

KINETICS OF MASS TRANSFER BETWEEN A BED OF SOLID PARTICLES AND A PULSATING STREAM OF LIQUID

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A study is made of the kinetics of mass transfer between a bed of solid particles and a pulsating stream of liquid. It is shown that the mass transfer process is intensified appreciably in these conditions. The authors establish the dependence of the degree of acceleration of the mass transfer process in the bed on the mechanical oscillation parameters.

The study of methods of intensifying mass transfer in a bed by creating flow pulsations is a matter of great practical interest, and one to which comparatively few papers have been devoted. Some authors have examined mass transfer between a bed of solids and a pulsating liquid stream in connection with dissolving [1] or leaching [2]. In others, these questions have been studied with reference to the sublimation of a bed of solids in a pulsating air [3-5] or gas medium [6]. It is clear from the references cited that the use of a pulsating stream intensifies mass transfer between a bed of solids and a medium (gas or liquid).

The object of the present paper is to study the kinetics of mass transfer between a bed of solid spheres and other particle shapes and a pulsating stream of liquid, and to establish the basic kinetic laws of the process.

The investigations were carried out in a vertical glass column. A bed of solid spherical particles of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ gypsum of diameter 0.57-0.5 cm, and a bed of particles obtained by crushing and screening to a mean diameter of 0.4-0.25 cm, were subjected to dissolution. The depth of the bed was about 0.1 m in all the tests. The porosity of the bed of spherical particles was 42%. The pulsation frequency was varied from 36 to 320 cpm, the amplitude being 0.12 and 0.4 cm. The Reynolds number, referred to particle diameter and determined from the flow velocity, lay in the range $11.4 < \text{Re}_f < 250$ for the bed of spheres, and in the range $4.5 < \text{Re}_f < 270$ for the bed of crushed particles. Harmonic oscillations were imparted to the ascending water stream with the aid of a reciprocating piston.

In the case of a uniform liquid stream passing through a stationary bed of solid particles, the mass transfer coefficient, for a fictitious stream velocity u , and liquid concentration $c_0 = 0$ upstream of the bed inlet, may be determined from the equation

$$k_0 = -\frac{u}{\sigma H} \ln \left(1 - \frac{c_2}{c_s} \right). \quad (1)$$

The dependence of mass transfer kinetics in a uniform liquid stream passing through a bed of

slightly soluble particles at a constant value of Prandtl number ($\text{Pr} = 600$) was obtained by reduction of the experimental data and may be represented as follows:

$$\text{Nu}_0 = 7.5 \text{Re}_f^{0.5}. \quad (2)$$

The dependence obtained $\text{Nu}_0 = f(\text{Re}_f)$ is in fully satisfactory agreement with the experimental data, as may be seen in Fig. 1, the mean square deviation being 9.3%.

For comparison, and to check the accuracy of our results, we made use of the data of Strel'tsov and Komarovskii [7] on the solution kinetics of a bed of crushed particles of NaCl, since the conditions in the system studied approximate to those of slightly soluble material. A number of test values spanning our range of investigation were recalculated and compared with the results of [7], giving satisfactory agreement.

If our data are compared with Gaffney's graphical relation [8], which generalized the results of his own tests and those of others on mass transfer from the surface of a bed of spheres, then at $\text{Re} < 250$ the exponent of the Reynolds number is approximately 0.45, i. e., very close to that obtained by us in Eq. (2).

Thus, our original test data and the results obtained on mass transfer kinetics for a stationary bed of spherical particles in a uniform liquid stream agree with the data of other authors, and are quite trustworthy.

In the presence of pulsations of the ascending stream, if the solution concentration at the bed outlet in the given conditions is taken to be c_K , the mass transfer coefficient may be determined from the equation

$$k_K = -\frac{u}{\sigma H} \ln \left(1 - \frac{c_K}{c_s} \right). \quad (3)$$

The degree of intensification of mass transfer in the presence of pulsations of the liquid stream will be determined by the ratio of the coefficients k_K/k_0 , which is equal to

$$\frac{k_K}{k_0} = \frac{\ln(1 - c_K/c_s)}{\ln(1 - c_2/c_s)}. \quad (4)$$

The parameters determining the ratio k_K/k_0 , or, which is the same, Nu_K/Nu_0 , are as follows: flow velocity u , particle size d , liquid viscosity ν , oscillation frequency ω and amplitude A . Therefore we may write

$$\text{Nu}_K/\text{Nu}_0 = f(u, d, \nu, \omega, A). \quad (5)$$

Analysis of (5) by dimensional theory gives the dimensionless parametric equation

$$Nu_K/Nu_0 = f(\omega dA/v, \omega A/u, d/A). \quad (6)$$

Our experimental investigations indicate that the influence of the group d/A is negligible, a conclusion also reached by other investigators [1].

