CAVITATION BOILING OF VARIOUS LIQUIDS

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By studying transient boiling of liquids not heated to the saturation temperature and noise-type boiling of He-II a hypothesis is developed regarding the identity of these phenomena.

The transition region is that part of the boiling curve on which the thermal flux density q decreases with increase in temperature head $\Delta T_w = T_w - T_s$. Many studies, a review of which was presented by the present authors in [1], have considered this boiling regime. The overwhelming majority of investigators have studied transient boiling of saturated liquids. Over the course of several years the authors have investigated heat exchange and the physical mechanism of transient boiling of liquids not heated to the saturation temperature. At high values of underheating $\Delta T_u = T_s - T_l$ an anomalous dependence of thermal flux density on temperature head was observed. In contrast to the normal boiling curve (Fig. 1, ΔT_u = 0°K), where there is a single maximum in thermal flux, with respect to the temperature head in the transition region a secondary q maximum appears (Fig. 1, ΔT_u = 30°K). In this case boiling is accompanied by strong acoustical effects of an explosive nature. We have termed such boiling cavitation boiling. The character of such boiling is very similar to noise-boiling of He-II.

The present study will offer results of an experimental investigation of heat transport and the physical mechanism of cavitation boiling in water, ethanol, and freon-113, and compare them to data obtained in a study of noise film boiling of superfluid liquid helium.

The experimental study of transition boiling of water, ethanol, and freon-113 was carried out in a thermostatic chamber 250 mm in diameter and 200 mm high, provided with a system for automatic maintenance of a given liquid temperature. A cylindrical piece of copper 20 mm in diameter on which the boiling took place was installed at the center of the bottom of the thermostatic vessel. Heat was supplied from a massive heatsink heated by a high power electric filament. Precise regulation of the heat flux to stabilize the process after the transition through q_{max} was preformed by a draft of gaseous nitrogen through special channels in the copper.

The thermal flux density was determined by differential thermocouples with working junctions located at depths of 5 and 10 mm from the surface being heated. The wall temperature T_w was measured by Chromel—alumel thermocouples with electrode diameter of 0.1 mm, with working junctions soldered flush to the heating surface and leads passing through drillings in

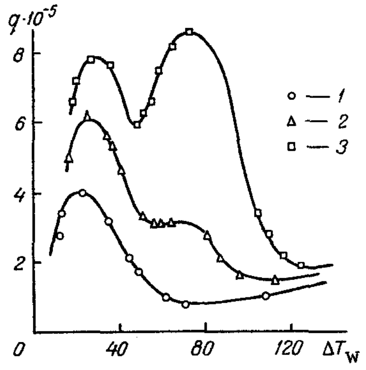

Fig. 1. Thermal flux density vs temperature head and liquid underheating below saturation temperature (copper—ethanol): 1) ΔT_u = 0°K; 2) 18; 3) 30. q, W/m²; ΔT_w, °K.

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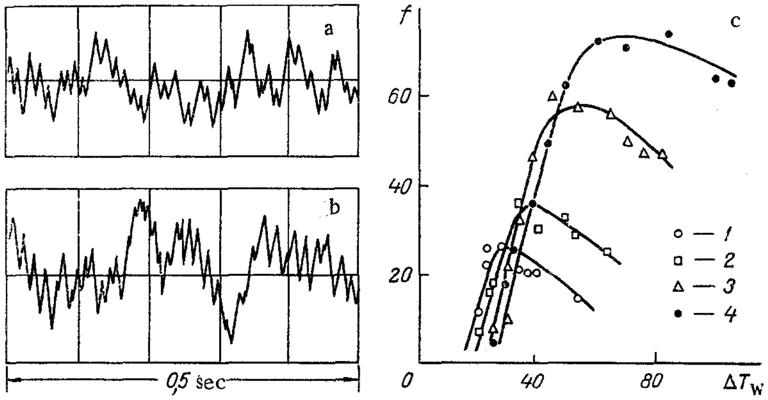

Fig. 2. Time characteristics of heat-exchange mechanism in cavitation and noise boiling: a) thermogram of wall temperature oscillations for cavitation boiling (copper—water, $\Delta T_u = 24°K$, $\Delta T_w = 51°K$); b) thermogram of wall temperature oscillations for He-II noise boiling [7] (Nichrome—He-II, $T_s = 1.91°K$, $q = 4.5\ W/cm^2$); c) frequency of T_w oscillations vs temperature head and liquid underheating (copper—freon-113; 1) $\Delta T_u = 0°K$; 2) 24; 3) 36; 4) 54). f, Hz.

the copper. These thermocouples were used to study oscillations of wall temperature and to determine the mean durations of contact with liquid and vapor (it was assumed that an abrupt drop in temperature corresponded to wall contact with the liquid, while during the period of wall contact with the vapor T_w increased). The uncertainty in thermal flux determination was within the limits of ±20%. The duration of contact of the various phases with the wall was determined with a uncertainty not exceeding 0.5-1 msec.

