EFFECT OF PROLONGED STAY OF THE HEAT-TRANSFER SURFACE IN WATER ON THE CRITICAL HEAT FLUX UNDER STEADY AND STEPWISE HEAT-RELEASE CONDITIONS

S. G. Obukhov

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The author presents results of experimental investigations of the effect of prolonged stay of the heat-transfer surface in water on the first critical density of the heat flux in boiling under steady and stepwise heat-release conditions.

There are problems of boiling heat transfer that, although rarely encountered in practice, are very important under certain extraordinary conditions. One of them is associated with studying the effect of the conditions of surface preparation on the critical heat flux q_{bl} and the intensity of bubble-boiling heat transfer. These quantities depend on many factors that are difficult to control and that determine the special properties of the interaction of the surface-liquid pair.

D. A. Labuntsov [1] noted that the effect on boiling heat transfer of such "weak" factors as small impurities of surface-active additions, contaminants, and small amounts of gases dissolved in the water, the special microgeometric features of the boiling surface due to the structure of the material and the technology of surface preparation and treatment, the absorption properties of the surface, etc. turns out to be much more significant than the action of such "strong" factors as the level of the gravitational-field strength, vibrations, and forced motion. In [2], it is stressed that "already the first publications of D. A. Labuntsov on the problems of bubble boiling present the fundamental proposition of the author that in the boiling of liquids that wet the surface the high intensity of heat transfer is governed mainly by intense pulsations of liquid particles directly at the heating surface."

In our opinion, it is precisely this circumstance that explains the fact of a strong effect of surface conditions, caused by the complex mechanism of interaction of the boiling liquid and the solid heating surface, on the integral characteristics of the boiling. The mutual effect of the boiling liquid and the heating surface, which is dynamic in character, explains the spread in experimental data, the failure to reproduce them, and the hysteresis of many characteristics of the boiling processes [3].

The effect of the time of surface operation on the critical heat flux q_{bl} is among the poorly studied problems of burnout although the presence of this action is beyond question [3-8]. However the authors of works in which such an effect is noted, explain lower q_{bl} for a "fresh" surface variously, singling out one or another aspect of this complex phenomenon: structural and chemical transformations in the heating surface associated with exoelectron emission because of thermocyclic oscillations [4]; separation of a scale layer that alters the boundary wetting angle [5]; deactivation of nucleation centers [6], etc. Unfortunately, there are no works in which the physical processes occurring in the period of "running-in" of the surface would ultimately be allowed for in design recommendations on the integral characteristics of boiling supported by a rather wide range of experimental data.

The practical value of investigating the effect of the time of surface operation in boiling is determined, first, by the methodological aspect of any experiment concerned with investigating boiling heat transfer since

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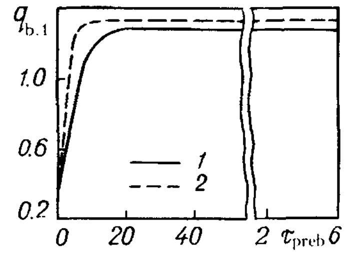
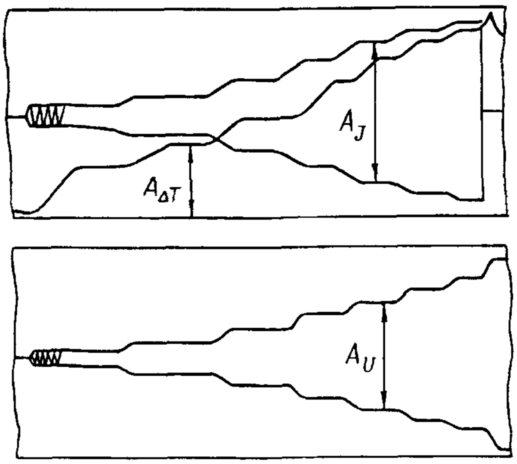


Fig. 1. Critical heat flux vs. time of preboiling with a load of 0.2–0.25 MW/m^2 in saturated water at atmospheric pressure: 1) distilled water (S = 2.5–3); 2) tap water (S = 60–80). q_{bl}, MW/m^2; τ_{preb}, min (h).

neglect of this problem leads to substantial errors in determination of q_{bl} and the heat-transfer coefficient α; second, the problem of the operating time of the heat-transfer surface under boiling conditions is very important in terms of the safety of thermal-power equipment in regulational and other work involving replacement of fuel elements and their reaching the operating regime with the rated heat power.

