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KINETICS OF THE SOLUTION OF MINERAL SALTS SUSPENDED IN A LIQUID FLOW

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Results are presented from an experimental study on determination of the mass liberation coefficient from particles of mineral salts suspended in a liquid flow. The experimental data are generalized in the form of a criterial equation which adequately describes the mass liberation coefficients. It is established that in analyzing the kinetics of mineral salt solution it is necessary to consider the changes in viscosity and density of the solution and the diffusion coefficients within the diffusion layer. The time required for exit to a diffusion regime of solution is estimated and the validity of using Eq. (4) to process experimental data is evaluated using the diffusion number Fo.

As has been demonstrated by Zdanovskii [1], the majority of mineral salts dissolve in a diffusion regime, in which the rate of solution is determined by the equation

$$-dM/dt = kF(C_s - C). \tag{1}$$

The diffusion rate coefficient K is of key significance, and under diffusion solution conditions that quantity is identical to the mass liberation rate. Numerous experimental values of the coefficient K have been established and are presented in [2]. A number of studies have presented methods for generalizing experimental data on the diffusion rate coefficient [3, 4].

For solid particles of mineral salts suspended in an incident liquid flow (rectilinear and uniform) such a generalization was performed by Aksel'rud, and independently by Zdanovskii. This generalization can be expressed in the form

$$\mathrm{Sh} = 0.31\sqrt[3]{\mathrm{Sc}}\sqrt[3]{\mathrm{Ar}}. \tag{2}$$

For a single individual salt with various particle dimensions this equation adequately describes the experimental data, the proportionality $\mathrm{Sh} \sim \sqrt[3]{\mathrm{Ar}}$ being observed, but experimental data on solution of a group of salts cannot be generalized with Eq. (2).

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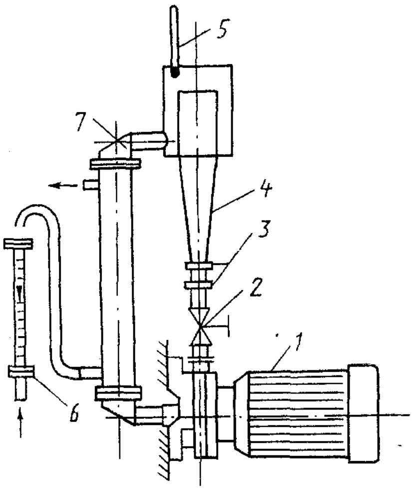

Fig. 1. Experimental apparatus for determining mass liberation coefficients from particles suspended in liquid flow.

The cause of this is that in deriving the equation assumptions were made which are realized to different degrees for each dissolving salt:

1) The liquid viscosity is constant over the entire range of distance from the surface (in fact, the liquid viscosity on the solution surface may be an order of magnitude higher than the viscosity in the overall mass of solution due to higher concentration);

2) the diffusion coefficient is constant (in reality the value of this coefficient changes upon approach to the solution surface);

3) the liquid density is constant (in reality the liquid density in the boundary layer depends on the concentration of dissolved substance, which decreases with removal from the solution surface).

To experimentally determine mass liberation coefficients the flow solution device proposed by Zdanovskii [5] was used. The experiments were performed with a modification of the device as shown in Fig. 1, differing from that of the original author in that it includes an electrical centrifugal pump 1, which provides for supply of the solvent (distilled water) into the reactor 4. Solvent volume flow rate is regulated by valve 2 in order to insure circulation of the dissolving particles at a height equal to 1/3 the height of the cone-shaped portion of the reaction vessel (H = 145 mm), for convenience in extracting the particles. The circulating solvent was cooled with a coaxial heat exchanger 7, with cooling water flow rate monitored by rotameter 6, and circulating solvent temperature measured by thermometer 5.

In the lower (cylindrical) portion of the reactor a pack 3 of two brass screens was installed, with a 1 × 1 mm mesh, spaced 30 mm from each other. The upper screen was located 10 mm from the cone shaped part of the reactor. Such screen positioning permits elimination of dependence of the mass liberation coefficient on solvent flow rate and makes it unnecessary to maintain a constant flow rate, as was demonstrated in [6].

The specimens used for the solution experiments were cylindrical particles with height approximately equal to the diameter $d_e = 9$ mm, formed by pressing finely ground powders of the salts to be studied at $P = 10^8$ Pa.