Finally, the parametric equation (6) may be written in the form of a power relation

$$Nu_K/Nu_0 = a(\omega A/u)^m (\omega dA/v)^n. \quad (7)$$

It is clear that (7) is suitable in the region which includes zero values of the parameters.

The tests were conducted on the experimental rig illustrated in Fig. 2, and consisting of the following basic elements: circulating column, oscillating mechanism, heating and supply system for distilled water, and control and measuring equipment.

The glass circulating column 1 was rigidly fastened by means of the clamp 2 and the gland 3 to the stationary plate 4, mounted on a support frame 5. Water was supplied to the column through the two pipes 6. In the central part of the column 1 there were grids 7, with the bed of solid particles 8 between them, its position being fixed by the clamp 9. The solution flowed out of the column through the tubes 10 and pipe 11. A measuring cylinder 12 was used to measure the flowrate of water and for sampling, and the temperature of the aqueous solution was measured with a thermometer 13.

The oscillating mechanism consisted of an electric motor 14, belt drive 15, and eccentric control unit 16, which, together with the connecting rod 17, communicated a reciprocating motion in the vertical direction to the piston 18. Because of the guide 19, the piston, passing through the seal 20 into the lower part of the column, communicated the oscillatory motion to the liquid. There is a micrometer 21 to measure the amplitude of the piston motion. The distilled water is supplied from thermostat 22 into the header tanks 26 along pipes 25 by means of pump 23 and electric motor 24.

A constant level of water in the tanks 26 is maintained with the aid of overflow tappings and tubes 27. The water reaches column 1 along the tubes 28 and pipes 6 from the header tanks 26, and its flowrate is controlled by the valves 29.

The method of conducting the tests was as follows. Specimens in the form of spherical particles or particles of other shapes were prepared from homogeneous natural gypsum and loaded into the circulating column 1 in the space between the two grids 7. The particle bed was compressed during the entire test with the aid of the pressure clamp 9, which excluded the possibility of relative movement of particles inside the bed.

Then pump 23 was turned on and valve 29 was opened, to establish the required water flowrate, as measured by a volume method. When conditions became settled, the oscillatory mechanism was turned

on to a preset frequency and amplitude. Samples were taken from tubes 10 both in uniform flow over the bed and in the presence of pulsations, at definite time intervals.

The flowrate would then be altered, and the tests repeated in the same order.

Solution of the gypsum particle bed was carried out with distilled water temperature of 298° K. The concentration of gypsum in the solution was determined by the average figure for titration of samples with Trilon B.

The amplitude of oscillation of the liquid above the bed was measured with an optical setup, and was controlled in accordance with the measured piston amplitude. The saturation concentration of gypsum was assumed to be $c_s = 2.05 \text{ kg/m}^3$.

For the spherical particles the tests were carried out at flow velocities of 0.16–7.25 cm/sec, liquid oscillation amplitude 0.12 cm, and frequency 5.3 and 3.2 cps; and at amplitude 0.35 cm and frequency 0.6, 1.6, 3.17, and 5.33 cps. The intensity of the oscillation was $\omega A = 1.87\text{--}0.21 \text{ cm/sec}$.

For the bed of particles obtained by crushing and screening, the tests were carried out in the same range of stream velocity, and at oscillation amplitude 0.35–0.4 cm, and frequencies of 0.6, 3.1, 5.0, and 6.5 cps. The intensity of oscillation was then $\omega A = 2.6\text{--}0.21 \text{ cm/sec}$. The flow velocity of the liquid stream was calculated according to the formula $u = Q/F$. The ratio of mass transfer coefficient in the presence of the oscillatory motion to its value in steady flow was determined from (4).

Figure 3 shows the dependence of solution concentration on velocity at various values of ωA . Curves 1 and 2 correspond to $\omega A = 0$, i. e., to the case of simple flow over the particle bed, and agree fully with the data of other authors [8, 9]. Curves 3–8 indicate increase of concentration with increase of oscillation intensity at various liquid stream velocities.

Figure 4 shows the dependence of Nu_K/Nu_0 , the degree of intensification of the process during pulsation on the ratio $\omega A/u$. It may be seen from the dependence obtained that the greatest increase in the degree of intensification of the process occurs at values of $\omega A/u < 2.5$.

Obviously, this region is of most practical interest, and therefore it is for this region only that the experimental data have been generalized with the help of the parametric equation (7).

