SUPERHEAT OF HEAT-EXCHANGE SURFACE IN FIRST BOILING CRISIS IN FREE-CONVECTION CONDITIONS

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A cavitation model of formation of vapor films in transition boiling is proposed; this model reveals the main features that determine the superheats at critical heat fluxes.

In [1] the relation $q(\Delta T)$ in liquid boiling was clearly determined for the first time and the existence of two extrema was discovered. The maximum heat flux (point C in Fig. 1) corresponds to the cessation of the intense heat transfer characteristic of nucleate boiling and is called the first critical heat flux. The minimum at point E corresponds to the onset of developed film boiling. Transition boiling (curve CE) is characterized by a space – time alternation of nucleate and film boiling on the given heating surface. The portion DF of the single-phase convection curve corresponds to the heat fluxes and, accordingly, to the superheats at which vapor-phase formation after single-phase convection leads to the formation of a stable vapor film on the heat-exchange surface, i.e., to the degeneration of nucleate boiling. The portion CD of the transition-boiling curve ($q_* < q_{\mathrm{cr\,us}} < q_{\mathrm{cr}1}$, $\Delta T_{\mathrm{cr}1} < \Delta T_{\mathrm{cr\,us}} < \Delta T_*$) corresponds to the critical heat fluxes for unstable boiling on surfaces depleted of nucleation sites, which were experimentally investigated in [2, 3]. Here q_* and ΔT_* are the minimum heat flux and superheat at which single-phase convection can change directly to film boiling, bypassing the nucleate boiling regime.

According to the hydrodynamic theory of heat-transfer crises [4], the transition from nucleate to film boiling (point C) is due to radical alteration of the hydrodynamics of the two-phase boundary layer, leading to a change in the heat-removal mechanism. The stability criterion obtained for the critical heat flux in this paper satisfactorily describes the experiments and allows the prediction of previously unknown effects.

Another important parameter of the heat-transfer crisis in boiling liquids is the heating-surface superheat relative to the saturation temperature $\Delta T_{\mathrm{cr}1}$ at which a stable vapor film is formed after nucleate boiling. The factors determining the value of this quantity have not yet been determined.

Kutateladze [5] found that developed nucleate boiling, which is characterized by rapid increase in the heat-transfer coefficient with increase in heat-flux density, is followed by a special subcritical boiling regime in which the heat-transfer rate is practically constant. In Fig. 1 the corresponding portion of the $q(\Delta T)$ curve lies between the points B and C. The existence of a regime with a practically constant heat-transfer rate was subsequently discovered in experiments on the bubbling of gas into a liquid through a microporous surface [6].

Thus, the first heat-transfer crisis in boiling occurs when the law governing the heat-transfer rate differs from that which operates in developed nucleate boiling and, hence, the true wall superheat when $q = q_{\mathrm{cr}1}$ is greater than in developed nucleate boiling. Consequently, the method of calculating $\Delta T_{\mathrm{cr}1}$ [7] based on the use of the equations for heat transfer in developed nucleate boiling and the critical heat flux does not always

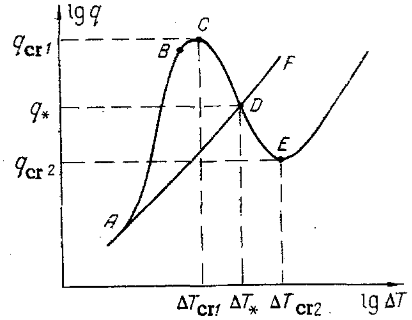

Fig. 1. Heat-removal regimes for vaporization in free-convection conditions.

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give correct results. Estimates of ΔT_{cr1} for the high-pressure region were made on the basis of a thermodynamic model of the boiling crisis in [8] and on the basis of a thermal model in [9].

Below we present a model of vapor-film formation in transition boiling, based on the decisive role of hydrodynamic disturbances in the boiling superheated layer of liquid near the wall.

Experiments on boiling on surfaces with a greatly reduced number of nucleation sites [3] allowed these investigations to be made in the region of superheats corresponding to transition boiling. The investigations showed that the mechanism of vapor-film formation in this regime is of a cavitational nature. There is avalanchelike production of microbubbles in the vicinity of the heater, due to disturbances introduced into the metastable superheated layer of liquid by vapor bubbles, and the subsequent formation of a vapor film.

