HETEROGENEOUS NUCLEATION MECHANISM IN THE FLOW OF A SUPERHEATED CRYOGENIC LIQUID

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A hypothesis on heterogeneous nucleation in a liquid volume is used as a basis for obtaining a relation to close a system of equations which describes non-equilibrium discharge.

Boiling occurs at a certain degree of superheating in the event of an impulsive drop in pressure in a liquid below the saturation pressure or heating of the liquid above the saturation temperature. A similar phenomenon is seen in the discharge of a liquid from pipes or nozzles into a medium in which the pressure is below the saturation pressure at the initial temperature.

The phase transformation to a superheated liquid depends on the number of boiling centers and the bubble growth law. Whereas bubble growth has been studied fairly completely [1], questions of determining the number of boiling centers and the nature of their formation remain only partly answered both for water and for cryogenic liquids. A theory of homogeneous nucleation [2] has now been developed. The amounts of superheating predicted by this theory are substantial and in actual situations are reached in liquids with initial parameters which are close to the parameters of the thermodynamic critical point. In other cases, the amounts of superheating achieved are considerably less than the theoretical values. A natural explanation of this fact is the effect of "ready" nucleation centers in the liquid volume and on the surface being washed. It is noted in [3] that in the boiling of hydrogen, solid particles of frozen gases, as well as dust and dirt particles, can act as nucleation centers.

The present article proposes a model of heterogeneous nucleation on impurity particles in the volume of the liquid and examines the possibility of using this model to describe hydrodynamic phenomena occurring in the discharge of boiling hydrogen. The main assumptions made in the model are based on data from experiments we conducted to study the steady-state discharge of boiling parahydrogen from short pipes (l/d = 5, 10; d = 4.3 mm, 6 mm) with a sharp inlet end.

The substance was discharged from a container, the lower part of which contained the vertically positioned pipe. The container was replenished during the experiment from a tank located above it. The volumetric flow rate of the liquid was measured with a tube-type flowmeter, while the mass rate was calculated with allowance for the pressure and temperature measured at the flowmeter inlet. The error of the rate determinations was no greater than 3% in any of the cases.

The pressure and pressure drop along the pipe were measured with potentiometric transducers, while the temperature of the liquid was measured with plantinum resistance thermometers. All of the measured parameters were recorded on magnetic tape and subsequently analyzed on a computer. The maximum error of the pressure was 4%, while the maximum pressure-drop error was 5%.

The container and test pipe were thermostatted during the tests to exclude heat inflow.

Figure 1a shows typical experimental diagrams of static pressure. The character of the diagrams is the same as in the case of discharge of boiling water [4]. The hydrodynamic discharge model used presumes the following flow structure (Fig. 1b): 1-2) flow in the inlet part of the pipe ($z/d \leqslant 0.5$) is separated and is represented by a convergent stream with a contraction coefficient typical of nonboiling liquid (μ = 0.61). Vapor bubbles of

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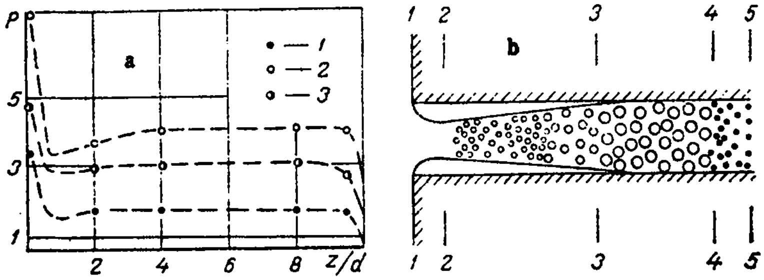

Fig. 1. Typical diagrams of static pressure for the discharge of boiling parahydrogen from short pipes with a sharp inlet end [1) d = 4.3 mm; P_g = 3.25 bar; T_g = 23.6 K; 2) 4.3; 7.36; 29.1; 3) 6; 4.73; 26.5] and the flow structure. P, bar.

critical size instantaneously appear in the minimum section of the stream; 2-3) an isobaric flow section. Vapor bubbles grow in the volume of separated liquid. At a volumetric vapor content $\varphi = 0.39$, the stream "closes" on the pipe wall; 3-4) flow of a vapor–liquid mixture with a bubble structure in the channel of constant cross section ($0.39 < \varphi < 0.74$); 4-5) flow of a vapor–liquid mixture with a vapor-drop structure ($\varphi \geqslant 0.74$).

