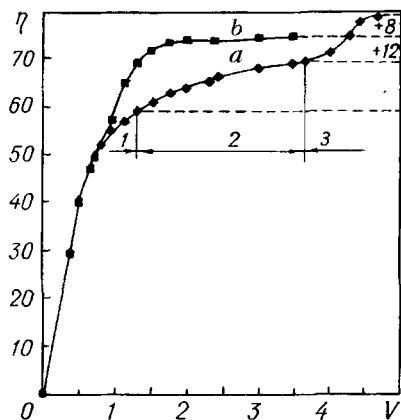


Fig. 3. Displacement of degassed light oil ($0.25 \mu\text{m}^2$, 25 MPa): a: 1) water; 2) MiB solution (water + CH_4 , $2.5 \text{ m}^3/\text{m}^3$; 353 K); 3) the same MiB solution with an addition of 0.05% OP-10 surfactant; b: MiB solution (water + CH_4 , $2.5 \text{ m}^3/\text{m}^3$; 353 K) with 0.05% OP-10 surfactant.

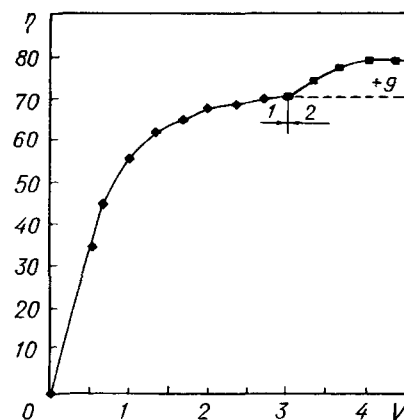


Fig. 4. Displacement of degassed light oil ($3 \mu\text{m}^2$, 25 MPa): 1) by a 0.05% aqueous solution of OP-10 surfactant; 2) the same with gas MiBs added (CH_4 , $2.5 \text{ m}^3/\text{m}^3$; 353 K).

Experiment 2. From the very beginning and to the end the oil was displaced at a pressure of 25 MPa by an MiB solution of methane in water of $2.5 \text{ m}^3/\text{m}^3$ with an addition of 0.05% OP-10 surfactant: the water-free displacement was 29%, and the final displacement was 75% after pumping-through 3.5 void volumes of the solution.

The results of the investigations show an increase of 12% (from 58 to 70%) in the displacement coefficient (η) owing to the gas MiBs added as compared to the displacement of oil by water and the possibility of efficient use of MiB water-gas solutions of chemical reagents for displacement of oil.

The increase in the displacement coefficient is inconsistent with the Buckley–Leverett theory of two-phase filtration since the viscosity of the MiB water-gas solution does not increase as compared to the basic agent. The mechanism of efficient displacement of oil by the MiB solution is associated with simultaneous enhancement of the surface-active and elastic properties of the displacing agent due to the presence of the gas MiBs added to the solution.

Figure 4 shows results of similar investigations but carried out in a stratum with an initial permeability of $3 \mu\text{m}^2$ (with respect to air). Oil was displaced at a pressure of 25 MPa in accordance with the scheme: 1) a 0.05% aqueous solution of OP-10 surfactant: a water-free displacement of 35% and then up to a final displacement $\eta = 71\%$ after pumping-through three void volumes; 2) additional displacement by the same surfactant solution but with an addition of methane MiBs ($2.5 \text{ m}^3/\text{m}^3$) to a final displacement of 80% after pumping-through an additional 1.35 void volumes. The total volume of pumping-through is $V = 4.35$.

In the last experiment it was established that due to the gas MiBs added to the aqueous solution of the surfactant the displacement coefficient increases by 9% (from 72 to 81%), which in itself is larger than the displacement due to the surfactant in some cases.

The above results make it possible to increase the efficiency of the technological processes of oil displacement by aqueous solutions of chemical reagents by substituting the gas MiBs added for part of the reagents in the solution.

It is important to note that as compared to chemical additives, whose sorptive retention by the porous medium attains 3–5 and sometimes 10–15% of the void volume and whose losses are not recoverable, sorption of an MiB gas is at least 1–2 orders of magnitude lower. Moreover, sorption losses of an active MiB gas additive are easily reversible by a periodic pressure increase (see Para. 1); as a result, the sorbed gas goes back

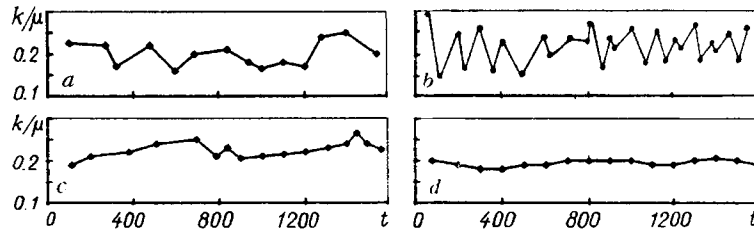


Fig. 5. Change in the mobility oscillations of an MiB solution (water + CH₄; 2 m³/m³; 298 K). *t*, sec.

into the solution, and in subsequent filtration the MiB effects take place again. It is possible that this is one of the most important properties of a new active additive from the viewpoint of technical applications.