Since the boiling crises are the boundary values of the transition-boiling curve we can naturally assume that the cavitational mechanism of vapor-film formation operates in the immediate vicinity of the first heat-transfer crisis in the boiling liquid (approach to crisis from the transition boiling side of the curve).

We consider an arbitrary volume V_* of superheated liquid in a boiling wall layer. We estimate the mean kinetic energy of pulsational motion of the liquid in this volume as $\rho' v_*^2 V_*$. Let n nucleation sites be formed in the considered volume of liquid. The work of their formation is then equal to $n\sigma R_*^2$ in order of magnitude.

As a criterion of vapor-film formation when $q \simeq q_{cr1}$, $\Delta T \simeq \Delta T_{cr1}$, we introduce the quantity

$$n\sigma R_*^2/(\rho' v_*^2 V_*) = \text{const}. \tag{1}$$

On the basis of Hsu's hypothesis [10] of a relation between the sizes of the nuclei and the mean thickness of the boundary layer, we estimate the radius of the nucleus for developed boiling conditions as

$$R_* \sim \delta. \tag{2}$$

Using the results of [11], we write

$$\delta \sim \nu / v_*, \tag{3}$$

$$v_* \sim \lambda \Delta T_{cr}^2 / (\sigma T''). \tag{4}$$

It is obvious that the number of nucleation sites n is directly proportional to the volume V_*. Since in the present model vapor-film formation is related to the formation of vapor bubbles within the superheated wall layer the number of nuclei per unit volume n/V_* can be determined in terms of the strength characteristics of the liquid. Such a characteristic is the critical cavitation nucleus which, as distinct from the vaporization nucleus R_*, is not a function of the superheat. Taking the radius of the critical cavitation nucleus (Fisher [12]) as a linear scale, we can write

$$n/V_* \sim \{\sigma/[kT'' \ln (NkT''/h)]\}^{3/2}. \tag{5}$$

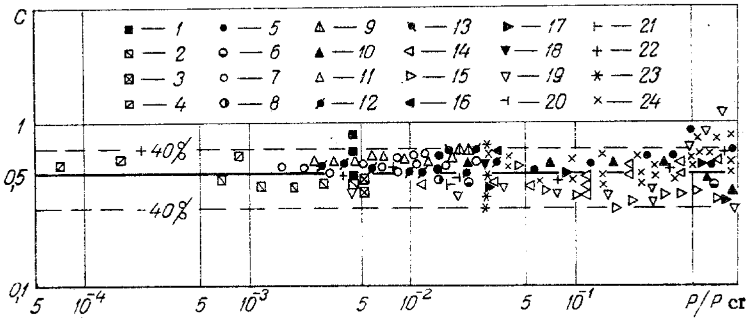

Fig. 2. Correlation of experimental data by Eq. (6). H_2O: 1) [13]; 2) [16]; 3) [15]; 4) [17]. C_2H_6O: 5) [18]; 6) [8]; 7) author's data; 8) [11]. C_6H_6: 9) [13]; 10) [18]; 11) author's data. CCl_4: 12) author's data; 13) [13]. N_2: 14) [19]; 15) [20]; 16) [21]; 17) [22]; 18) [23]. O_2: 19) [19]; 20) [24]; 21) [25]. H_2: 22) [22]. $C_2F_3Cl_3$: 23) [14]. C_5H_{12}: 24) [8]. $C = \Delta T_{cr1} \Big/ \left(\frac{\sigma T}{\lambda}\right)^{1/2} \left(\frac{\sigma}{\rho}\right)^{1/8} \nu^{1/4} \left(\frac{\sigma}{kT \ln \frac{NkT}{h}}\right)^{3/16}$

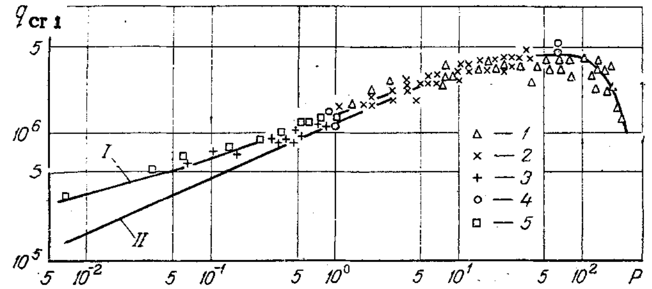

Fig. 3. Experimental q_{cr1} data for water: 1) [26]; 2) [27]; 3) [28]; 4) [29]; 5) [30]. I) Calculation from Eq. (10); II) from (9); q_{cr1}, W/m^2; P, bar.