The experimental data were processed with mass liberation equation (1). Since for solution of suspended cylindrical particles the particle form remains practically unchanged, the solution surface will be related to the particle mass by the expression

$$F = \frac{3\pi}{2}\left(\frac{4M}{\pi\rho_T}\right)^{2/3}. \tag{3}$$

Substituting Eq. (3) in Eq. (1), by integration of the latter we find an expression for calculation of the mass liberation coefficient from particles of cylindrical form

$$K = \frac{\rho_t^{2/3}(M_0 - M)}{\varkappa(C_s - C)}. \tag{4}$$

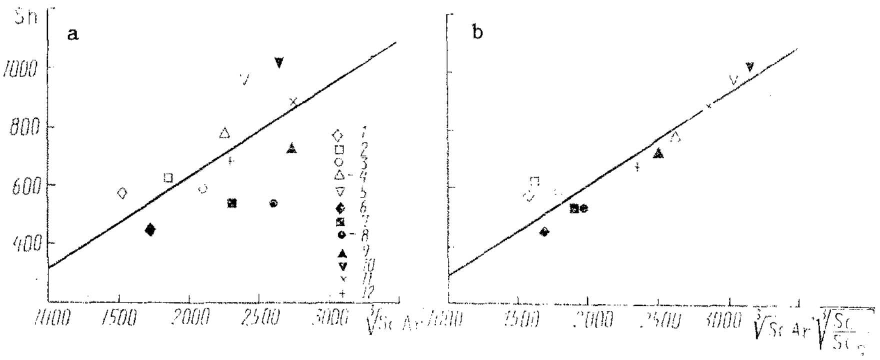

Fig. 2. Correlation of mass liberation data for mineral salt particles suspended in liquid flow using the equation of Aksel'rud and Zdanovskii (a) and the equation considering a change in physicochemical parameters of the solution in boundary layer (b): 1) NH_4Cl; 2) KCl; 3) NaCl; 4) KBr; 5) KI; 6) NH_4NO_3; 7) $NaNO_3$; 8) $NaNO_2$; 9) K_2SO_4; 10) $(NH_4)_2SO_4$; 11) $(NH_4)_2Cr_2O_7$; 12) $K_2Cr_2O_7$.

TABLE 1. Physicochemical Parameters of Salt Solutions Studied and Mass Liberation Coefficients

Salt	ρ_s, kg/m^3	$\mu_s \cdot 10^3$, Pa·sec	$D_s \cdot 10^9$, m^2/sec	$D \cdot 10^9$, m^2/sec	$K \cdot 10^4$ m/sec
KI	1717	0,872	2,331	2,00	3,15
KBr	1379	0,894	2,43	2,02	2,069
$K_2Cr_2O_7$	1090	0,91	1,05	1,05	0,868
K_2SO_4	1086	1,144	0,90	1,08	0,731
$NaNO_3$	1391	1,74	1,30	1,44	0,881
$NaNO_2$	1368	4,00	1,21	0,90	0,458
NaCl	1199	1,79	1,61	1,61	1,00
$(NH_4)_2Cr_2O_7$	1184	1,00	1,24	1,24	0,793
KCl	1178	0,96	1,21	1,99	1,338
$(NH_4)_2SO_4$	1280	1,45	1,135	0,53	0,652
NH_4NO_3	1320	0,923	1,54	1,92	1,169
NH_4Cl	1076	0,94	2,22	2,00	1,052

To generalize the experimental data obtained in the form of a criterial equation it is necessary to use a number of physicochemical parameters of the salts and their aqueous solutions. Values of viscosity, density, and diffusion coefficients for the salts NaCl, KCl, NH_4Cl, NH_4NO_3, KBr, KI, $(NH_4)_2SO_4$ were taken from [7-9]. The parameters indicated for $NaNO_3$ were presented in [10].

The densities of saturated solutions of $NaNO_2$, $(NH_4)_2Cr_2O_7$, $K_2Cr_2O_7$, K_2SO_4 were determined experimentally by pycnometry. The dynamic viscosity coefficients of saturated solutions of these salts was determined by a VPZh-2 liquid capillary viscosimeter. Diffusion coefficients were determined over a wide concentration range by the rotating disk method [11].

Table 1 presents values of the physicochemical parameters of the salt solutions studied, together with mass liberation coefficients calculated with Eq. (4). The values of salt density and saturation concentration used below are available in handbooks [12].

Figure 2a shows an attempt at generalization of the experimental data with Eq. (2). The high scattering of the data (mean square deviation of 17.5%) is related to assumptions 1), 3). A more accurate approximation can be achieved using a method widely employed in heat transport [13], which leads to the equation

$$\mathrm{Sh} = 0.31\,\sqrt[3]{\mathrm{Sc\,Ar}}\,\sqrt[3]{\mathrm{Sc}/\mathrm{Sc}_s}\,. \qquad (5)$$

In this case the mean square deviation decreases to 9%. The results of generalizing the experimental data with Eq. (5) are shown in Fig. 2b.

As is evident from Fig. 2, comparison of the generalizations by Eqs. (2) and (5) indicates that in a number of cases in analyzing solution kinetics it is necessary to consider changes in viscosity, density, and diffusion coefficient in the diffusion layer of liquid flowing over the dissolving particle.