The experiments showed that the minimum value of underheating at which cavitation boiling was observed depended on the type of liquid used. With increase in underheating (Fig. 1) in the transition boiling region a region of constant thermal flux appears first, and then with further increase in ΔT_u an additional maximum in thermal flux occurs. For ethanol, at $\Delta T_u = 30°K$ in the cavitation boiling region $q_{max} > q_{cr1}$, while for boiling in the transition region of freon-113 at an underheat $\Delta T_u = 54°K$ no clearly expressed secondary maximum was observed in the thermal flux density.

In analyzing pulsations in wall temperature T_w it was established that for the cavitation boiling region a higher frequency of change of the phase in contact with the heating surface as compared to transition boiling of the saturated liquid (Fig. 2c) was characteristic. The mean duration of vapor isolation of the wall t_v for cavitation boiling remains practically unchanged with increase in temperature head, while for transition boiling of the saturated and slightly underheated liquid t_v increases monotonically with increase in ΔT_w. Increase in liquid underheating from the saturation temperature increases the mean time of liquid contact with the wall over the entire temperature head range of the transient boiling region [2]. Visual and acoustic observations revealed that for cavitation boiling the spatial scale of vapor formations on the heating surface decreases abruptly, simultaneously with the onset of intense noise. The entire surface is covered by a set of pulsating films with linear dimensions of 0.2-1 mm.

Noise boiling of liquid He-II is a specific phenomenon which has up to the present been related to film boiling. The visual observations of the present authors, agreeing with data of a number of other studies, have shown that in this regime in contrast to noiseless film boiling the vapor film is most unstable and constantly decays into individual bubbles which first grow and then collapse. In its external attributes noise boiling of He-II, like transition boiling of greatly underheated liquids, recalls cavitation. Near the heating surface the growing and collapsing vapor bubbles form a specific vapor-liquid layer, the mean thickness of which increases with increase in the thermal flux density q_w (for constant temperature of the liquid helium bath and immersion depth of the boiling surface).

Study of the boundaries of the noise boiling region confirmed the principles established in [3-7]. For low immersion depth of the boiling surface H noise boiling does not develop

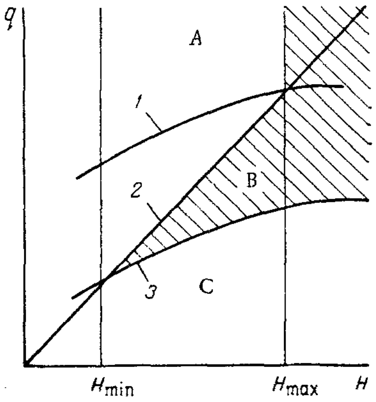

Fig. 3. Boundaries of noise and noiseless film boiling of He-II [5]: 1) $q_{max} = f(H)$; 2) $q_i = f(H)$; 3) $q_{min} = f(H)$; A) noiseless boiling region; B) noise boiling; C) filmless.

(similarly to the way in which at low underheating ΔT_m cavitation boiling of water, ethanol, and freon-113 is not observed). Beginning at some minimum depth H_{min}, which is dependent on liquid helium bath temperature and the dimensions of the heating surface, the existence of noise boiling becomes possible. With further increase in immersion depth the region of q_w values over which noise boiling of He-II is observed expands. Analogously, with increase in underheating ΔT_u the range of temperature heads over which cavitation boiling of conventional liquids occurs expands.

Temperature pulsations of the heating surface during boiling of superfluid helium were studied in [7]. The change in wall temperature during noise boiling (Fig. 2b) is of the same character as that in cavitation boiling of high boiling point liquids (Fig. 2a). According to the data of [7], the frequency of temperature pulsation for noise boiling of He-II increases monotonically with increase in immersion depth of the heating surface for constant values of the helium bath temperature and thermal flux density. Similarly, for cavitation boiling of conventional liquids the frequency of heating surface temperature pulsations increases with increase in underheating for constant mean wall temperature (Fig. 2c).