Substituting (2)-(5) in (1) and changing the subject to ΔT_{cr1}, we obtain

$$\Delta T_{cr\,1} = \text{const}\,(\sigma T''/\lambda)^{1/2}\,\nu^{1/4}\,(\sigma/\rho')^{1/8}\,\{\sigma/[kT''\ln(NkT''/h)]\}^{3/16}. \tag{6}$$

The superheats in boiling crises have not yet been adequately investigated experimentally in comparison with the critical heat fluxes. The effect on ΔT_{cr1} of the material of the heat-transfer surface and its roughness, which may be significant, as was shown in [13, 14], for instance, has not been determined.

In Fig. 2 the experimental data of different authors [8, 13-25] for the critical superheats in the boiling of various liquids are correlated. It is apparent that the data are given, with a scatter of ±40%, by relation (6) with a constant equal to 0.5 in the entire investigated pressure range. The scatter of the ΔT_{cr1} data is due not only to the difference in experimental procedures, but also to the effect of the material of the heat-transfer surface and its roughness, which is not taken into account in expression (6).

Having expression (6) for the critical superheat we can estimate the fraction of heat brought from the heat-transfer surface through the liquid at heat flux close to the conditions of the developed hydrodynamic crisis [11]:

$$q_L \sim \lambda\Delta T_{cr\,1}/\delta \sim (T''\lambda\sigma)^{1/2}\,\nu^{-1/4}\,(\sigma/\rho')^{3/8}\,\{\sigma/[kT''\ln(NkT''/h)]\}^{9/16}. \tag{7}$$

We define the total heat flux in the case of the crisis in pool boiling as

$$q_{cr1} = q_{crh} + q_L, \tag{8}$$

where

$$q_{crh} = kr\rho''^{1/2}\,[g\sigma(\rho' - \rho'')]^{1/4} \tag{9}$$

is the critical heat flux due to the purely hydrodynamic mechanism [4].

Figure 3 compares the experimental data for the first critical heat flux density in pool boiling of water with calculations (curve I) from the formula

$$q_{cr} = 0.14\,r\rho''^{1/2}\,[g\sigma(\rho' - \rho'')]^{1/4} + 10^{-5}\,(\sigma\lambda T'')^{1/2}\,\nu^{-1/4}\,(\sigma/\rho')^{3/8}\,\{\sigma/[kT''\ln(NkT''/h)]\}^{9/16} \tag{10}$$

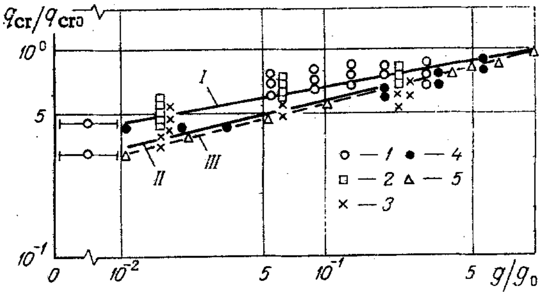

Fig. 4. Critical heat flux as function of gravitational acceleration. Calculation: I) from (10) for H_2O; II) from (10) for N_2, O_2; III) from (9): 1) H_2O [32]; 2, 3) H_2O [31]; 4) N_2 [21]; 5) O_2 [33].

and (9) (curve II). It is apparent that the second term in expression (10) takes into account the removal of heat through the liquid, which becomes significant at reduced pressures.

The experimental investigations of different authors, cited in [31], on the effect of gravitational forces on the first critical heat flux showed that relation (9) satisfactorily represents the experiments when $g > 0.1g_0$. Here $g_0 = 9.81$ m/sec^2. When $g < 0.1g_0$, however, the experiments give a weaker dependence of q_{cr_1} on g and when $g \to 0$, q_{cr_1} tends to a nonzero value.

