MASS TRANSFER OF SOLIDS IN A PULSATING LIQUID FLOW

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A study is made of the kinetics of mass transfer in a solid—liquid system in a column with a pulsating flow and in a circulation loop.

Subsidiary perturbations of a liquid lead to an intensification of mass transfer in systems with a solid phase [1, 2]. It is thus very important to study methods of intensifying mass transfer in continuous apparatus through the creation of impulsive fluid flows in a column or closed loop, with vibrating delivery of the liquid continuous medium [3].

We conducted three series of tests involving the dissolution of fixed single particles of gypsum in an ascending vibrating flow and in a circulation loop and the dissolution of suspended particles in a circulation loop. In three other series of tests we conducted, a layer of fixed particles of gypsum was dissolved in a uniform flow, in a pulsating flow, and in a pulsating flow moving through a circulation loop.

In all of the cases except for uniform flow, the liquid was supplied by a mechanical vibrating pump [4] which provides for pulsating flows of liquid with a piecewise-constant velocity. The tests involving dissolution of single particles of gypsum were conducted on the experimental unit described in [3] and shown in Fig. 1a.

The unit consists of a vibrating pump 4, container for water 1, mass-transfer column 7 with circulation tube 12, funnels 9, and control-and-measuring instruments 14 and 16. Vibrating feed of the liquid is provided for by the pump, which has two semibalanced weights 5. The pump is connected by means of a belt drive 17 to the electric motor 18, which provides for forced drive of the weights 5. A suction tube 20 with hemispherical valves 2 is installed in the pump housing. The pump is mounted on shock absorbers 19 and is connected, by means of the siphon 6 with spherical corrugation, to the column 7. The top part of the column 7 has a drainage and conducting pipe 8 and an expanded section 10, to prevent entrainment of the particles. Also installed here are the funnel 9 and a feeder for supplying the particles 13. The lower part of the column 7 is connected by means of flexible hose 15 — which performs the function of a hose pump — to the circulation tube 12. The top part of the tube 12, in turn, is connected with the column by means of the flexible hose 11 in order to complete the circulation loop. A thermometer 3 measures the temperature of the liquid. The number of rotations of the dc motor 18 is controlled with a rheostat and measured with a tachometer, while the amplitude is measured with an amplitude meter. Also, an RF-731M optical device 14 connected to a loop oscillograph is provided to measure the frequency and amplitude of the particle oscillations and particle velocity in the circulation loop [5].

The unit worked in the following manner in the experiments involving dissolution of individual particles under conditions of vibrating delivery of the liquid, without connection of the circulation loop. After the water was heated in the container 1 with the hose 15 pinched off, the drive of the vibrating pump 4 was turned on. The pump operating conditions were adjusted according to requirements. During operating of the pump, the liquid was delivered through inlet valve 2 and along inlet tube 20 and siphon 6 to the column 7. The liquid completed its upward movement along this path at a piecewise-constant speed.

In the tests in which we dissolved particles in the circulation loop, after turning on the pump 4, we connected the elastic element 15 (which performed as a hose pump). The liquid entered the circulation tube 12, was lifted upward and at the same time entrained the particle, left through the knee 11 into the column 7, and descended while at the same

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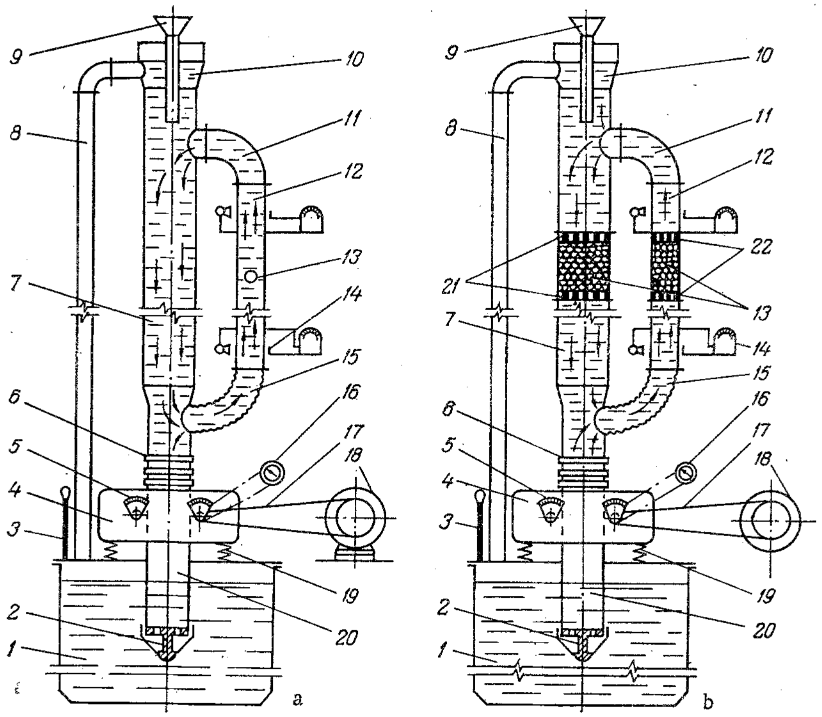