It is also not ruled out that the presence of MiBs of a gas in aqueous solutions of chemical reagents decreases the sorption of the chemical reagents themselves by changing the surface-active properties of the rock partially occupied by microbubbles of the gas. Here, the sorption of the gas by the rock in aqueous solutions of chemical reagents (surfactants, polymers) increases substantially due to sorption of the latter, which entrain gas microbubbles.

The results (see Para. 4) concerning the disproportionately high increase in the coefficients of displacement of oil due to the MiB gas in the water-gas solutions, including the solutions of chemical reagents (by 5–10%), are also explained by the effect of gas sorption: due to the presence of sorbed chemical reagents in the water or of the oil phase in the void volume the limiting capacity of sorptive retention of "soft" MaBs inside the void volume increases by a factor of 5–10 (against 0.5–2% determined in [1]) or by 5–10% of the void volume. A water-gas solution containing "soft" gas macrobubbles in an amount of 1% of the solution volume saturates the indicated sorption capacity after pumping-through the solution in an amount of 5–10 void volumes by displacing the oil in it an additional 5–10% – precisely this result is obtained in Para. 4.

5. Influence of Intraphase Exchange on Nonequilibrium Filtration of Micronucleate Solutions. Filtration of MiB gas-liquid solutions at high rates of change in pressure or at high flow velocities turns out to be significantly nonequilibrium due to the delay of the inflow-outflow of gas molecules from the solution into gas MiBs and back, the coalescence of "soft" MaBs, and the delay of sorption saturation of the rock near the saturation state of the solution.

Each of the exchange processes mentioned is determined by at least one or two characteristic relaxation times; in combination they determine the rather complicated relaxation properties of filtration of MiB solutions.

As is known, the nonequilibrium relaxation properties of a flow that are related to interphase and intraphase exchange interactions manifest themselves in the form of spontaneous oscillations of the flow parameters.

Figure 5 presents characteristic oscillograms of the variability of the filtrational-mobility coefficient obtained for filtration of an MiB solution of methane in water (2 m³/m³; 298 K) in a porous medium with an initial water permeability of 0.35 μm² at a constant filtration rate of 10⁻⁵ m/sec. Curve *a* corresponds to a mean pressure of 16 MPa in the model, which is close to the pressure of the onset of the effect of the MiB gas on the solution mobility; curve *b* depicts oscillations of 12 MPa near the maximum mobility coefficient; curve *c* depicts oscillations at 10 MPa at the macrosaturation level; curve *d* represents oscillations at 9 MPa at a level below macrosaturation.

6. Evaluation of the "Gas-Lubrication" Effect. Now we will determine the increase in the filtrational mobility of MiB gas-liquid solutions by using very simple relations, namely, proportionality of the liquid flow rate to the flow area normal to the flow direction and its inverse proportionality to the action of viscous friction in the flow, $Q \sim S/\mu$. We denote by the subscript "zero" $Q_0 \sim S_0/\mu_0$ the state where there are no gas microobjects in the flow. If gas objects appear in the flow, the area S occupied by the solution decreases by a quantity ΔS equal to the projections of the area of the gas objects on a surface normal to the flow, and consequently, $S = S_0 - \Delta S$. The shear stresses in the flow decrease by a quantity proportional to the projections of the gas objects on a plane tangent to the flow; in turn, on the normal plane S these tangential projections of

the stress of the gas objects are projected by certain arcs with a total length L . With neglect of the liquid friction on the surfaces of the gas objects (gas lubricant – bearing), the length L_0 of the arc enveloping the surface S_0 , on which the main energy losses by friction with the channels walls take place, decreases by ΔL , and consequently, $L = L_0 - \Delta L$. Then the change in the flow rate of the solution across the area S after the appearance of gas microobjects in it, all other things being equal, is $\alpha = Q/Q_0 \cong SL_0/S_0L$.

To evaluate L/L_0 and S/S_0 , it is sufficient to use one dimensionless combination consisting of two independent linear scales: the characteristic linear dimension h of the gas layer on the channel surface (in the solution volume) and the characteristic linear scale H of the void volume containing the moving solution. In the physics of porous media, the latter scale is determined as the square root of the permeability of the porous medium, $H = \sqrt{k}$. From the independent linear scales indicated, we can construct a single dimensionless combination $v = h/H$, which is the argument of the function $\alpha(v)$.

In determining L/L_0 , we will directly use the parameter v , while in calculating S/S_0 the square of this parameter will be used, so that $S = S_0 f[(\varepsilon v)^2]$, $L = L_0 \phi(\varepsilon v)$, where $1 < \varepsilon < 2$ is the fractal dimension of the line L_0 on the surface S_0 , which is an additional characteristic of the structure of the void space. In [11] for sandstones with a porosity $m = 0.05-0.3$ the volume fractal dimension of the size distribution of the pores is 2.57–2.87; hence the linear fractal dimension is $\varepsilon = (2.57-2.87)^{1/3} = 1.37-1.42$.

