

MASS TRANSFER BETWEEN SOLID PARTICLES AND A
PULSATING LIQUID FLOW

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Mass transfer in a solid-liquid system with a flow subjected to pulsations is investigated. Large acceleration of mass transfer is obtained. Criterial equations are derived, describing mass transfer under pulsating flow conditions.

Impulsive effects in a medium accelerate extradiffusional transfer in systems containing a solid phase [2, 3]. As a rule, however, this topic is investigated under conditions of pulsations of a liquid medium in the absence of steady fluid flow.

We have investigated external mass transfer in the example of extradiffusional dissolution of solid particles in a pulsating liquid flow in the transitional and turbulent regimes.

The first series of experiments was conducted under conditions of liquid flow past solid particles without the application of a mechanical vibration field, for values of $100 < Re_0 < 10,000$ in the interval of particle diameters $0.004 < d < 0.028$ m. The experimental results of this series formed a basis of comparison with the experimental data under pulsating flow conditions.

The results obtained in this case are in good agreement with the data of [1], which are generalized by the equation

$$Nu = 0.8Pr^{1/3} Re_0^{1/2}. \quad (1)$$

For flow of a pulsating liquid past a fixed particle without translational motion of the liquid the hydrodynamic situation at the phase-interaction surface changes appreciably, so that the criterial equation (1) is modified. Another criterion $2A/d$ is added formally to that equation, giving it the new form

$$Nu = BPr^{1/3} Re^n \left(\frac{2A}{d} \right)^m. \quad (2)$$

In our own experiments and in the work of other researchers it has been shown that under the condition $2A/d > 1$ the form of Eq. (1) can be retained, i.e., the influence of the criterion $2A/d$ ignored. The main influence is still the criterion Re , which for oscillatory motion of a liquid medium takes the form

$$Re_M = \frac{\omega A d}{\nu},$$

and in our experiments it was varied over the range $500 < Re_M < 22,000$.

The following criterial equation has been established on the basis of processing of the experimental data:

$$Nu = 0.185 Pr^{1/3} Re_M^{0.67}. \quad (3)$$

We now consider the case of interaction of a solid particle with a sinusoidally pulsating liquid flow. The instantaneous velocity of the continuum is

$$W^* = W_0 + \omega A \sin \omega t. \quad (4)$$

To retain the criterion Re as the governing factor it is necessary to introduce the integral-mean flow velocity, which depends both on the translational and on the oscillatory motion of the liquid. This velocity [4] is defined as

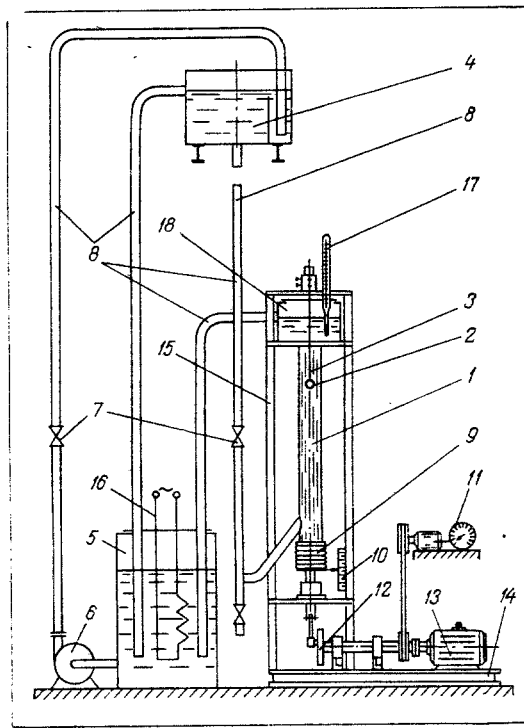


Fig. 1. Experimental arrangement. 1) Column; 2) test sample; 3) needle; 4) supply tank; 5) feeder tank; 6) pump; 7) valves; 8) pipelines; 9) syphon bellows; 10) amplitude gauge; 11) tachometer; 12) eccentric mechanism; 13) motor; 14) bedplate; 15) frame; 16) thermostatic control element; 17) thermometer; 18) overflow tank.

$$\bar{W} = \begin{cases} W_0, & \varphi \leq 1; \\ W_0 \frac{2}{\pi} \left(\arcsin \frac{1}{\varphi} + \sqrt{\varphi^2 - 1} \right), & \varphi > 1, \end{cases} \quad (5)$$

where $\varphi = \omega A / W_0$.

