KINETICS OF LIBERATION OF DISSOLVED GAS IN A LIQUID STREAM

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The results are presented for an experimental study of the rate of formation of the gaseous phase during the turbulent flow along a cylindrical channel of a liquid supersaturated with a gas.

The liberation of dissolved gas in a liquid stream ("gas cavitation") is observed in many industrial systems [1]. However, the kinetics of this process has not been studied quantitatively. At present the most effective method for its study is an experiment set up on the basis of similarity theory.

In this connection an experimental installation [2], for which a schematic diagram is presented in Fig. 1, was created to study the kinetics of gas liberation. Water 1, saturated at the pressure p_s with air or carbon dioxide, was supplied to the horizontal smooth Duralumin or glass tube 2. Upon passage through the set of wire screens 3 the solution becomes supersaturated because of the pressure drop in the stream to a value $p < p_s$ and gas liberation begins. The volumetric fraction of the gaseous phase in each cross section of the stream was determined with the radioactive detector 4 which was moved along the tube during the experiment.

A study of the kinetics of gas liberation in cylindrical channels of round cross section was performed on the installation. The main task of the study was to obtain a criterial relationship permitting the determination of the rate of the process in the section where it is no longer affected by the form of the local resistance. In all the experiments the movement of the medium was steady, forced, and turbulent, the stream had a bubbly structure, and the Mach number was considerably less than one. The temperature of the stream was practically constant along the tube, and heat exchange with the external medium was absent. The liquid phase could be considered as diluted by the solution of the "gas" in the liquid, while the gaseous phase could be considered as a one-component ideal gas (because of the low elasticity of water vapor). For such conditions it was assumed that the "linear" rate of gas liberation is

$$\frac{d\varphi}{d\chi} = F(s, \nu, R, \mathrm{Re}, \mathrm{We}, \varphi, \chi), \tag{1}$$

where φ is the volumetric fraction of the gaseous phase;

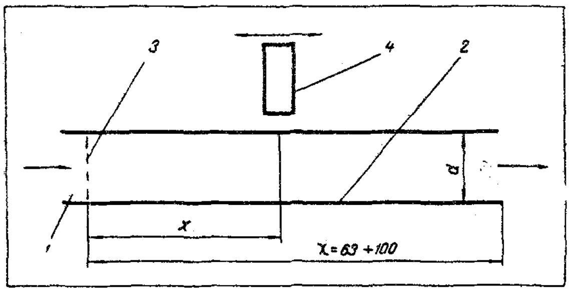

Fig. 1. Schematic diagram of installation.

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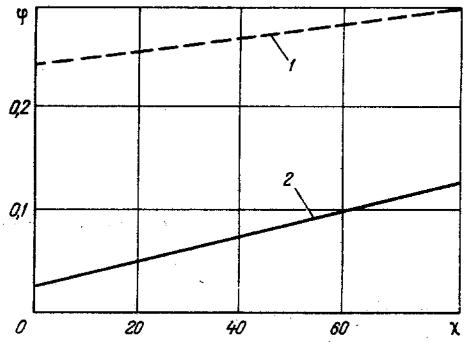

Fig. 2. Typical variation in gas content along channel. Solution of CO_2 in H_2O; Re = 150,000; 1) equilibrium gas content; 2) true gas content.

$$\chi = \frac{x}{d};\ s = \frac{p_s}{p};\ \nu = \gamma p_s;\ R = \frac{\rho''}{\rho'};\ \mathrm{Re} = \frac{\rho' w d}{\mu'};\ \mathrm{We} = \frac{\rho' w^2 d}{\sigma},$$

where γ is the Henry's constant normalized to the dimensionality Pa; ρ'' and ρ' are the density of the gas and liquid, respectively; μ' is the viscosity of the liquid; σ is the coefficient of surface tension; $w = 4G/\pi\rho' d^2$ is the stream velocity normalized to the total flow rate G of the medium and the density of the liquid.

We note that the Schmidt number was not included in the set of similarity criteria, since the role of molecular mass transfer was assumed to be negligible in the presence of developed turbulent motion of the stream. The slipping of the phases was expressed through the other parameters with the help of the ratio between the true and flow-rate gas contents [3]. The degree of dispersion of the gaseous phase was also assumed to be a function of the parameters enumerated above [4].