Fig. 1. Diagram of experimental unit for conducting tests on dissolving single particles (a) and a layer of particles (b).

time transporting the dissolved particle(s). We thus created a closed circulation loop which could be operated as long as necessary. Here, part of the solution could be drawn off into the container through the drainage pipe 8. The diameter of the main cylindrical part of the column was $4 \cdot 10^{-2}$ m, while its height was 2 m. The diameter of the circulation tube was $2 \cdot 10^{-2}$ m, with a length of 1.5 m.

The test conditions were as follows:

a) the specimen, in the form of a spherical gypsum stone of a certain diameter, was secured on a needle and inserted into the central column 7;

b) the vibrating pump created pulsations in the flow in the vertical direction which had a piecewise-constant velocity;

c) the amplitude of the pulsations of the liquid in the region of the particle suspension was within the range $(1.5\text{–}7.5) \cdot 10^{-3}$ m, while the frequency of the pulsations was 5-16 Hz;

d) the equivalent diameter of the particles was varied from $2 \cdot 10^{-3}$ to $14 \cdot 10^{-3}$ m, while the ratio d_e/A was varied from 0.5 to 2.3;

e) the Prandtl number was held constant and was equal to 600;

f) the modified Reynolds number was within the range $Re_m = 200\text{–}10{,}000$;

g) the particles were dissolved in distilled water at a temperature of 298°K.

The mass-transfer coefficients were determined from the commonly accepted relation

$$k = \Delta G / t F_{av} \Delta C. \tag{1}$$

The correlation shown in Fig. 2 was obtained from an analysis of the experiment data. The Nusselt number increased 1.5-1.7 times compared to the case of the dissolution of fixed particles in a uniform flow. The mass-transfer process is described by the following equation for the region $Re_m < 2500$

$$Nu_k / \sqrt[3]{Pr} = 1.99 Re_m^{0.345} (d_e/A)^{0.122}, \tag{2}$$

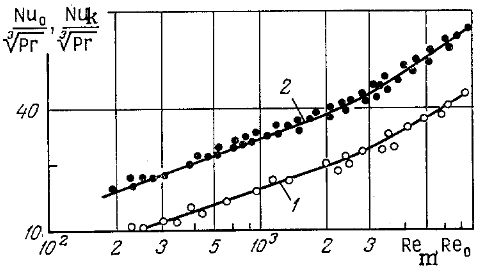

Fig. 2

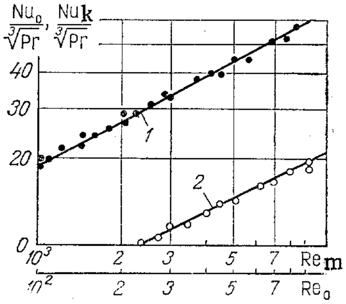

Fig. 3

Fig. 2. Test data on kinetics of solution of single fixed particles in normal (1) and pulsating (2) flows of liquid.

Fig. 3. Test data on the solution of single fixed particles in a circulation loop (1) and in a normal liquid flow (2).

while for $\mathrm{Re}_m > 2500$

$$\mathrm{Nu}_k/\sqrt[3]{\mathrm{Pr}} = 0.768\mathrm{Re}_m^{0.474}(d_e/A)^{0.205}. \tag{3}$$

In the second series of tests, we studied the mass transfer of particles in the circulation loop. The tests here were conducted on the same experimental unit, but with the following difference: oscillating in the vertical plane, the liquid was lifted upward through the circulation tube 12 by means of the hose pump as a result of the vibrating delivery, and then descended in the column 7. Thus, circulation of the liquid about the loop was accomplished thanks to the hose pump in combination with the vibrating feed. As in the previous case, the particles were fixed inside the column 7. The tests were conducted under similar conditions. Figure 3 shows the relationship between the Nusselt numbers Nu_k obtained for the circulation loop and in the absence of the oscillations. As can be seen, dissolution of the particles in the loop leads to an increase in the mass-transfer coefficient by nearly threefold compared to its values in the case of the liquid simply flowing around the particle in the region $\mathrm{Re}_m = 800$-10,000. Analysis of the test data on a Minsk-22 computer yielded the following criterional relation:

$$\mathrm{Nu}_k/\sqrt[3]{\mathrm{Pr}} = 0.836\mathrm{Re}_m^{0.459}(d_e/A)^{0.067}. \tag{4}$$