Thus, there is much in common between noise boiling of He-II and cavitation boiling of water, ethanol, and freon-113. This permits the proportion that one and the same physical mechanism is the basis of these phenomena.

Results of visual, photographic, and thermometric studies of the physical mechanism of He-II noise boiling and cavitation boiling of normal liquids indicates that sequential contact of every portion of the heating surface first with liquid, then with the vapor phase of the boiling medium is characteristic.

In cavitation boiling of water and similar materials in the period of liquid contact with the heating surface a layer of superheated liquid is formed, in which vapor bubbles form and glow. At a high temperature head, which determines the amount the liquid is heated, the bubbles grow at a rapid rate, setting into motion the surrounding layers of liquid. When the bubble diameter exceeds the thickness of the overheated layer, intense condensation of vapor begins on that portion of the bubble surface which is in contact with the underheated liquid. However, inertial motion of the liquid layers captured by the bubble produces a further increase in bubble volume. As a result the pressure within the bubble decreases and the process continues as the cavitation: after the inertial force comes into equilibrium with the increasing pressure change, the vapor cavity begins to collapse rapidly. This leads to an intense dynamic collision of liquid with the wall, producing a local pressure increase and spreading of the liquid over the wall. This process then repeats periodically.

One of the specific features of liquid superfluid helium is its extremely high thermal conductivity, because of which the liquid temperature at any immersion depth H is practically equal to the saturation temperature T_s corresponding to the pressure P_0 on the free surface. Upon immersion of the heating surface to a depth H the pressure $P_H = P_0 + \rho gH$ corresponds to a saturation temperature $T_i > T_s$. Thus, at a depth H at thermodynamic equilibrium on the vapor–liquid phase boundary there exists a temperature head $\Delta T_i = T_i - T_s$, which can be considered an analog of liquid underheating (quasiunderheating). As was shown in [6, 7]. for noiseless film boiling of He-II to maintain the temperature head ΔT_i on the external boundary of the vapor film a thermal flux density q_i proportional to the immersion depth H is required. At a low depth where the minimum thermal flux density in the film boiling region q_{min} satisfies the condition $q_{min} \gtrsim q_i$, the heat removed from the wall is sufficient to maintain the

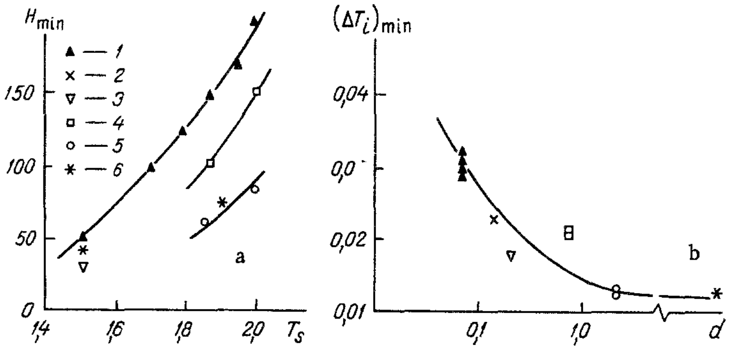

Fig. 4. Lower limit for development of He-II noise film bliling: a) H_{min} vs He-II bath temperature and heater surface diameter; b) $(\Delta T_i)_{min}$ vs heater surface diameter. 1) d = 0.0762 mm [2]; 2) 0.125 [3]; 3) 0.2 [3]; 4) 0.8 [5]; 5) 2 [5]; 6) a × b = 6.4 mm², planar surface [5]. T_s) $(\Delta T_i)_{min}$, °K; d, H) mm.

temperature head ΔT_i, and noise boiling does not develop (Fig. 3). At a greater depth H, where $q_{min} < q_i$, for a thermal flux $q_s < q_i$ the quantity of heat supplied to the liquid boundary proves insufficient to maintain the temperature head ΔT_i. This leads to vapor condensation on the interphase boundary, decrease in pressure in the vapor film, and subsequent cavitation collapse of the latter. Upon contact of the liquid helium with the overheated wall new vapor formations develop, which first grow and then collapse under the influence of condensation. Thus the mechanism of noise boiling is analogous to that of cavitation boiling with the sole difference that for normal liquids the dominant role in the process is played by underheating, while for He-II the temperature head ΔT_i (quasiunderheating) is important.

However even with the identical mechanism of He-II noise boiling and cavitation boiling of normal liquids the development of these processes is accompanied by different changes in heat liberation. The intensity of heat exchange in cavitation boiling of water, ethanol, and freon-113 increases due to increased turbulization of the liquid at its point of impact with the wall. On the other hand, in noise boiling of He-II a reduction in the intensity of heat exchange occurs, which can be explained by development of a poorly thermally conductive interlayer of He-I in the region of increased pressure produced by liquid braking on the heating surface.