It is known that critical heat fluxes in bubble boiling that are stable over time are obtained after a certain service life. The running-in time depends on many factors, the main ones of which are the thermal load of preboiling, the pressure, the liquid-wall pair, and the number of virtual nucleation centers (i.e., the dimensions and range of microcracks and the degree of their gas saturation). It is practically impossible to evaluate by quantitative recommendations the running-in time as a function of the effect of the indicated factors; here we must rely on available experimental data. In our opinion, it is more beneficial to bring out the relationships between the characteristics of boiling on the run-in surface, i.e., with parameters stable over time and well known to researchers, and the unrun surface. To identify the run-in and unrun surfaces, the effect of the running-in time on q_{bl} at a fixed preboiling load of 0.2–0.25 MW/m^2 was investigated experimentally in [7, 8]. The experiments showed (Fig. 1) that the values of q_{bl} become stabilized and correspond to the traditional ones for these conditions (pool boiling of saturated water at atmospheric pressure) after 15–20 min for distilled water and after 8–10 min for tap water. Thereby, conditions were determined for surface preparation for correspondence to the state and term "run-in surface." In experiments on the effect of subcooling and pressure it was revealed that they do not change the relation between the critical thermal loads on the run-in and new surfaces. Based on this discovered fact a correlation for determining q_{bl} on a new heat-transfer surface is proposed [8].

We investigated the effect of the time of stay of the surface in water on q_{bl} under steady and stepwise heat-release conditions. As experimental elements we used solid-drawn tubes of outside diameter d_{out} = 10 mm and wall thickness δ = 0.2 mm with a roughness parameter Ra of 0.68 (All-Union State Standard 2789-73), which corresponds to surface finish class 7, that were made of stainless steel 12Kh18N9T (shortened fuel elements of nuclear reactors) and were oriented horizontally in a large volume (a glass vessel of capacity 10 liters) of distilled water at rest (S = 2.5–3) and of tap water (S = 60–80). The salinity was determined from the electrical resistance on a salinometer in a chemical laboratory. The working length of the tube was 130 mm. The selection of this size is associated with elimination of the effect of the geometry on the critical heat flux [9]. The specimen was heated by an alternating current from a 100-kW TK-404 welding transformer that was passed through an AOMN-404-40-220-75 adjustable-ratio autotransformer under steady conditions and bypassed it (without an autotransformer) in the case of a surge. The thermal load was determined from the voltage drop on the specimen and the strength of the current. The wires for measuring the voltage drop were soldered to the experimental specimen at a distance of no less than 5 mm from the site of connection of the specimen with the feeder busbars. This distance, which guarded against the effect of end heat losses, was calculated by the procedure of [10]. The strength of the current was determined from the voltage drop on a standard noninductive resistor connected in the secondary circuit of a UTT-6 current transformer of class 0.2. Burnout was achieved by gradually increasing the electric power supplied and was determined visually from the reddening of the section; as burnout was approached, the thermal load was increased more gradually (Fig.



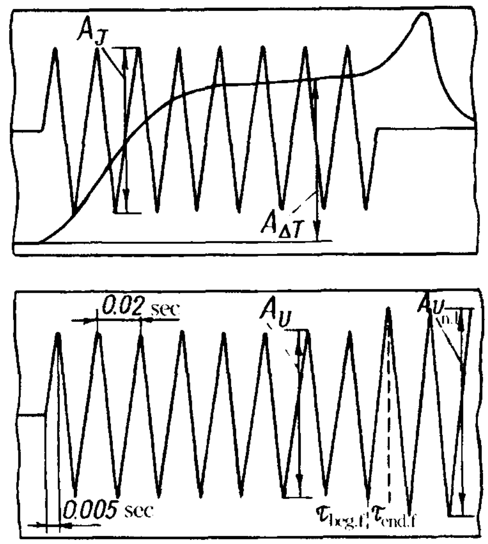


Fig. 2. Doubling of the parameters of the process on oscillograph tapes. A_j, A_U, and $A_{\Delta T}$ are the amplitudes of the signals of the strength of the current, voltage drop, and temperature (temperature head). Other auxiliary signals are not shown.

Fig. 3. Oscillograms of the change in the signals of the strength of the current, temperature, and electric voltage: $\tau_{\text{beg.f}}$ and $\tau_{\text{end.f}}$ are, respectively, the time of the beginning and end of specimen failure; $A_{U_{\text{n.l}}}$, amplitude of the signal of the transformer's no-load voltage.

