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INVESTIGATION OF CHEMICAL NUCLEATE BOILING

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The effect of the solution viscosity and particle size on chemical boiling kinetics is established. A quantitative estimate is obtained for chemical nucleate boiling under conditions of free convection.

By chemical boiling we understand the heterogeneous diffusion processes taking place between a solid and a liquid reactant, accompanied by gas release. The investigated reactions between acids, on the one hand, and calcite, magnesium, malachite, and manganese, on the other, take place in the diffusion regime, as confirmed by a series of studies [1-4]. In these processes it is possible to distinguish a region in which the mass transfer coefficient increases with the driving force (reactant concentration). By analogy with boiling heat transfer, it is called the region of the nucleate boiling regime. The kinetics of chemical boiling under conditions of free convection were examined in [5], where the experimental results were quantitatively generalized in the form of criterial relations. The particle diameter, normally used for analyzing mass transfer processes with a dispersed phase, was taken as the linear dimension.

It should be noted that in the experimental results analyzed the diameter of the prepared spherical particles varied only slightly and was equal to 20 ± 3 mm. The diffusion Prandtl number also varied only slightly and accordingly we used the relation

$$\mathrm{Nu} \sim \sqrt[3]{\mathrm{Pr}}, \tag{1}$$

which has been recommended for mass transfer processes by a number of authors, for example in [6].

As shown by the experimental data on boiling heat transfer, in the region of developed nucleate boiling the heat transfer rate is unaffected by the Prandtl number and the geometric dimension [7]. It therefore became necessary to probe more deeply into the effect of certain parameters on the chemical boiling kinetics.

Above all, it is a question of establishing the dependence of the mass transfer coefficient on the particle diameter and the viscosity of the solution as they vary over a fairly wide range. We began by preparing spherical particles of different sizes which were subsequently immersed in a reactant solution with a given concentration and temperature. From the weight loss of the particle ΔM on a certain experimental time interval τ we found the mass transfer coefficient

$$k_R = \frac{\Delta M}{nFc_R\tau}. \tag{2}$$

It is clear from Fig. 1 that in the region of the nucleate boiling regime on the particle diameter interval 7.5-25 mm the quantity k_R is self-similar relative to the dimension of the solid phase. As the linear dimension it is convenient to use the linear scale of capillary-gravitational interaction ℓ^* [7]:

$$l^* = \left[\frac{\sigma}{g(\rho' - \rho'')}\right]^{1/2}. \tag{3}$$

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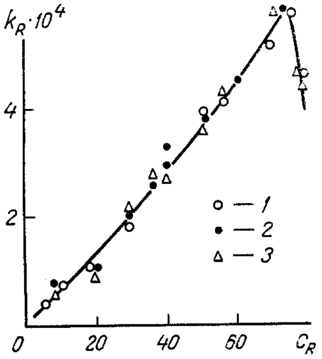

Fig. 1

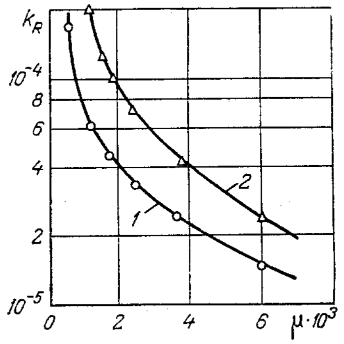

Fig. 2

Fig. 1. Mass transfer coefficient k_R (m/sec) as a function of the reactant concentration c_R (kg/m^3) for the reaction between hydrochloric acid and spherical magnesium particles, diameter: 1) 7.5; 2) 15; 3) 25 mm.

Fig. 2. Mass transfer coefficient k_R (m/sec) as a function of the dynamic viscosity of the solution μ (Pa·sec) for the reaction between magnesium and hydrochloric acid, concentration: 1) 25; 2) 55 kg/m^3.