With decrease in diameter of the cylindrical heater d contact of the liquid with the heated wall is made more difficult, and therefore noise boiling develops at higher values of minimum required quasiunderheating $(\Delta T_i)_{min}$, i.e., at a greater depth H_{min}. Data of various authors regarding the limit of existence of He-II noise boiling H_{min} as a function of liquid helium bath temperature T_s and heating surface diameter d are shown in Fig. 4a. For a given temperature T_s to each value of H_{min} there corresponds a quasiunderheating $(\Delta T_i)_{min}$ which can be determined from the saturation curve $P_s(T)$ for He-II with the algorithm $T_s \rightarrow P_0 \rightarrow P_u \rightarrow T_i \rightarrow \Delta T_i$. Results of such calculations are shown in Fig. 4b. It can be seen that each series of data obtained on one heating surface are grouped practically at a single point in coordinates $(\Delta T_i)_{min} = f(d)$. This indicates that use of the quasiunderheating $(\Delta T_i)_{min}$ permits description of the noise boiling boundary both with respect to liquid temperature T_s and immersion depth H, i.e., reduction in the number of independent variables.

NOTATION

q, specific heat flux; T, temperature; t, time; H, immersion depth of heating surface in liquid He-II; P, pressure; ρ, density; g, acceleration of gravity; f, oscillation frequency; d, diameter; $\Delta T_u = T_s - T_l$, liquid underheating from saturation temperature; $\Delta T_w = T_w - T_s$, temperature head. Subscripts: w, wall; v, vapor; u, underheat; l, liquid; s, saturation; max, maximum; min, minimum; i, at vapor-liquid phase boundary in He-II.

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CONDITIONS AND RATES OF HEAT TRANSFER DURING VAPORIZATION ON PROFILED SURFACES

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A relationship is given for calculating heat transfer during evaporation and boiling on profiled heating surfaces.

The problem of organizing vaporization processes on profiled heat-exchange surfaces is a timely one for various types of industrial equipment, and in particular in heat pipes of the so-called channel-capillary construction. The interest in such surfaces and their application for the intensification of transfer processes began a considerable time ago, since here microfilm evaporation is combined with acceptable hydrodynamic parameters (which are more favorable than in the case of porous structures.) However, the wide and effective introduction of profiled surfaces has not been possible because of the lack of information on the heat and mass transfer behavior under various conditions. Further extension of the investigations into transfer processes on channel-capillary structures facilitated carrying out work on heat pipes. The main results of this work can be characterized as follows.

1. The flow of the liquid has been determined to be laminar in channels of normal geometrical shapes under the influence of surface forces and the forces of gravity and friction, with the formation of menisci of cylindrical shapes [1-8].

2. The maximum heat flux is fixed by the known hydrodynamic limits on the operation of the heat pipe [1, 3, 6, 9].

3. There is no consensus of opinion as to the possible heat-transfer regimes or on the boundaries for the transition from one regime to another. The assumption that there is boiling of the liquid in the grooves is made in [6], and this is used as the basis for explaining the high heat-transfer rates. It is noted in [1] that boiling is not very probable in channels of such small dimensions, but on the other hand it was shown on the basis of an actual physical model that a high heat-transfer intensity can also be achieved during evaporation. Temperature fluctuations of the surface of an arterially grooved heat pipe with amplitudes of 150-250°K were noted in [6]. As the heat flux increased, the frequency of the fluctuations also increased, and then the fluctuations were no longer observed. The author did not explain the reason for the pulsations.

4. Even for the simplest evaporation regime there are essentially no experimental, design-analytical, or empirical relationships for calculating the thermal resistance which cover the ranges of the main factors needed in practice. The results of the experimental investigations have been treated differently by the authors, and the known solutions [1-4, 10-12] and the data on the thermal resistances of profiled surfaces [3-5, 7, 12] are of a partial nature only.

A group of investigations of the heat transfer processes in open capillary channels carried out in the OTIPP [Technological Institute of the Food Industry, Odessa] has shown that three vaporization regimes are possible: evaporative, evaporative-pulsating (quasievaporative), and boiling. The occurrence and coexistence of these regimes are governed mainly by the value of the heat flux, the heat-transfer medium, and the geometry of the surface. The evaporative regime has been stably observed on the plate L1 (Table 1), for which the length

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