We will describe the joint flow of the phases by using a two-speed, two-temperature model of two-phase flow in a unidimensional steady-state approximation. We will assume that the vapor–liquid flow is a moving, monodisperse mixture of a liquid (vapor) with spherical bubbles (drops) uniformly distributed in the carrier phase. We will further assume that the vapor in the bubbles is saturated. We also suppose that the phases are not in equilibrium only with respect to temperature in the bubble flow region, while the phases are characterized by both temperature and velocity nonequilibrium in the vapor-drop region of flow.

We write the differential equations for the case of motion of a vapor–liquid mixture with a bubble structure:

$$\frac{d}{dz}[\varphi u \rho_v + (1-\varphi) u \rho_q] f = 0, \tag{1}$$

$$[\varphi\rho_v + (1-\varphi)\rho_q] u \frac{du}{dz} + \frac{dP}{dz} + F_c = 0, \tag{2}$$

$$(1-\varphi)\rho_q u \frac{di_q}{dz} + q_q = 0, \tag{3}$$

$$\varphi\rho_v u \frac{di_v}{dz} - \varphi u \frac{dP}{dz} + q_v = 0, \tag{4}$$

$$\frac{dm_v}{dz} - (q_q + q_v)\frac{f}{r} = 0. \tag{5}$$

On the section 1 – 2, P = const (assumption), u = const, $T_v = T_s(P)$, $q_v = 0$. System (1)-(5) is simplified to the form

$$(1-\varphi)\rho_q u \frac{di_q}{dz} + q_q = 0, \tag{6}$$

$$\frac{dm_v}{dz} - q_q \frac{f}{r} = 0. \tag{7}$$

In (6) and (7) the unknown functions are T_q ($i_q = i(T_q)$) and m_v. An increase in m_v as a result of vapor formation under the condition u = const unambiguously determines the change in the cross-sectional area of the free stream. With $\varphi = 0.39$, the area of the stream becomes equal to the area of the pipe cross section, and subsequent calculation is done by means of system (1)-(5). If the vapor content of the mixture in the channel reaches 0.74, it is presumed that the flow acquires a vapor-drop structure. Here, the system of equations contains equations of motion for each phase, while the equations describing heat flow to the vapor phase (4) contain terms connected with the velocity nonequilibrium.

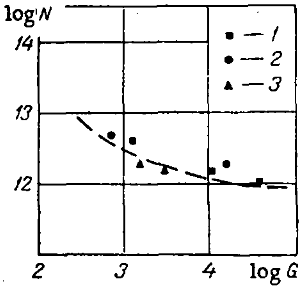

Fig. 2.

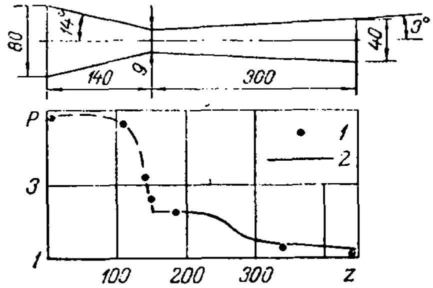

Fig. 3.

Fig. 2. Dependence of the number of bubbles per unit volume of superheated parahydrogen on the Gibbs number in the minimum section of the stream: 1) d = 6 mm; l/d = 10; 2) 4.3; 10; 3) 4.3; 5.

Fig. 3. Geometric dimensions of Laval nozzle and static-pressure diagram in the flow of boiling parahydrogen (P_g = 4.8 bar, T_g = 26.2°K): 1) experiment; 2) calculation. z, mm.

The system of equations describing the flow of the vapor–liquid mixture with a bubble (drop) structure is closed if we prescribe the laws of interaction of the components of the mixture, their equations of state, the channel geometry, and relations for determining the number of vapor-formation centers per unit volume of the liquid.

