MASS TRANSFER IN THE CHEMICAL INTERACTION OF A SOLID WITH A MOVING LIQUID, COMPLICATED BY THE EVOLUTION OF A GAS PHASE

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The mass transfer taking place during the interaction of a spherical solid with a moving liquid is analysed for the case in which a gaseous reaction product is also evolved.

It was shown earlier [1] that the kinetic characteristics of heterogeneous diffusion processes, complicated by the evolution of a gas phase in the "bubbling" condition, were determined by the mode of formation and motion of the bubbles close to the reaction surface. On the basis of theoretical and experimental data, the following critical equation was derived

$$\mathrm{Nu}_0 = 6.9\,\mathrm{Re}_0^{0.57}\,\mathrm{Pr}^{1/3}, \tag{1}$$

describing the kinetic characteristics of the processes in question in the quiescent part of the liquid. In this equation

$$\mathrm{Nu}_0 = \frac{qnl}{c_R D_R}\sqrt[3]{\frac{D_R}{D_g}}; \quad \mathrm{Re}_0 = \frac{ql}{\rho_g \nu}; \quad \mathrm{Pr} = \frac{\nu}{D_g};$$
$$l = \sqrt{\frac{\sigma}{g(\rho - \rho_g)}}.$$

The effect of the motion of the liquid on the rate of interaction of calcite ($CaCO_3$), magnesium, and manganese with acid solutions was studied in [2] and [3]. With increasing number of revolutions of the stirring rotor [3] there was a proportional increase in the velocity of the process. In both papers the diffusive character of the processes taking place was asserted; however, the indeterminacy of the hydrodynamic situation prevented any quantitative estimation of the phenomenon.

We accordingly attempted a theoretical and experimental analysis of the kinetic characteristics of heterogeneous diffusion processes complicated by the evolution of a gas phase in the "bubbling" mode of operation when the liquid flowed directly around the solid. We studied the interactions of magnesium, manganese, and calcium carbonate (marble) with inorganic acid solutions of various concentrations. The following are the equations of these reactions:

$$\begin{gathered} Mg + 2HCl = MgCl_2 + H_2, \\ Mg + H_2SO_4 = MgSO_4 + H_2, \\ Mn + 2HCl = MnCl_2 + H_2, \\ CaCO_3 + 2HCl = CaCl_2 + CO_2 + H_2O. \end{gathered} \tag{2}$$

The experimental apparatus (Fig. 1) for studying the kinetic characteristics of the processes under the envisaged conditions consists of a centrifugal pump 1, a receiving tank 2, a tube 4, a heat exchanger of the tube-in-tube type 5, an inductive flowmeter 6, and a system of tubular conduits with a cut-off and regulating value 7. In order to prevent corrosion and the evolution of subsidiary gaseous products, the inner surfaces of the tubes and pump were coated with chlorinated polyvinyl chloride paint.

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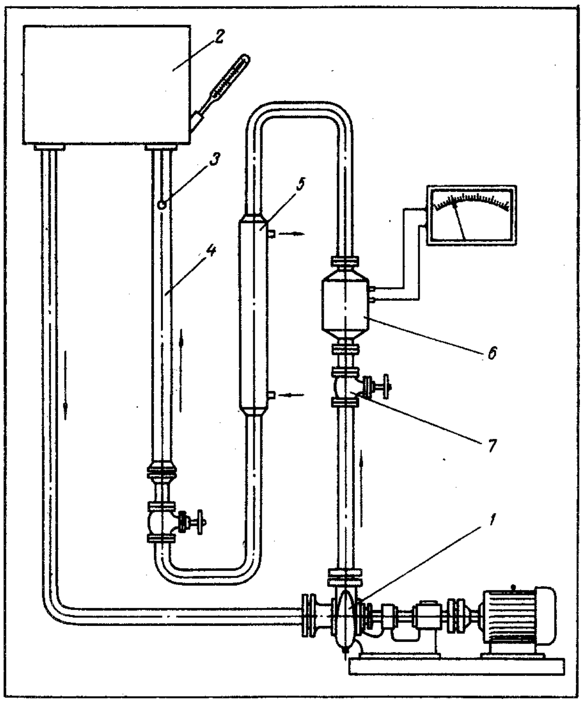

Fig. 1

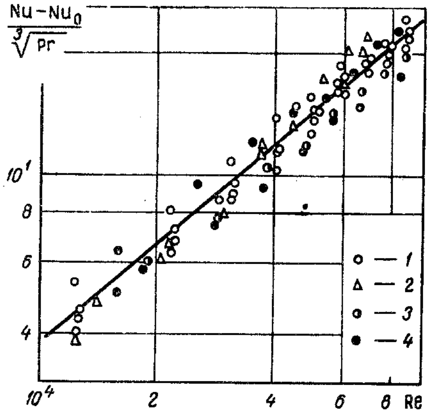

Fig. 2

Fig. 1. Arrangement of the experimental apparatus for studying the kinetic characteristics of heterogeneous diffusion processes when the liquid flows directly around the solid.