Considering the positive results of the first two series of tests, it was thought useful to change over from conditions of the solution of fixed particles to conditions of continuous solution of suspended particles in the circulation loop, since such an equipment model [3] would permit circulation of suspended particles through a loop simultaneously with pulsation of the liquid medium as a result of its vibrating delivery. Here, mass transfer could take place continuously (with the suspension of particles of different sizes) until complete dissolution of the solid phase (with partial removal of the solution) was achieved. In connection with this, we conducted a third series of tests, dissolving suspended particles in a pulsating liquid flow moving through the loop. The tests were conducted under conditions similar to those which prevailed in the solution of the fixed particles.

The test data is approximated by the expression

$$\mathrm{Nu}_k/\sqrt[3]{\mathrm{Pr}}\,\sqrt[3]{\mathrm{Ar}} = a + b\,\mathrm{Re}_m. \tag{5}$$

The values of the coefficients a and b were obtained on the computer: $a = 0.174$; $b = 3.332 \cdot 10^{-5}$. The Archimedes number was within the range $1400 \cdot 10^2$-$4800 \cdot 10^4$, while the range of the modified Reynolds number was 800-8000. The test data agree satisfactorily with the data calculated from Eq. (5). The standard deviation is 8.3%.

The above substantial effect of intensified mass transfer indicates the expediency of using mass-transfer apparatus, instruments, and procedures based on those proposed by the authors of the model with a circulation loop.

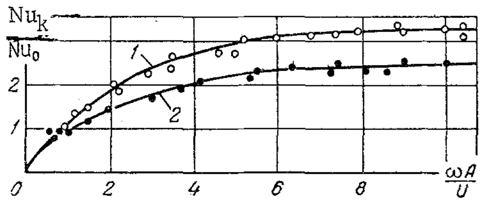

Fig. 4. Dependence of degree of intensification of mass transfer Nu_k/Nu_0 in a layer, with vibrating feed of the liquid, on the ratio $\omega A/U$ for layers of particles fixed inside a circulation loop (1) and in the column of the apparatus (2).

The tests involving dissolution of a layer of fixed particles of gypsum in a uniform flow, in a pulsating flow, and in a pulsating flow moving about a circulation loop were conducted on an experimental unit described in detail in [3] and shown in Fig. 1b. The layer of particles 13 was located between sievelike gratings 21, 22 installed in the middle part of the column 7 and circulation tube 12.

The test procedure was as follows. Specimens in the form of spherical particles of gypsum were dried to a constant weight in a drier, weighed, and introduced into the column 7 or circulation tube 12 in the space between the two grids 21 or 22. The layer of particles was dissolved at a liquid temperature of 298°K. The tests were conducted at flow rates of 0.001-0.35 m/sec and amplitudes and frequencies of fluid oscillation of 0.0015-0.0075 m and 10-17 Hz, respectively. The frequencies and amplitudes were measured with control-and-measuring instruments 14 and 16 [5]. After dissolution, the particles were dried to a constant weight and weighed on analytical balances. The diameter of the dissolved particles was within the range 0.005-0.008 m. The rate of filtration of the liquid flow was calculated from the formula $U = Q/f_t$. The height of the layer was kept at about 0.1 m in all of the tests. The porosity of the layer of spherical particles was 43.8%. The Reynolds number, corrected for the particle diameter and found from the filtration rate for the layer of spherical particles, was within the range $50 \leq Re_f \leq 2500$. The mass-transfer coefficient was calculated from Eq. (1).

The following relation describing the mass-transfer kinetics for a uniform liquid flow permeating the layer was obtained after analyzing the empirical data and calculations on the computer:

$$Nu_0 = 12.5 Re_f^{0.51} . \tag{6}$$

Equation (6) is in complete accord with the test data and the data in [6, 7], in which the Reynolds number exponent was equal to 0.5 and 0.45, i.e., very close to that obtained in Eq. (6).