2). Over the course of the experiment and at the time of burnout the current, voltage, and temperature were recorded from the readings of multipurpose voltmeters (of class not lower than 0.5); simultaneously two N-117 oscillographs recorded the signals of the limiting current, voltage, and temperature. In the case of a thermal-load surge, all the information was recorded on the oscillographs (Fig. 3). The evaluations performed showed that the maximum relative error in determining the heat-flux density does not exceed 4 and 7%, respectively, for steady and unsteady conditions. The minimum q_{w} (the power released in the element referred to the heat-transfer surface) at which burnout (failure) occurred upon switching on the heating source of the test element was taken as the unsteady critical density of the heat flux $q_{\text{bl}}^{\text{unst}}$. Each experimental value was determined as a result of a series of experiments for a surge. The experimental setup and the experiments are described in greater detail in [4-6] for steady conditions and in [11] for a surge.

The experimental procedure was as follows: the specimen was immersed in a vessel of water with an ambient temperature T_{f} = 18–20°C and was kept there for a long time; then the water was heated to the saturation temperature at atmospheric pressure using an extraneous electric heater. Next (under steady conditions), the thermal load was gradually (in 30–60 sec) increased until burnout occurred. Figure 4 shows the first critical density of the heat flux and the unsteady critical density of the heat flux as functions of the time of stay of the heat-transfer surface immersed in the water in boiling under steady conditions and in stepwise heat release. It is seen that, for steady conditions, running-in of the surface occurs after 2–3 days of its stay in the water and the determined q_{bl} corresponds to traditional values of the quantity under these conditions. In stepwise heat release and after a 30-day stay of the tube in the water there is no running-in, and the value of $q_{\text{bl}}^{\text{unst}}$ on the surface kept in the water for a long time is equal to q_{bl} determined on a new surface (not run in by preboiling and not kept in the water for a long time). This important discovered fact can be explained as follows: after a prolonged stay in the water, the entire surface was covered with small gas bubbles 1–1.5 mm in diameter (larger formed bubbles leave the surface during the prolonged stay of the tube in the water) that do not leave the wall and, in stepwise heat release, create a situation in the adjacent layer of liquid such that burnout occurs

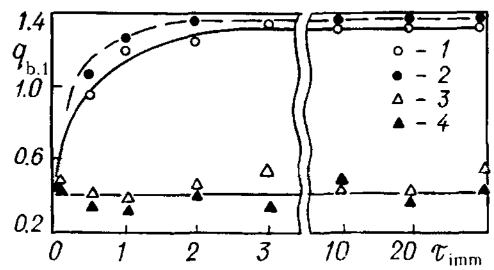


Fig. 4. Critical heat flux (minimum unsteady critical density of the heat flux) vs. time of stay of the heat-transfer surface immersed in water in boiling under steady conditions and in stepwise heat release: 1 and 2) steady conditions; 3 and 4) stepwise heat release; 1 and 3) distilled water; 2 and 4) tap water. q_{bl}, MW/m^2; τ_{imm}, days.

at thermal loads much lower than q_{bl}^{unst} on the run-in surface (for water, it is equal to the critical thermal load q_{bl} on the run-in surface); under steady conditions, conversely, over the time of gradual increase in the thermal load (30–60 sec) all the bubbles leave the surface already at the initial instant, and boiling follows known laws.

It is obvious that the surface, staying for a long time under the liquid level, undergoes running-in [5]. However, up to now the effect of a prolonged stay of a heat-transfer surface in a liquid on the characteristics of boiling (q_{bl}) has been investigated only under steady (heat-release) conditions. In actual power units cooled by a single-phase heat-transfer agent, there can occur thermal disturbances, including those of the impact character. Then, in evaluating the efficiency of heat-transfer surfaces, prediction of the heat-transfer regime is required, which is impossible without knowledge of the critical thermal load in boiling on the unrun surface kept for a long time under a liquid layer under conditions of stepwise heat release.

CONCLUSIONS

1. After a stay of the surface in water for more than 2–3 days it is run-in and q_{bl} determined in the experiments correspond to the critical density of the heat flux that is well known for these conditions.

2. In stepwise heat release on the surface that stays in water for a long time there is no running in. The unsteady critical density of the heat flux is equal to its steady-state value on a new surface that is not run in by preboiling; a design recommendation for this surface is given in [8].

3. No significant difference in q_{bl} for distilled water and tap water is detected; this difference is absent for q_{bl}^{unst}.

NOTATION

A, amplitude, mm; q, heat-flux density, W/m^2 (MW/m^2); S, salinity, mg/kg; T, temperature, K; α, heat-transfer coefficient, W/(m^2·K); τ, time, sec (min, h, days); J, strength of the current; ΔT, superheating; U, electric voltage; $U_{n.l}$, no-load voltage. Subscripts: bl, first burnout; beg.f, beginning of failure; end.f, end of failure; preb, preboiling; imm, immersion; f, ambient medium; w, surface. Superscript: unst, unsteady.

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