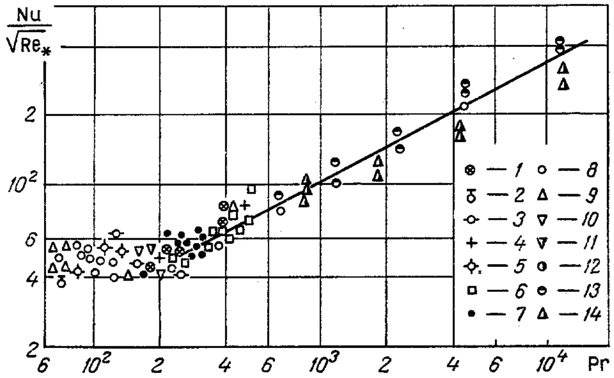

Fig. 3. Experimental data on chemical nucleate boiling kinetics: 1) Mg + HNO_3; 2, 4) $CaCO_3$ + HCl [2) solution temperature 298; 4) 290 K]; 3) $CaCO_3$ + HNO_3; 5) Mg + H_2SO_4; 6-9) Mg + HCl [6) solution temperature 285; 7) 293; 8) 313; 9) 333 K]; 10) $(CuOH)_2CO_3$ + HNO_3; 11) $(CuOH)_2CO_3$ + HCl; 12) Mn + HCl; 13, 14) Mg + HCl in aqueous glycerin solution [4, 5) data of [4]; 10-12) [10]].

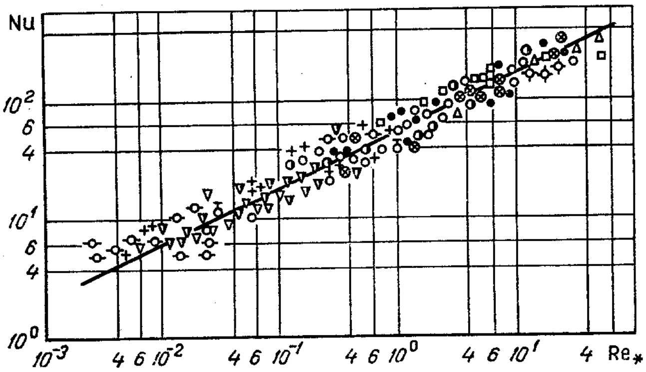

Fig. 4. Generalization of experimental results on chemical nucleate boiling kinetics at Pr < 300 (for notation see caption to Fig. 3).

The term "capillary" takes into account the action of the surface tension of the liquid. The quantity ℓ^* is proportional to the size of the gas bubble forming on the solid surface. As noted by S. S. Kutateladze [7], the local scales of motion of the liquid are determined by the dimensions of the gas or vapor bubbles forming on the wall. It is known that in the growth of a gas bubble the velocity of the liquid front and hence the generation of turbulence will be greatest at the moment of time following its nucleation, since [4]

$$\frac{dR}{d\tau} \sim \frac{1}{R}.$$

Thus, the introduction of the dimension ℓ^* into the analysis is logically justified.

The effect of the viscosity of the solution on mass transfer in the presence of gas release was investigated with reference to the same reaction but using an acid solution to which various amounts of glycerin had been added. The experimental data show (Fig. 2) that as the viscosity increases the mass transfer coefficient decreases. This had also been noted previously, in investigating the effect of soluble products on the kinetics of the process [8]. It was qualitatively established that as the concentration of soluble reaction products increases the mass transfer coefficient decreases, precisely in the region of the nucleate boiling regime. In the region of the postcritical regime this effect is unimportant. The velocity w entering into the Reynolds number was estimated from the rate of gas formation [5], and the physical constants from the average temperature of the boundary layer.

Plotting the dependence $Nu/\sqrt{Re_*} = f(Pr)$ in a logarithmic coordinate system (Fig. 3) shows that two regions can be distinguished. The first corresponds to the interval of Prandtl numbers below 300. In this range the ratio $Nu/\sqrt{Re_*}$ is self-similar relative to the Pr number, and the generalized dependence (Fig. 4) can be represented by the expression

$$\mathrm{Nu} = 55\sqrt{\mathrm{Re}_*}. \tag{4}$$

Relation (4) generalizes the experimental results on the interval $Re_* = 10^{-3}$-10^2.

