EXPERIMENTAL INVESTIGATION OF THE ANALOGY BETWEEN THE PROCESSES OF BOILING AND BUBBLING

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Zhurnal Prikladnoi Mechaniki i Tekhnicheskoi Fiziki, No. 2, pp. 140–143, 1966

In papers [1, 2] it was pointed out that boiling crisis in liquids is due to hydrodynamic causes and should therefore have a common physical nature with the phenomenon of the bubbling crisis (loss of stability of dynamic two-phase layer). In [3] it was shown that the bubbling of gas through a liquid develops, as far as visual observation is concerned, in the same way as the boiling process, i.e., nucleate, developed, and film boiling follow one another in the region of the wall.

The first results of our attempts to obtain a direct quantitative check on this analogy were published in [4].

The investigations described in this paper were carried out on apparatus which differs from that described in [4] only in that the working vessel permitted operation at higher pressures. We used six liquids (distilled water, ethyl and methyl, alcohols, benzene, acetone, and carbon tetrachloride) and four gases (hydrogen, helium, nitrogen, and argon).

The tests were concerned with the investigation of the dependence of the hydrodynamic stability criterion of the two-phase boundary layer on the particular conditions under which the boiling process takes place. The results were compared with data on the critical conditions of boiling. At the same time, we investigated the saturation of the boundary layer by gas during bubbling and by vapor during boiling.

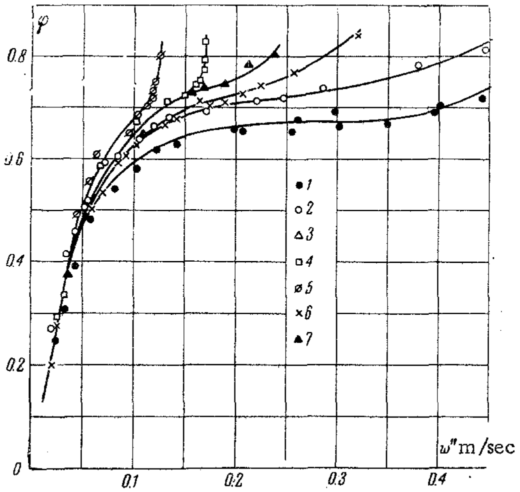

Fig. 1. Variation of gas content with load; the points correspond to the following pressures: 1) 58.7, 2) 108, 3) 157, 4) 304, 5) 402 [10^4 N/m^2].

The critical conditions were determined by measuring the electrical resistance of the two-phase boundary layer during the bubbling and boiling of electrically conducting liquids and from the dependence of the volume flowrate of gas on the pressure difference in the porous plate-boundary layer system during the bubbling of electrically non-conducting liquids [3].

Measurement of the electrical resistance of the two-phase boundary layer provides data on its degree of saturation by the gas or vapor and permits calculation of the law governing the variation of the gas (vapor) content.

Notation

γ	- specific gravity,	φ	- gas content,
σ	- surface tension,	p	- pressure,
r	- latent heat of vaporation,	R	- radius of a bubble,
q	- heat flowrate,	μ	- molecular weight of gas,
w	- specific velocity,	B	- universal gas constant,
n	- number of vaporization centers,	T	- absolute temperature,
F	- surface area,	I	- current passing through the boundary layer.

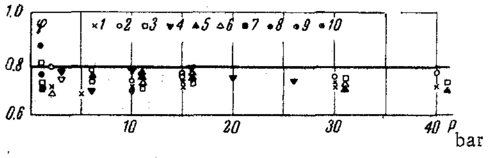

Fig. 2. Curves $\varphi_* = f(\mathrm{p})$ for boiling and bubbling. Bubbling through water at 9.8 • 10 N/m^2: the points represent: 1) N; 2) Ar; 3) He; 4) H; 5) Ar; 6) N; 7) He with ethanol. Boiling: the points represent: 8) water, 9.8 • 10^4 N/m^2; 9) ethanol, 9.8 • 10^4 N/m^2; 10) ethanol, 9.8 • 10^4 n/m^2.

The indices denote: ′—values applying to the liquid; ″—values applying to the vapor (gas); *—critical values; 0—initial values.

The hydrodynamic stability criteria were obtained by processing the experimental data using the Kutateladze equations

$$k = \frac{w_*'' \sqrt{\gamma''}}{[g^2\sigma(\gamma' - \gamma'')]^{1/4}} \quad \text{(during bubbling)},$$

$$k = \frac{q_*}{r\sqrt{g\gamma''}\,[\sigma(\gamma' - \gamma'')]^{1/4}} \quad \text{(during boiling)}.$$

	k_1	k_2
Distillate	0.161 0.166 0.158	0.156 0.165 0.177
Methyl alcohol	0.142 0.139 0.145	0.145 0.158 0.148
Ethyl alcohol	0.142 0.136 0.139 0.140	0.130 0.141 0.145 0.155
Acetone (chem. pure)	0.154 0.158 0.156	0.150 0.137 —
Benzene	0.163 0.166	0.176 —
CCl$_4$	0.177 0.173	— 0.190

The gas (vapor) content of the boundary layer was calculated from the equation

$$\varphi = 1 - \frac{I}{I_0}. \quad (2)$$

The first series of tests was carried out at atmospheric pressure.