Now we will represent the functions f and ϕ , which decrease with increase in v , as Taylor series in the vicinity of $v = 0$, which is the onset of the influence of the MiB gas on the solution flow, and their ratio f/ϕ in the form of a polynomial. For convenience, we restrict ourselves to the polynomial of third degree $\alpha = 1 + A\varepsilon v + (\varepsilon v)^2 + B(\varepsilon v)^3 - \dots$, where A and B are expansion parameters. Here, from the condition of smoothness of the influence of the MiBs on the flow $v = 0$ we have $A = 0$.

In projection on the plane S , the fraction of the void volume occupied by MiBs of the gas is determined as $S_g = (h/d)^2$, where d is the characteristic dimension of the pores that is determined in the physics of porous media in terms of the porosity and the permeability of the medium by the relation $d = \lambda H$, $\lambda = 4\sqrt{2/m}$. Using it, we find $S_g = (h/d)^2 = (v/\lambda)^2$, whence $v = \lambda\sqrt{S_g}$. Now we rewrite the function α with the more convenient argument S_g , which has a clear physical meaning. Then

$$\alpha \cong 1 + (\varepsilon\lambda)^2 S_g + B (\varepsilon\lambda)^3 S_g^{3/2} + \dots$$

We denote by $S_g = S_{g^*}$ the critical gas saturation of the void volume with MiBs (here, in essence, already MaBs) of the gas, above which the phase mobility of the liquid can decrease (see Figs. 1, 2), so that $\alpha(S_{g^*}) = 1$. From this condition we determine the parameter $B = -(\varepsilon\lambda)^{-1} S_{g^*}^{-1/2}$. Finally, the relative increase in the solution mobility due to MiBs of the gas in the region of saturation of the void volume with the gas $0 < S_g < S_{g^*}$ is written as

$$\alpha = (k/\mu)/(k/\mu)_0 = 1 + (\varepsilon\lambda)^2 S_g (1 - \sqrt{S_g/S_{g^*}}) \dots$$

and at the point of the extremum (with respect to S_g) we have

$$S_g = S_{g,m} = 4S_{g^*}/9 \quad \text{and} \quad \alpha(S_{g,m}) = \alpha_m = 1 + 4 (\varepsilon\lambda)^2 S_{g^*}/27.$$

As an example, $m = 0.2$, $\lambda = 12.6$, and, following [1], $S_{g^*} = 0.005-0.02$. Then $S_{g,m} = 0.0022-0.009$, i.e., a maximum of the increment in the solution mobility is reached upon saturation of the void volume with the MiB gas at the level of (0.22–0.9)%; and next, for $\varepsilon = 1$ (the topology of a one-dimensional straight capillary), the maximum of the mobility due to the MiB gas in the solution is $\alpha_m = 1.12-1.47$; for $\varepsilon = 1.4$ (a characteristic fractal dimension of a porous medium), $\alpha_m = 1.23-1.92$; and for $\varepsilon = 2$ (the plane topology), $\alpha_m = 1.47-2.98$.

The results obtained are in quantitative agreement with the experimental data presented in Paras. 1, 2. They explain why an increase in the filtrational mobility is manifested in low-permeability media and is reached at high pressures – in low-permeability media the void volume occupied by a moving solution is

smaller (it is proportional to $d^2 \sim k/m$), and therefore, here, equal volumes of the MiB gas in the solution reach extreme fractions of the void volume $S_{g,m}$ earlier.

In Figs. 1, 2 the position of the points of the maximum of $k/\mu(P)$ corresponds, with respect to the pressure argument, to $(P_0 - P_m)/(P_0 - P_*) = R = 0.75$; here, P_0 is the pressure of the onset of the effect of the MiB gas on the solution mobility; P_* is the pressure, to which the decrease in k/μ to the initial level $(k/\mu)_0$ or $\alpha = 1$ corresponds; P_m is the pressure at the point of the maximum of the mobility (indicated in Fig. 2).

On this basis, we evaluate the order of the dependence of the capacity of sorption saturation of the rock with the gas MiBs on the pressure in the form $S_g = S_{g*}[(P_0 - P)/(P_0 - P_*)]^n$, where n is the unknown order. Here S_g refers to the immobile part of the gas MiBs sorbed by the surface, which determines the effect of "gas lubrication." From $S_{g,m}/S_{g*} = [(P_0 - P_m)/(P_0 - P_*)]^n = R^n = 4/9$ and $R = 0.75$ we find $n \cong 2.8$.

The authors are obliged to A. Kh. Mirzadzhanzade for the formulation of the problems and discussion of the results of the investigations considered in the work.

NOTATION

k , permeability of the porous medium, μm^2 ; μ , solution viscosity, mPa-sec; m , porosity coefficient of the medium, fractions; Q , solution flow rate; S , flow area of the solution; S_g , fraction of the area S or the void volume occupied by MiBs of the gas; ε , fractal dimension of the pore space; S_{g*} , critical gas saturation; $S_{g,m}$, gas saturation of the solution that provides a maximum of its mobility; V , void volume, units.

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