On the interval of Prandtl numbers above 300 the effect on the kinetics cannot be neglected. On the range Pr = 300-12,000 the calculated dependence takes the form:

$$\mathrm{Nu} = 3{,}1\sqrt{\mathrm{Re}_*}\sqrt{\mathrm{Pr}}. \tag{5}$$

As noted in [9], in mass transfer processes the exponent of the Prandtl number can take values from 0.25 (theoretical value obtained by V. G. Levich) to 0.5 (established by M. Kh. Kishinevskii). The latter value corresponds to mass transfer under unsteady conditions when the contact between the reactant and the solid is brief and the formation of a diffusion boundary layer has only just begun. These conditions are satisfied in the case of mass transfer with gas release. The site of a bubble separating from the surface is approached by fresh reactant from the core of the flow. Since the bubble separation rate is fairly high, steady-state conditions are not observed.

Most important from the practical standpoint is the first result (Eq. (4)). This corresponds to the majority of actual processes.

NOTATION

$Nu = k_R\ell^*/D_R$, diffusion Nusselt number; $Pr = \nu/D_R$, diffusion Prandtl number; $Re_* = nc_Rk_R\ell^*/(\rho''\nu)$, Reynolds number; c_R, reactant concentration, kg/m^3; D_R, reactant diffusion coefficient, m^2/sec; ν, kinematic viscosity of the solution, m^2/sec; ρ, density, kg/m^3; σ, surface tension, N/m; F, interaction surface area, m^2; g, acceleration of gravity, m/sec^2; n, stoichiometric coefficient. Superscripts: ') liquid, ") gas.

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DETERMINATION OF THE THERMAL STATE OF MATERIAL SUBJECTED TO EROSIVE DEGRADATION

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The experimental data are generalized and governing parameters and analytic relations for estimating the thermal state of material subjected to the thermoerosive action of a dusty gas flow are proposed. Comparison of the results of numerical calculations obtained using the method described in [1] with estimates based on the relations proposed gives the error of the latter.

When a high-velocity two-phase flow acts on a target material, the temperature field in the latter changes periodically as it is progressively eroded by particle impact [1]. The presence of condensed particles in the flow, on the one hand, intensifies the convective heat transfer between the gas and the wall and, on the other, discretely reduces the thermal energy stored in the wall material as a result of removal of the heated surface layer. Depending on the velocity V_{pw} and the size of d_p of the particles striking the wall and on the time between successive impacts τ_{er} the relation between the thermal energies supplied and stored varies widely, which seriously complicates the estimation of the thermal state of wall. The problem becomes even more complex if one takes into account the fact that, as a rule, the thickness of the eroded surface layer δ_{er} (depth of crater) increases considerably with increase in wall temperature [2].

As distinct from thermochemical degradation, the erosion mechanism depends on breakage of the wall material over a considerable depth, commensurable with the size of the impacting particle d_p. Accordingly, layers of material at different temperatures and hence with different bond rupture energies take part in the process. For a nonuniform temperature distribution within the wall material as the leading parameter it is possible to select the mean-integral temperature over the crater depth δ_{er}:

$$T_s = \frac{1}{\delta_{er}} \int_0^{\delta_{er}} T(y)\, dy.$$

For a quasisteady wall erosion regime, when the temperature profile has an exponential form [3], the mean-integral temperature is related to the thermophysical parameters of the material (ρ_M, c_M, λ_M) and the erosion rate by the expression

$$\frac{T_s - T_0}{T_w - T_0} = \frac{\lambda_M}{c_M \delta_{er} G_\Sigma}\left[1 - \exp\left(-\frac{c_M \delta_{er} G_\Sigma}{\lambda_M}\right)\right], \qquad (1)$$

where $G_\Sigma = G_T + G_{er}$. However, a quasisteady regime is established only when the temperature-profile relaxation time τ_T is less than the characteristic time τ_{er}. The relaxation time

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