In bubbling tests nitrogen at 18–20° C was used.

The measurements of the gas content in the boundary layer showed that there are two stages of saturation during both boiling and bubbling.

During the first stage bubbles are formed and rise in the liquid without marked interaction between individual bubbles, while the gas content markedly changes with load [4]. This region (the region of free rising of the bubbles) is independent of the pressure and is limited by the specific velocities of the light component $w'' \approx 0.10$–0.15 m/ /sec. At this load the gas content of the two-phase boundary layer reaches its maximum value. The second stage of saturation of the boundary layer by gas (vapor) is a region of intense interaction between bubbles. In this region an increase of load causes an insignificant change of the gas content, which does not exceed 15%.

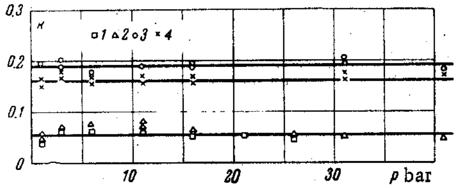

Fig. 3. Dependence of the stability criterion k on the pressure p for distilled water: the points correspond to 1) H, 2) He, 3) Ar, 4) N.

Calculations show that the gas content is determined by the ratio

$$\varphi = \frac{\pi}{6}\frac{n}{F}D_0^2 .$$

Here n/F is the specific density of centers, sources of bubbles, and D_0 is the diameter of the bubbles.

In the region of free motion of the bubbles the gas content is determined by the values of n/F, since here D_0 = const. In the region of intense bubble interaction the determining quantity is the diameter of the bubbles, because n/F ≈ const.

The tests showed that the character of saturation of the boundary layer is retained despite an increase of pressure, but the region of intense interaction of the bubbles shrinks, i.e., the critical velocity of the gaseous phase decreases (w_*'' follows a hyperbolic law as predicted by theory).

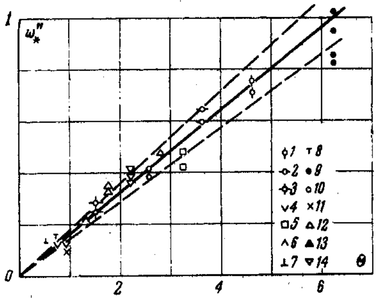

Fig. 4. $w_*'' = f(\Theta)$ curves. Bubbling: the points represent: 1, 2, 3, 4) Water-nitrogen (9.8, 19.6, 98, 392) • 10^4 N/m^2; 5, 6, 7) ethanol-argon (9.8, 49, 294) • • 10^4 N/m^2; 8) water-argon 294 • 10^4 N/m^2. Boiling: the points represent: 9) water 9.8 • 10^4 N/m^2; 10) ethanol 9.8 • • 10^4 N/m^2; 11) methanol 9.8 • 10^4 N/ /m^2; 12) pentane 9.8 • 10^4 N/m^2; 13) heptane 9.8 • 10^4 N/m^2; 14) benzene 9.8 • 10^4 N/m^2.

Figure 1 shows the variation of gas content with increasing load for various pressures during the bubbling of nitrogen through distilled water. It can be seen that the gas content in the second region is different for different pressures, but the differences are small. For this reason the critical value of the gas content φ_* remains constant and is not affected by pressure. Tests show that this value is dependent on the type of bubbling gas and on the type of liquid through which it is passed. Figure 2 gives the data on the critical value of the gas content for two different liquids through which four different gases are passed. It also contains the experimental data on the boiling of ethyl alcohol and distilled water.

The processing of the experimental data on the critical conditions of boiling and bubbling showed that in the case of bubbling the criterion of stability $k = k_1$ for all gas-liquid pairs processed is close to the value $k = k_2$ observed for boiling of the same liquids (see table).

During the bubbling of a gas through a porous plate crisis occurs, i.e., the structure of the boundary layer changes, at zero temperature difference between the surface of the porous plate and the liquid. Nevertheless, the stability criterion was practically the same for boiling as for bubbling. Consequently, it may be stated that during boiling the temperature of the surface is not a determining factor. On the contrary, the temperature level of the heating surface is a direct consequence of the rate of cooling, i.e., of the intensity of motion of the liquid. The distortion of the thermodynamic conditions of heat transfer from the heating surface existing during nucleate boiling results in an accumulation of heat by the plate and causes its heating.