For a bed of spheres this equation acquires the following form:

$$Nu_K/Nu_0 = 1.15 (\omega A/u)^{0.41} (\omega dA/v)^{0.21}. \quad (8)$$

The agreement of the calculated data obtained from the reduced equation (8) with the experimental data is illustrated in Fig. 5.

For the bed of particles obtained by crushing and screening, the dependence in this region is similar in nature and is described by the equation

$$Nu_K/Nu_0 = 1.22 (\omega A/u)^{0.35} (\omega dA/v)^{0.18}. \quad (9)$$

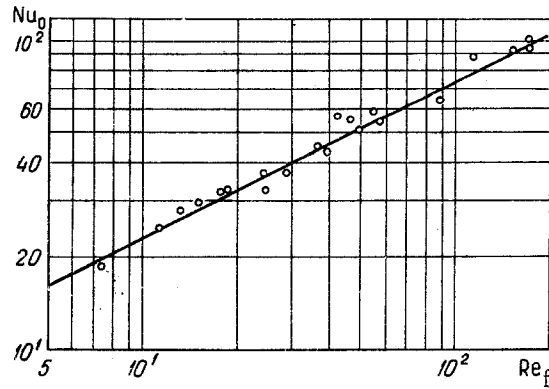


Fig. 1. Solution kinetics for a bed of spherical gypsum particles in a uniform stream of water.

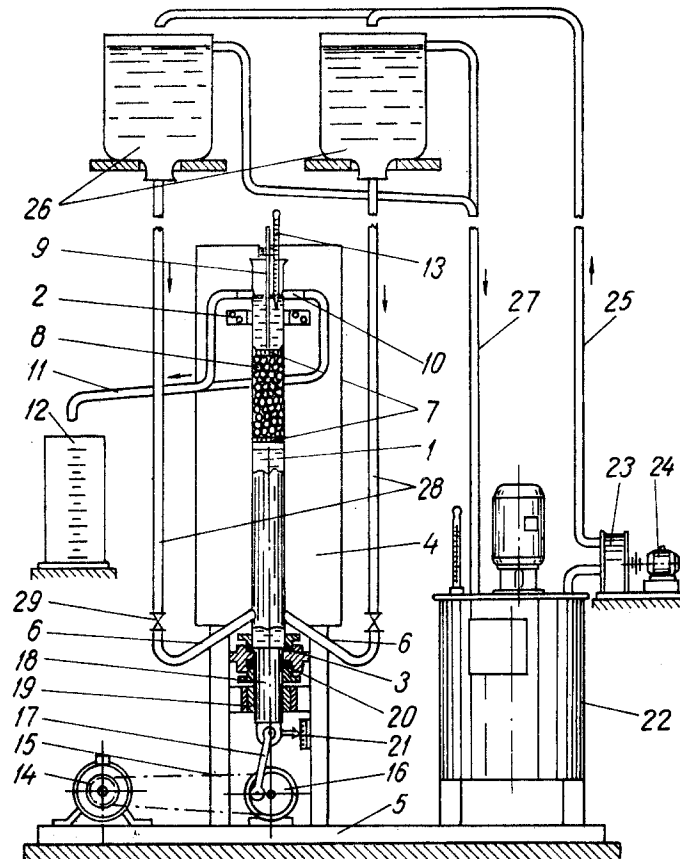


Fig. 2. Schematic of the experimental equipment.

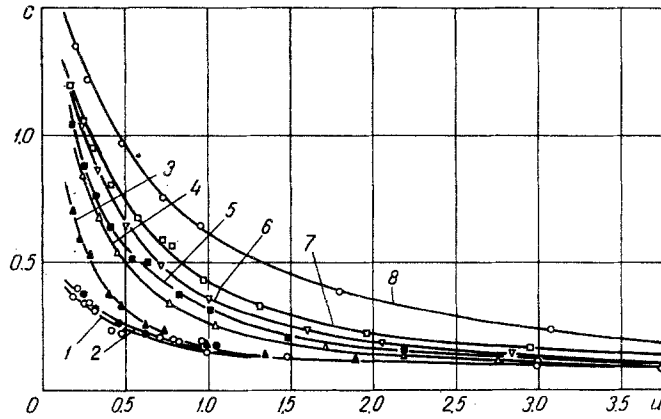


Fig. 3. Solution kinetics of solid spherical gypsum particles in a bed in uniform and pulsating liquid streams (c in kg/m^3 ; u in m/sec): 1, 2) for $\omega A = 0$; 3, 4, 5, 6, 7, 8) for $\omega A = 0.21, 0.384, 0.56, 0.64, 1.11, \text{ and } 1.87$, respectively.