The criterion Re_{re} determined from this velocity enters into the equation

$$Nu = C Pr^{1/3} Re_{re}^n \varphi^k. \quad (6)$$

To determine the constant parameters of this equation we conducted a series of experiments on the dissolution of single particles in distilled water. The experimental apparatus is shown in Fig. 1; it consists of a vertical column, a motor-driven pulsator, and a system for feeding water into the column.

The samples 2 of benzoic acid are inserted on a special needle 3 into the working column 1, which has a diameter of 0.057 m. Flow is created by feeding water into the lower part of the column from the supply tank 4. Distilled water from the feeder tank 5 is delivered by the pump 6 into the constant-level supply tank 4. The water flow is regulated by the valves 7. A timing device is used to set the test time. The liquid flow rate, pulsation frequency, and the previously displayed amplitude are measured in the experiment. The quantity of substance transferred into solution is determined by a weighing method. Prior to weighing, the samples are dried at a temperature of 323°K. The value of the diffusion coefficient for benzoic acid in water is $D = 1.15 \cdot 10^{-9}$ m²/sec, and the saturation concentration of benzoic acid is $C_s = 3.4$ kg/m³. The mean diameter of the samples is determined from three measurements with slide calipers.

The mass-transfer coefficient is determined from the expression

$$k = \frac{\Delta G}{\tau F \Delta C}. \quad (7)$$

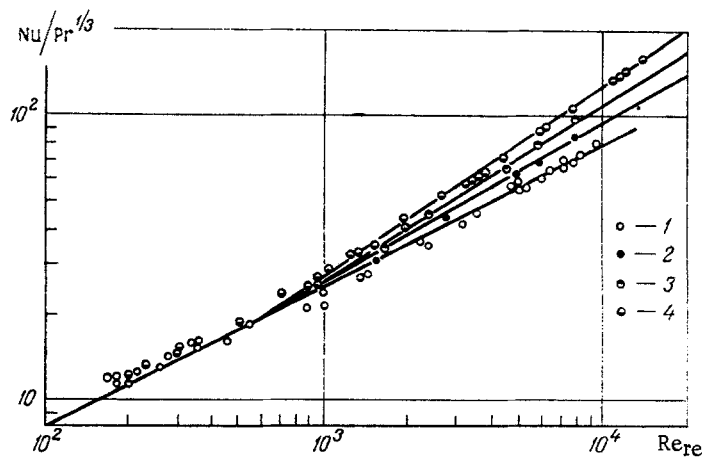


Fig. 2. Mass-transfer kinetics of solid particles in a pulsating flow. 1) $\varphi = 0$; 2) 0.35; 3) 0.65; 4) $\varphi \geq 1$.

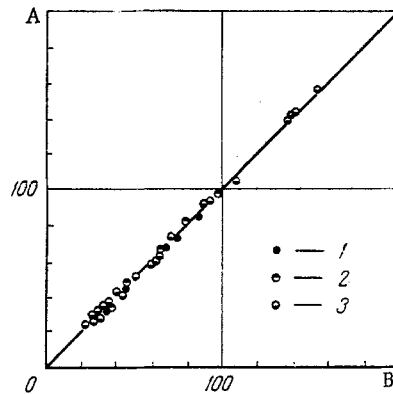


Fig. 3. Comparison of experimental and calculated data. A) Experimental values of $(Nu/Pr^{1/3})_o$; B) calculated values of $(Nu/Pr^{1/3})_c$; 1) $\varphi = 0.35$; 2) $\varphi = 0.65$; 3) $\varphi \geq 1$.