Thus, the results of our experimental study of the kinetics of mass transfer of a layer of spherical particles in a uniform liquid flow agree with the data obtained by other authors and are fully reliable.

The degree of intensification of the mass-transfer process in the presence of pulsations of the liquid flow may be generalized with the criterional equation

$$Nu_k/Nu_0 = f(W_c d_e/\nu,\ \omega A/U,\ d_e/A). \tag{7}$$

Experimental studies which we and several other authors [6, 7] conducted indicate the slight effect of the simplex d_e/A, so that Eq. (7) can be written in the final form

$$Nu_k/Nu_0 = a(W_c d_e/\nu)^n (\omega A/U)^m. \tag{8}$$

Equation (8) is valid in the region not containing zero values of the criteria.

For an immobile layer of spherical particles fixed in the column of the apparatus, Eq. (8) takes the form

$$Nu_k/Nu_0 = 0.728 (W_c d_e/\nu)^{0.107} (\omega A/U)^{0.057} . \tag{9}$$

For a layer of particles in a circulation loop, the relationship is similar in character in the same region and is described by the equation

$$\mathrm{Nu}_k/\mathrm{Nu}_0 = 0.676\,(W_c\,d_e/\nu)^{0.115}\,(\omega A/U)^{0.164}\,. \tag{10}$$

Satisfactory agreement was obtained between the data calculated from Eq. (10) and the empirical data. The standard deviation is 9.8%.

Figure 4 shows the dependence of $\mathrm{Nu}_k/\mathrm{Nu}_0$ on $\omega A/U$. It is apparent that the most substantial increase in the degree of intensification of the mass-transfer process in the layer is seen at $(\omega A/U) < 3.5$; the value is somewhat lower for a layer of particles dissolved in the column than it is for a layer dissolved in the loop.

Consequently, mass transfer in a layer in the investigated apparatus is significantly accelerated (by a factor of 3-3.5) in a pulsating flow of liquid moving about a circulation loop compared to dissolution in a uniform flow or a pulsating flow in the apparatus column (by a factor of 1.5).

The intensification of mass transfer in the layer in the presence of a pulsating medium in the column and circulation loop is due to the fact that the boundary layer at the surface of the particles is agitated, and conditions are created which are favorable for the elimination of stagnant zones close to points of contact among the particles.

Thus, the creation of a pulsating liquid flow in a circulation loop can be used to intensify mass transfer in a layer (bed), and the relations obtained here can be used in designing mass-transfer apparatus which are to operate on the principles of the model proposed by the authors of [13].

NOTATION

k, mass-transfer coefficient, m/sec; t, dissolution time, sec; F_{av}, mean surface area of specimen, m^2; ΔG, specimen weight loss in the process of dissolution, kg; $\Delta C = C_s - C_1$, driving force in the dissolution process, kg/m^3; C_s, saturation concentration, kg/m^3; C_1, solution concentration, kg/m^3; $\mathrm{Nu}_k = kd_e/D$, Nusselt diffusion number; $\mathrm{Re}_m = W_k d_e/\nu$, modified Reynolds number; $W_k = W_0 2/\pi(\arcsin W_0/\omega A + \sqrt{(\omega A/W_0)^2 - 1})$, corrected rate of oscillatory motion of liquid, m/sec; W_0, velocity of uniform liquid flow, m/sec; ω, frequency of oscillations, Hz; A, amplitude of oscillations, m; d_e, equivalent diameter of dissolved particles, m; D, diffusion coefficient of dissolved particles, m^2/sec; ν, kinematic viscosity, m^2/sec; $\mathrm{Re}_m = W_c d_e/\nu$, modified Reynolds number for circulation loop conditions; $W_c = 2/\pi\omega A$, corrected velocity of liquid in the loop, m/sec; $\mathrm{Pr} = \nu/D$, Prandtl number; $\mathrm{Ar} = (\rho_1 - \rho/\rho)gd_e^3/\nu^2$, Archimedes number; ρ_1, density of the solid particles, kg/m^3; ρ, density of the liquid, kg/m^3; g, acceleration due to gravity, m/sec^2; U, theoretical rate of flow of liquid, m/sec; Q, flow rate, m^3/sec; f_t, cross-sectional area of apparatus, m^2; $\mathrm{Nu}_0 = k_0 d_e/D$, Nusselt diffusion number (uniform liquid flow); $\mathrm{Re}_f = Ud_e/\nu$, Reynolds number found from filtration rate; $\mathrm{Re}_0 = W_0 d_e/\nu$, Reynolds number for uniform liquid flow.

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