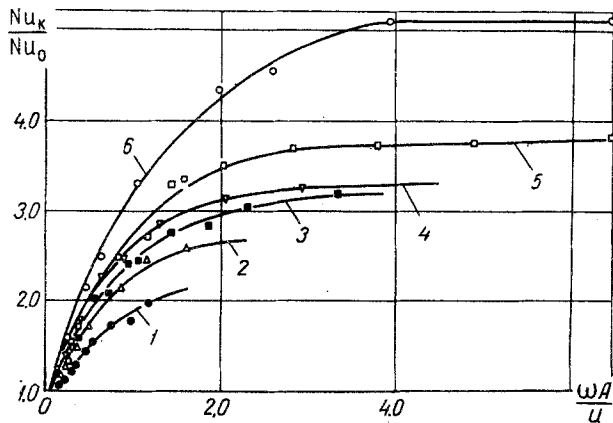


Fig. 4. Variation of mass transfer intensity Nu_k/Nu_0 in the bed in the presence of pulsations as a function of $\omega A/u$: 1, 2, 3, 4, 5, 6) for $\omega A = 0.21, 0.384, 0.56, 0.64, 1.11, \text{ and } 1.87$, respectively.

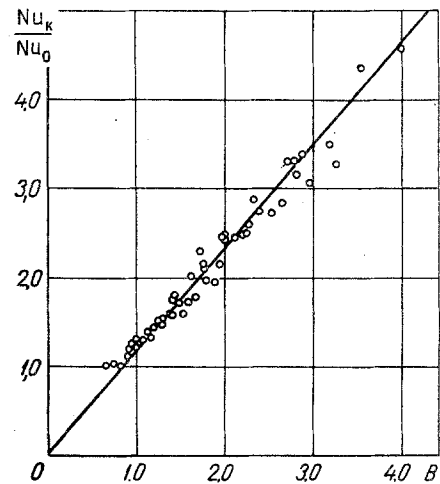


Fig. 5. Mass transfer kinetics in a bed of spherical particles with a pulsating liquid stream (generalized correlation). $B \equiv (\omega A/u)^{0.41} (\omega A/\nu)^{0.21}$.

Equations (8) and (9) show that the degree of intensification of mass transfer in the bed, other conditions being equal, is somewhat less for the crushed particles than for the bed of spherical particles.

Thus, application of an oscillatory process during mass transfer in a bed of solid particles leads to considerable acceleration of the mass transfer, up to a factor of 4.5 in our tests, as may be seen from Fig. 5.

As investigation in the range $\omega A/u < 2.5$ has shown, the degree of enhancement of mass transfer for a bed of particles of the shape mentioned obeys a single relation.

Acceleration of mass transfer in the bed in the presence of pulsations of the medium is evidently due to the following causes. In simple flow over the bed, at regions close to the points of contact of the particles, there are stagnant zones, where the velocity of liquid motion is insignificant, and the motion is laminar. When the mechanical oscillations are superimposed on the stream of liquid, the velocity of flow over the particles is increased appreciably, making the boundary layer turbulent at the surface of the particles. Therefore, as a result of the pulsating motion of the liquid and of its pulsating displacement, conditions are created which remove the stagnant zones close to the points of contact of the particles. It is to be expected that the effect caused by breakdown of the stagnant zones will be the greater, the larger the stagnant zones themselves.

In the case of cylindrical particles, the regions in which motion of the liquid is limited will exceed the analogous regions for spherical particles, which touch one another only at points. Therefore, the degree of enhancement of mass transfer in the case of cylindrical particles should be greater than in the spherical particle case. This rule is actually observed in practice, and is confirmed by the results of our investigations and those of others [1].

Thus, the creation of pulsations in the liquid flow may be used to enhance mass transfer in a bed of

particles of various shapes, and the relations obtained here may be useful for calculation of technical processes and equipment in which pulsating motion of the liquid medium is employed.

NOTATION

k_0 —mass transfer coefficient in simple flow over a bed of solid particles; c_0 —liquid concentration upstream of bed inlet; u —flow velocity of stream, m/sec; σ —specific area of bed of solid particles; H —depth of bed; c_2 —liquid concentration at bed outlet; c_3 —saturation concentration of gypsum; k_K —mass transfer coefficient for pulsating liquid stream; c_K —liquid concentration at bed outlet for pulsating stream; ω —oscillation frequency; d —diameter of solid particle; A —oscillation amplitude; ν —kinematic viscosity of liquid; Q —liquid flow rate; F —cross-sectional area of column.

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