The results of processing the experimental data are given in Fig. 2 in the form $Nu/Pr^{1/3} = f(Re_{re})$ for $\varphi = \text{const}$. Two intervals of the graph are discernible, corresponding to different values of Re_{re} .

For $Re_{re} < 1000$ we obtain the criterial equation

$$Nu = 0.8 Pr^{1/3} Re_{re}^{1/2}, \quad (8)$$

describing mass transfer in pulsating flow in the interval $0 \leq \varphi < \infty$.

For $Re_{re} > 100$ the mass transfer is more vigorously accelerated with growth of the pulsating component of the integral-mean flow velocity than is predicted by (8).

The results of processing of the experimental data are represented by the criterial relations

$$Nu = \begin{cases} (0.8 - 0.55\varphi) Pr^{1/3} Re_{re}^{0.5+0.17\varphi} & 0 \leq \varphi \leq 1, \\ 0.25 Pr^{1/3} Re_{re}^{0.67} & \varphi \geq 1. \end{cases} \quad (9)$$

The results of a comparison of the experimental data with calculations based on Eqs. (9) are given in Fig. 3.

NOTATION

$Nu = kd/D$, Nusselt number; $Pr = \nu/D$, Prandtl number; $Re_o = W_o d/\nu$, Reynolds number defined on the steady-flow velocity; $Re_M = \omega Ad/\nu$, modified Reynolds number defined on the

pulsation velocity amplitude; $Re_{re} = \bar{W}d/\nu$, reduced Reynolds number defined on the integral-mean relative flow velocity; W_0 , W^* , \bar{W} , steady-flow, instantaneous pulsation, and integral-mean pulsation velocities, respectively; ωA , pulsation velocity amplitude; $\varphi = \omega A/W_0$, ratio of pulsation velocity amplitude to steady velocity component; $\omega = 2\pi f$, cyclic frequency; A , pulsation amplitude; k , mass-transfer coefficient; d , diameter of experimental sample; D , diffusion coefficient of benzoic acid in water; ν , kinematic viscosity coefficient; ΔG , weight loss of dissolved sample; ΔC , difference between saturation concentration and concentration in main mass of the solution; F , dissolution surface; τ , dissolution time.

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FREE CONVECTION IN A HETEROGENEOUSLY CATALYZED REACTION

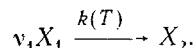
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Limits have been defined for the monotonic convective instability in a horizontal layer of gas when a heterogeneous catalyzed reaction occurs at the lower boundary.

If a heterogeneous reaction is to be conducted under given conditions, it is necessary to know the precise details of the heat and mass transfer; in some instances, natural convection can accelerate the heat and mass transfer substantially, which can react back on the process. Therefore, it is important to define the conditions for free convection.

Consider an unbounded planar horizontal layer filled with a reacting liquid or gas and bounded by solid surfaces; a constant temperature and a constant reagent concentration are maintained at the upper surface. The lower surface is provided by the catalyst and is thermally insulated from the environment; the surface produces a catalytic reaction of the type



Convection can arise under such circumstances on account of the heating (cooling) at the surface and on account of the difference in molecular weight between the initial substances and the products.

The dimensionless equations are as follows in the Boussinesq approximation:

$$\frac{\partial V}{\partial \tau} + \text{Pr} V \nabla V = -\nabla p + \text{Pr} \Delta V + (R_1 \theta + R_2 a) \bar{e}, \quad (1)$$

$$\frac{\partial a}{\partial \tau} + \text{Pr} V \nabla a = \Delta a, \quad (2)$$

$$\frac{\partial \theta}{\partial \tau} + \text{Pr} V \nabla \theta = L \Delta \theta \quad \left(L = \frac{1}{Le} \right), \quad (3)$$

$$\text{div} V = 0 \quad (4)$$

subject to the boundary conditions [1]

$$z = 1, \quad V = \theta = a = 0, \quad (5)$$

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