In Fig. 4 data on the critical heat fluxes in the boiling of water, nitrogen, and oxygen are compared with calculations from formulas (9) and (10) in the reduced gravity range. Here q_{cr0} is the critical heat flux when $g = g_0$. It is apparent that the introduction of a term independent of g into the expression for q_{cr1}, formula (10), provides a more accurate characterization of the dependence of q_{cr1} on the gravitational constant when $g/g_0 < 0.1$.

NOTATION

q, heat flux; q_{cr1}, critical heat flux; $q_{cr\,us}$, critical heat flux in unsteady boiling; q_*, minimum heat flux for transition from single-phase convection to film boiling; ΔT, surface superheat relative to saturation temperature; ΔT_{cr1}, surface superheat in first boiling crisis; $\Delta T_{cr\,us}$, surface superheat in crisis after unstable boiling; ΔT_*, minimum superheat for transition from single-phase convection to film boiling; T'', saturation temperature; V_*, volume of liquid in superheated wall layer; v_*, mean pulsation velocity of liquid due to growing vapor bubbles; R_*, radius of vapor-phase nucleus in developed nucleate boiling; δ, mean thickness of boundary layer; r, heat of vaporization; σ, coefficient of surface tension; λ, thermal conductivity of liquid; ν, kinematic viscosity of liquid; ρ', ρ'', densities of liquid and vapor; k, Boltzmann constant; N, Avogadro's number; h, Planck's constant; g, gravitational acceleration.

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STABILITY OF OPERATION OF A STEAM-GENERATING CHANNEL FROM LOW-FREQUENCY PRESSURE FLUCTUATIONS

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The onset and development of vibrational instability in a steam-generating channel is investigated by an analysis of the fluctuations of pressure and temperature of the transfer fluid.

Experience in the operation of heat-power installations of the channel type shows that the flow of transfer fluid can become unstable, with concomitant fluctuations of the flow rate, pressure, and channel wall temperature [1, 2]. Depending on the hydrodynamic characteristic of the channel, the heat load, and the parameters of the transfer fluid the instability can be aperiodic, manifested in a variable hydrodynamic characteristic of the channel, or oscillatory.

Aperiodic instability arises in a channel with low hydraulic resistance and it can usually be eliminated by increasing the channel resistance by the installation of baffle plates. Oscillatory instability is characterized by quasiperiodic changes in the thermophysical parameters of the flow, occurs more often than aperiodic instability, and is not always eliminated by simple throttling [3]. Flow instability adversely affects heat transfer and promotes the onset of the heat-transfer crisis.

An important factor for improving the reliability and safety of operation of channel-type heat-power installations is early prediction of hydrodynamic instability of the steam-generating channels. For instance, it was shown in [4] that the spectrum of steam-content fluctuations completely determines the stability reserve of the channel and can serve as an indicator of the onset of hydrodynamic instabilities. Our investigations of oscillatory instability were made on a laboratory apparatus consisting of a closed circulation loop with a constant-level tank containing outgassed distilled water (Fig. 1a). Pump 1 drives water from the thermostat 2 through a flowmeter 3, the working channel 4, and a glass inspection tube 5. Power from an ac line, monitored by the measuring unit 8, is delivered to the working channel 4 through an autotransformer 6 and power transformer 7. During the measurements the temperature of the fluid at the entrance and exit of the working channel, and also the pressure at its exit, were recorded.

The temperature-measuring circuit includes a Chromel – Copel thermocouple 9 with time constant 0.2 sec, placed in the flow of fluid, a dc amplifier 10, and a compensator 11 for the constant component of the signal, which increases the sensitivity of the system.

The pressure is measured with a specially designed mechanotron transducer 12 (Fig. 1b), based on a 6MKh2B mechanotron, with a power unit 13. The wide dynamic range (from 10 N/m^2 to 10^4 N/m^2) and the 0- to 100-Hz transmission band allow this transducer to be used for measurement of static pressure or pressure fluctuations.

The signal of the measuring circuits was recorded by a multichannel recorder 14.

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