To determine the function (1) we performed 86 experiments, in the course of which the similarity criteria were varied within the following limits:

$$s = 1.1 - 8.1;\ \nu = 0.9\cdot 10^{-4} - 0.7\cdot 10^{-2};\ R = 10^{-3} - 10^{-2};$$

$$\mathrm{Re} = 5\cdot 10^{3} - 1.5\cdot 10^{5};\ \mathrm{We} = 26 - 24\,000;\ \varphi = 0 - 0.4.$$

To give an idea of the dimensional parameters we should say that the water temperature in the experiments was varied from +4 to +20°C and the saturation pressure from $3\cdot 10^5$ to 10^6 Pa. The diameters of the tubes were 10 and 16 mm, and the length was 1000 mm. As the local hydraulic resistances we used fine screens of stainless steel and brass (wire thickness and cell size 0.2 mm each) collected into packets of 1-10 screens and completely covering the channel cross section.

A typical distribution of the true volumetric gas content along the channel is shown in Fig. 2. The value of the equilibrium gas content in each cross section was calculated from the local value of the static pressure.

The experimental data were analyzed by the methods of regression analysis [5] with different forms of the dependence (1).

It was discovered that if the similarity criteria are calculated from the values of the parameters in the stream cross section under consideration then the function (1) does not depend explicitly on χ when $\chi \gtrsim 25$. In other words, the effect of a local resistance of the grid type on the intensity of gas liberation does not extend farther than $\chi \simeq 25$. This fact makes it possible to generalize the well-known concept of stabilization of frictional and heat-exchange processes for the movement of a liquid along tubes to processes of gas liberation. As a result of the study it was found that for the section of the stabilized process of gas liberation the following equation is valid with an rms error of 35% in the range of variation of the similarity criteria indicated above:

$$\frac{d\varphi}{d\chi} = 0.11\,(s-1)^{0.25}\,\nu^{0.47}\,R^{-0.5}\,\mathrm{Re}^{-0.13}\exp\left[-3.79\,(1-\varphi)^2\right]. \quad (2)$$

The effect of the Weber number proved to be insignificant.

In the section of the nonstabilized process ($\chi < 25$) the rate of formation of the gaseous phase is higher than in the section of the stabilized process and is not expressed by a simple analytical equation.

In a theoretical analysis of flows having phase transformations it is more convenient to characterize the intensity of gas liberation not by the value $d\varphi/d\chi$, but by the mass rate of gas liberation J, which has the dimensionality $kg/m^3\cdot sec$. One can convert from $d\varphi/d\chi$ to J with the help of the continuity equation of [6]. As a result, with allowance for slipping of the phases, it is found that in the section of stabilized gas liberation

$$\bar{J} = \frac{Jd^2}{\mu'} = 0.11\,(s-1)^{0.25}\,\nu^{0.47}\,R^{0.5}\,\mathrm{Re}^{0.87}\,(a + b\varphi^{c}). \quad (3)$$

In Eq. (3)

$$\text{when } \varphi \leqslant 0.2 \quad a = 0.023;\ b = 3.67;\ c = 1.89;$$

$$\text{when } 0.2 \leqslant \varphi \leqslant 0.4 \quad a = 0.100;\ b = 30.9;\ c = 3.57.$$

To clarify the qualitative effect of the form of the hydraulic resistance 3 (see Fig. 1) and of the roughness of the tubes 2 on the kinetics of the process under investigation several experiments were conducted with local resistances in the form of throttle disks and with the creation of artificial roughness of the surface of the tubes. When throttle disks were used the length of the section of the nonstabilized process and the rate of gas liberation in it increased considerably (these parameters were not studied quantitatively). In this case when the relative opening of the disk was small enough (0.39) the volumetric fraction of the gaseous phase beyond it under certain conditions (Re = 48,000) was close to the equilibrium value. The results of the experiments using rough tubes with a relative roughness on the order of 0.01-0.02 hardly differed from the results of an experiment with smooth tubes. This indicates the determining role of the gas liberation in the core of the stream.

NOTATION

γ	is Henry's constant, (mole/mole)·(1/Pa);
μ'	is the viscosity of liquid, kg/m·sec;
ν	is the molar fraction of gas dissolved in liquid;
ρ'	is the density of liquid, kg/m^3;
ρ''	is the density of gas, kg/m^3;
σ	is the coefficient of surface tension, N/m;
φ	is the true volumetric gas content (volumetric fraction of gaseous phase);
χ	is the dimensionless coordinate of channel cross section;
a, b, c	are the dimensionless coefficients;
d	is the channel diameter, m;
G	is the total mass flow rate of medium, kg/sec;
J	is the mass rate of gas liberation, $kg/m^3 \cdot sec$;
$\tilde{J}$	is the dimensionless mass rate of gas liberation;
p	is the static pressure in stream, Pa;
p_s	is the saturation pressure of liquid by gas, Pa;
R	is the ratio of phase densities;
Re	is the Reynolds number;
s	is the degree of supersaturation of solution;
We	is the Weber number;
w	is the stream velocity normalized to flow rate G and density ρ', m/sec;
x	is the coordinate of channel cross section, m.

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