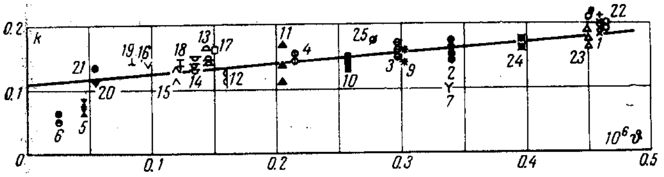

Fig. 5. The relation $k = f(\vartheta)$ according to (3). Bubbling: the points represent: 1) argon-water; 2) nitrogen-water; 3) argon-ethanol; 4) nitrogen-ethanol; 5) helium-water; 6) hydrogen-water; 7) nitrogen-liquid [5]; 8) argon-liquid [5]; 9) air-water [7]. Boiling: the points represent: 10, 11) ethanol(9.8 • 10^4, 9.8 • 10^4) N/m^2; 12, 13, 14, 15, 16) methanol (98, 196, 294, 392.5, 588) • 10^4 N/m^2; 17, 18, 19, 20, 21) water (9.8, 440, 540, 1860.5, 2060) • 10^4 N/m^2; 22) pentane 9.8 • • 10^4 N/m^2; 23) benzene 9.8 • 10^4; 24) propane 9.8 • 10^4 N/m^2; 25) heptane 9.8 • 10^4 N/m^2.

During the blowing of various gases (hydrogen, helium, nitrogen, and argon) through the same liquid at a constant pressure a dependence of the criterion of hydrodynamic stability on the nature of the bubbling gas and the liquid through which it is passed is observed.

A similar relationship was observed in [5] in which the value k = 0.10 was found for the pair nitrogen-water, while for the pair argon-water the corresponding value was k = 0.21. Since the gases have different specific and molecular weights, we carried out a further series of tests at high pressure (up to 40 bars) in order to determine the physical properties whose variation causes the change of k.

The results of tests with distilled water are given in Fig. 3. From this graph it can be seen that the criterion of stability of bubbling, as well as for boiling, is independent of pressure and, consequently, of the specific gravity[1] of the gas, provided that this is varied by means of pressure. However, it may be seen that the differences in the criteria of hydrodynamic stability for the various gases are retained.

Thus, the variations of k are connected not with the change of specific gravity but with certain other physical properties of the gas-liquid pair (molecular weight, velocity, and size of molecules).

Figure 4 gives the experimental values

$$w_*'' = f(\theta), \qquad \theta = \left(\frac{g^2\sigma(\gamma' - \gamma'')}{\gamma''^2}\right)^{1/4}.$$

The tangent of the angle of incidence of the averaging curve is the criterion of hydrodynamic stability; its value is 0.16. Figure 4 shows that there are deviations from the average values both for boiling and for bubbling of the various systems, but these do not exceed 10–15%.

In view of the analogy between the processes of boiling and bubbling observed above, it may be assumed that the variations of the criterion of hydrodynamic stability during the boiling of various liquids and during the bubbling of various gases through such liquids observed above are due to the same causes, i.e., to factors directly associated with the molecular weight of the vapor enclosed in the bubble.

Equation (1) for the calculation of the stability criterion takes the Laplace pressure directly into account; it is therefore worthwhile to consider whether the variations of the Thompson pressure difference

$$\Delta p'' \sim \frac{\sigma}{R}\,\frac{\gamma''}{\gamma' - \gamma''},$$

which is produced by the deviation of the actual shape of the bubble from the spherical have any effect. In this case the effect of the variations of this quantity must depend on the absolute pressure level, i.e., the following parameter can be introduced:

$$\Pi = \frac{\Delta p''}{p} \sim \frac{\gamma''}{p}\left(\frac{\sigma}{\gamma' - \gamma''}\right)^{1/2}.$$

The processing of the experimental data on the bubbling of gases through a porous plate and of the data on boiling obtained by various workers (Kazakova, Morozov, Bobrovich) for a wide range of pressures (up to $206 \cdot 10^5\ \mathrm{N/m^2}$) is shown in Fig. 5. It may be seen that all points for boiling and bubbling are satisfactorily grouped about the straight line

$$k = 0.11 + 1.58 \cdot 10^5 \vartheta \left(\vartheta = \frac{\gamma''}{p}\left(\frac{\sigma}{\gamma' - \gamma''}\right)^{1/2}\right). \qquad (3)$$

Here p is taken in $\mathrm{N/m^2}$ and γ in $\mathrm{N/m^3}$.

A marked deviation from the general relationship is observed, as before, in tests on bubbling hydrogen and helium through distilled water.

By the use of the Clapeyron equation the relation (3) can be represented in the following form:

$$k = 0.11 + 1.58 \cdot 10^5 \frac{\mu}{BT}\left(\frac{\sigma}{\gamma' - \gamma''}\right)^{1/2} (\mu \text{ is the molecular weight of gas}). \qquad (4)$$

Equation (4) shows the independence of the criterion of hydrodynamic stability on pressure, which was observed in tests. Equation (4) also shows that k is independent of the viscosity of the liquid.

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20 July 1965 Novosibirsk