In conclusion we will determine the time required for exit to a steady state diffusion regime using the expression $\delta \sim \sqrt{Dt}$, used in [14] to evaluate the kinetics of the heat-mass transport process. This expression can be written in dimensionless form as

$$\mathrm{Fo} = \frac{Dt}{R^2} = \frac{\delta^2}{R^2} \tag{6}$$

and used to define the range of the criterion Fo.

Calculations show that this range has the limits: $\mathrm{Fo} = 2.1 \cdot 10^{-5}$ for NH_4NO_3 (Sh = 430); $\mathrm{Fo} = 3.9 \cdot 10^{-6}$ for $(NH_4)_2SO_4$ (Sh = 1010). Corresponding times for exit to the diffusion regime comprise: t = 0.3 sec for NH_4NO_3; t = 0.07 sec for $(NH_4)_2SO_4$. The overall solution time for each experiment was on the average t = 60 sec, much greater than the time for exit to the diffusion regime. The results obtained show that the kinetics of the mass exchange process from particles of mineral salts suspended in a liquid flow can be described by Eq. (1), since the conditions of the solution process correspond to the boundary film model.

CONCLUSIONS

1. Analysis of the kinetics of solution of mineral salts cannot be performed without consideration of the change in viscosity and diffusion coefficients within the limits of the diffusion layer.

2. Equation (5) adequately describes mass liberation and diffusion coefficients from mineral salt particles upon their solution in water and aqueous solutions in the suspended state.

NOTATION

M, mass; K, solution rate coefficient; F, surface; t, time; ρ, density; C, concentration; $\varkappa$, form coefficient; d_e, equivalent diameter; D, diffusion coefficient; μ, dynamic viscosity coefficient; g, acceleration of gravity; δ, thickness of diffusion boundary layer; $R = d_e/2$, corrected radius of cylindrical particle; $\mathrm{Sh} = Kd_e/D$, Sherwood number; $\mathrm{Ar} = gd_e^3\rho(\rho_t - \rho)/\mu^2$, Archimedes number; $\mathrm{Sc} = \mu/(\rho D)$, $\mathrm{Sc}_s = \mu_s/(\rho_s D_s)$, Schmidt number; $\mathrm{Fo} = Dt/R^2$, Fourier number. Subscripts: t, dissolving substance; s, saturated solution; 0, commencement of solution process.

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TWO-DIMENSIONAL FILTRATIONAL FLOW IN THE DISPLACEMENT OF PETROLEUM FROM BEDS IN A BOREHOLE SYSTEM

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An approximate analytical method is developed for calculating plane filtrational flows of a two-phase multicomponent incompressible liquid in a porous medium. The method is based on the assumption that the streamlines in multiphase multicomponent filtration are the same as in the flow of homogeneous incompressible liquid. On this assumption, the initial problem reduces to solving the two-dimensional problem of the filtration of a homogeneous incompressible liquid and the one-dimensional problem of multiphase displacement. Accurate solutions of both problems are obtained. The integral characteristics of the flow are calculated. As an example, the displacement of petroleum by means of an aqueous polymer solution is considered.

Consider the two-dimensional filtration problem describing the displacement of petroleum by solvents, water, and reagent solutions in a borehole system, which reduces to a system of equations of two-phase filtration with interphase mass transfer [1]. Such filtrational flows are calculated by means of the approximate method of rigid current tubes, on the basis of the assumption that the streamlines in two-phase displacement are the same as in the filtration of homogeneous fluid [2]. Several current tubes are isolated here, and the process of one-dimensional displacement in each one is analytically calculated [3]. It was shown in [4, 5] that, even with a large difference in viscosity between the displacing and displaced phases, the streamlines are not much deformed in the course of displacement. This offers the possibility of using the given assumption in developing numerical methods of multiphase multicomponent displacement [6].

On the assumption of rigid streamlines, the solution of the two-dimensional system of equations of two-phase multicomponent filtration reduces to solving two independent problems: the plane problem of the filtration of a homogeneous incompressible liquid in a borehole system and the one-dimensional problem of two-phase displacement in a current tube of variable cross section with a specified pressure difference. In [7], approximate solutions of each of these problems were found.

In the present work, accurate solutions of both problems are obtained, and on this basis an analytical method of calculating the two-dimensional displacement of petroleum by slugs (finite portions) of active impurity carried through the bed by water is developed. This method may be used in calculating groundwater filtration, in geochemistry, hydrology, and reclamation, in water-pressure development of gas fields, in the displacement of petroleum by gases, solvents, and slugs, and in describing the noninertial and filtrational heterogeneous flows encountered in chemical technology [8].

Formulation of the Problem

Consider the two-dimensional displacement of petroleum by a reagent slug carried through the bed by water. In the large-scale approximation, this process is described by the system of equations [9, 10]

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