The laws of thermal and mechanical interaction, as well as the laws of friction between the phases and the wall of the channel, will be prescribed similarly to [5, 6]. Below we examine the problem of describing the kinetics of nucleation.

Boiling of the liquid at a nucleus with the above-described flow structure is possible with either homogeneous or heterogeneous nucleation in the volume of the liquid. We will examine the case when the Gibbs numbers $G = 16\pi\sigma^3/3\,KT_q(P_s - P)^2(1 - v_q/v_v)^2$ corresponding to the maximum overheating of the liquid in the minimum section of the stream are large and homogeneous nucleation can be ignored. We will assume that the liquid is "dirty," i.e., that it contains impurity particles having a certain size spectrum $n(\delta)$, where δ is the diameter of the nucleus. These particles are "weak" points in the liquid, where viable nuclei can appear. With a certain superheating of the liquid ($P_s - P$), boiling will occur on those particles of greater than critical diameter:

$$\delta_q \simeq \frac{4\sigma}{P_s - P}\,.$$

The total number of boiling centers will be determined by the expression

$$N(G) = \int_{\infty}^{\delta_q} n(\delta)\,d\delta\,[\mathrm{m}^{-3}].$$

In the case of low Gibbs numbers ($G \ll 88$) in the superheated liquid, the number of boiling centers formed by the action of the mechanism of homogeneous nucleation is significantly greater than with heterogeneous nucleation, and the contribution of the latter mechanism becomes insignificant.

The spectrum of the impurity particles in the liquid is generally not known beforehand, but it can be determined by solving inverse problems of steady-state discharge of a boiling liquid and resorting to the appropriate tests. The initial conditions in the calculations are assigned on the basis of the tests, and a number N(G) is chosen such that the calculated pressure distribution coincides with the experimental pressure distribution and the boundary condition $dP/dz \to -\infty$ is satisfied at the pipe (nozzle) edge. In solving the inverse problems, we calculated the discharge of subheated parahydrogen n–H_2 with an initial stagnation pressure $P_g \leqslant 7$ bar. Gibbs numbers $600 \leqslant G \leqslant 60{,}000$ were realized in the minimum section of the stream of superheated liquid, the lower Gibbs numbers corresponding to higher initial parahydrogen parameters. The results of the calculations are shown in Fig. 2. In the range of Gibbs numbers investigated, the number of viable vapor-formation centers N lies within the range 10^{12}–$6 \cdot 10^{12}$ m^{-3}. The resulting relation N = N(G) allows us to obtain a closed system of equations describing the nonequilibrium steady-state discharge of boiling parahydrogen within the above-noted range of Gibbs numbers. The reliability of the hydrodynamic model was evaluated by conducting experimental and theoretical studies of the flow of boiling parahydrogen in a Laval nozzle. Figure 3 shows the geometric dimensions of the nozzle and an example of the pressure diagram. Following [7], we took 0.85 for the contraction coefficient of the stream. The discrepancy between the calculated and experimental values of mass rate for six regimes of discharge of subheated parahydrogen with $P_0 \leqslant 7$ bar was no greater than 8%.

Thus, characteristics of the steady-state discharge of boiling parahydrogen were calculated with sufficient accuracy for the range of parameters investigated.

NOTATION

l, channel length, m; d, channel diameter, m; P, pressure, bar; T, temperature, °K; u, velocity, m/sec; ρ, density, kg/m^3; z, axial coordinate, m; φ, volumetric vapor content; i, enthalpy, J/kg; r, heat of phase transformation, J/kg; f, cross-sectional area of channel, m^2; N, number of bubbles per unit volume of mixture, m^{-3}; m, mass rate, kg/sec; F_c, friction of mixture against channel wall, N/m^3; q, interphase heat flow, W/m^3; σ, surface tension, N/m; v, specific volume, m^3/kg; k, Boltzmann constant, $1.38 \cdot 10^{-23}$ J/K; δ, bubble diameter, m. Indices: q, liquid; v, vapor; f, phase boundary; s, saturation parameters; g, stagnation parameters; i, actual parameters.

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