Fig. 2. Correlation of the experimental data by reference to Eq. (4) for the interaction of $CaCO_3$, Mg, and Mn with acids: 1) Mg + HCl; 2) Mg + H_2SO_4; 3) Mn + HCl; 4) $CaCO_3$ + HCl.

From the solid material (magnesium, manganese, marble) we machined spherical samples 20 mm in diameter, these subsequently being fixed to an auxiliary, easily dismantled holder 6 mm in diameter. The samples with the holder were introduced into the tube (internal diameter 57 mm) and centered along the axis of the flow. In order to facilitate visual observation of the process, the tube 4 was made of Plexiglas. All the experiments were carried out at 30°C, hot or cold water being introduced into the heat exchanger 5 for this purpose. The velocity of the liquid was varied between 0.2 and 1.4 m/sec and recorded by means of an inductive flowmeter of the IR-11 type. The period of interaction between the phases was taken as 2-6 min, depending on the concentration of the reagent and the velocity of the liquid. Within this interval hardly any changes were observed in the configuration of the solid as a result of its dissolution. The amount of solid which had reacted was determined from the weight loss of the sample after washing and drying. This loss was subsequently converted to the weight of gas evolved, referred to normal conditions.

If the test sample largely blocks the tube cross section, there may be a local change in mass transfer owing to the increase in the velocity of the liquid through the narrowest open section. The influence of blocking may be taken into account by introducing a correction factor φ to the mean flow velocity, this being given [4] by the expression

$$\varphi = \frac{1}{1-0.95\eta^2}.$$

Since under the conditions of our experiments the value of the correction factor φ was comparable with the experimental error, no allowance was made for the influence of blocking on the mass transfer when analyzing the experimental data.

The primary experimental data were presented in the form of a system of equidistant curves; the position of each curve was the higher, the greater the value of Nu_0. We accordingly analyzed the experimental data on the basis of a relation of the following type

$$\frac{Nu-Nu_0}{\sqrt[3]{Pr}} = f(Re), \tag{3}$$

where

$$\mathrm{Nu} = \frac{qnl}{c_R D_R}\sqrt[3]{\frac{D_R}{D_g}};\quad \mathrm{Re} = \frac{wD}{\nu}.$$

It follows from Fig. 2 that Eq. (3) takes the form

$$\frac{\mathrm{Nu}}{\sqrt[3]{\mathrm{Pr}}} = 6.9\,\mathrm{Re}_0^{0.57} + 20.3\cdot 10^{-4}\mathrm{Re}^{0.82}. \tag{4}$$

On considering Eq. (4) we immediately see that the total rate of mass transfer from the solid surface may be approximately calculated by determining the influence of bubbling and the influence of the flow of liquid around the solid on the mass-transfer processes and then adding these two effects together.

Assuming our conception of the diffusion-type boundary layer to be valid, we may now indicate the difference between the ways in which bubbling and the motion of the liquid affect the thickness of this layer. Thus the evolving gas bubbles are able to turbulize and disrupt the boundary layer immediately next to the surface of the solid, while the motion of the liquid leads to a systematic reduction in the thickness of the boundary layer.

It follows from Eq. (4) that the contribution of the first term, which reflects the influence of bubble formation and development on the boundary layer, is extremely significant. Thus on dissolving magnesium in hydrochloric acid (concentration 20.8 kg/m^3) with a Reynolds number of $87\cdot 10^3$ the first term equals 13.02 and the second 24.78.

The results obtained in this investigation may clearly be used for constructing a "cold" model of the heat-transfer processes accompanying the boiling of liquid under bubbling conditions.

NOTATION

c_R	is the concentration of hydrogen ions, kg/m^3;
D_g	is the diffusion coefficient of the gas, m^2/sec;
D_R	is the diffusion coefficient of the hydrogen ions, m^2/sec;
$\eta = d/D$	is the blocking factor;
D	is the internal diameter of the tube, m;
q	is the mass flow density of the gas, kg/m$^2\cdot$sec;
w	is the velocity of the liquid, m/sec;
l	is the characteristic linear dimension proportional to the separation diameter of the bubble, m;
n	is the stoichiometric coefficient, kg of hydrogen/kg of gas;
g	is the gravitational acceleration, m/sec^2;
Pr	is the Prandtl diffusion number;
Nu	is the Nusselt diffusion number;
Re	is the Reynolds number;
σ	is the surface tension, N/m;
ν	is the kinematic viscosity of the liquid, m^2/sec;
ρ	is the density of the liquid, kg/m^3;
ρ_g	is the density of the gas, kg/m^3;
d	is the diameter of the spherical sample, m;

Subscripts

R	denotes the reagent;
g	denotes the gas;
o	denotes the parameters relating to the process in the quiescent liquid.

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