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NONSTATIONARY CRISIS OF NUCLEATE BOILING UNDER THE CONDITIONS OF AN ELECTRICALLY CONTROLLED HEAT LOAD

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Experimental data on the nonstationary heat exchange under a controlled heat load are presented. Investigations were carried out with cut plates specially formed to shape, on which the distribution of the heat-flow density is near-exponential (from the periphery to the center). Empirical dependences of the critical density of a heat flow and the heat-transfer coefficient on the rate of heating have been obtained.

The safety and reliability of highly forced heat exchangers is determined first of all by their serviceability under transient and emergency operating conditions. One method of removal of large heat flows is by boiling. The majority of investigations on heat exchange in the process of boiling were carried out for stationary and quasistationary conditions, under which the rate of change in the regime parameters does not exceed the rate of development of boiling.

The absence of correlation relations for the heat-exchange coefficient α under nonstationary conditions results in the value of α for stationary conditions being frequently used in mathematical models, which leads to the appearance of large errors in calculations.

The nonstationary crisis of nucleate boiling depends substantially on the rate of change in the heat load [1, 2]; the change to film boiling happens at $q > q_{\text{cr1}}$, where q_{cr1} corresponds to nuclear boiling under stationary conditions. Below, we present the results of experiments carried out at different rates of thermal loading of a sample. The experiments were performed with cut plates specially formed to shape, on which the distribution of the heat-flow density is near-exponential. The heat-flow density at the center of the plates is two times larger than that at their periphery. Such a distribution of a heat load should be provided in different technological equipment and military heat devices; in this case, the heat-flow density averaged over an area can exceed the critical heat-flow density by an order of magnitude or more.

A plate in which narrow slots made in a chess order do not reach its end is called a profiled plate. In this case, the whole of the plate experiences a current flowing along special tracks. In order that the heat load at the center of the plate be higher than that at its periphery, the distribution of the heat-flow density over the plate surface should be exponential and not uniform, unlike ordinary "nonprofiled" plane plates; therefore. on this plate, the larger the distance of a track from the plate periphery, the deeper its milling.

It was established in [3] that the smaller the area of a plate, the larger the critical density of a heat flow propagating over it. Moreover, a number of methodical experiments on determination of the minimum area of a heat-transfer surface, beginning with which the heat-flow density ceases to increase, were conducted in this work. We used the results of these experiments to select the sizes of plates.

As the heat-transfer agent, we used a TS-1 kerosene, whose temperature was held at 16–18°C in the course of an experiment.

Hydrocarbon fuels, representing boiling liquids, possess a number of features [4]. First, the fractional compositions of fuels of one and the same type can be different because of the difference in nature between petroleum and

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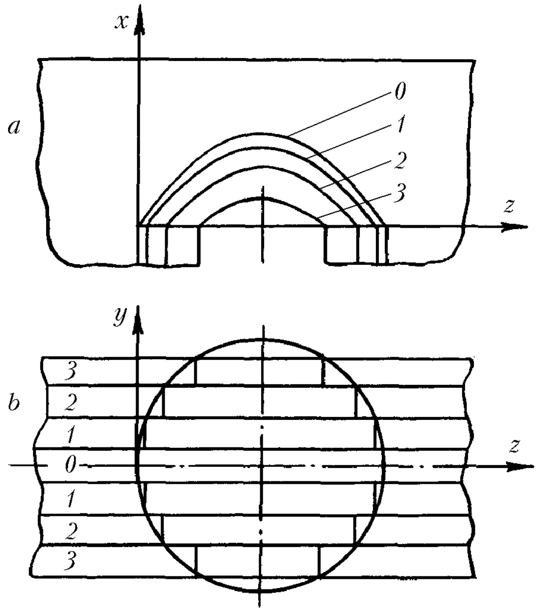

Fig. 1. Diagram of division of a heater into strips (a) and their profiles (b): 0, 1, 2, 3) numbers of strips different in thickness.

products of its refining. Second, the petroleum products in a fuel being heated are subjected to pyrolysis, as a result of which their thermal-oxidative stability decreases and a coke is formed on the channel walls, which deteriorates the heat transfer, and the boiling crisis happens not on the surface but on a scale layer. A coke is formed as a result of the oxidation of the fuel components by the dissolved oxygen. Third, it is known that mass transfer occurs simultaneously with heat transfer in a boiling fuel: the vapor bubbles formed on the surface are enriched with light fractions and the near-wall layer is enriched with heavy fractions. In this case, the saturation temperature of the liquid in the near-wall layer increases and the operating thermal pressure and, consequently, the heat-transfer coefficient decrease (as compared to those in a boiling one-component liquid with properties of a mixture).

The authors of [2, 5, 6] note that, despite a number of features characteristic of kerosene, the dependence $\alpha \sim f(q)$ agrees satisfactorily in character and level of quantities with that of a boiling one-component liquid.

In the experiments, the results of which will be presented below, a plate was heated by an alternating current flowing through it. The plate was cut into several strips of different thickness. The diagram of division of the heater into strips and their profiles is shown in Fig. 1. The thickness of each strip was approximated by a sinusoidal dependence:

$$h_i = h_0 — A_i \sin \frac{\pi (l_i/r - z)}{l_i} ,$$

where A_i is the thickness of the metal layer removed from the central part of the ith strip (in this case, the coordinate Z is measured from the center of the band), h_0 is the initial thickness of the plate, and l_i is the length of the ith strip.

Plates of duralumin D16T with a thickness δ = 2.5 mm and a diameter of the profiled part d = 50, 70, and 90 mm were used in the experiments. To obtain a profile of the required thickness, two problems on nonstationary heat conduction were solved, with the result that the coordinates of each profile have been numerically determined. Heaters were made in accordance with the sizes determined. Experimental verification has shown that the profile of heat flows is close to the calculated one. For example, for a plate with a diameter of the profiled part of d = 75 mm, the experimental and calculated ratios between the density of the heat flow at a distance of 37.5 mm from the center and the density of the heat flow at the center were respectively 0.53 and 0.5, i.e., the relative error comprised 6%. At other points of the surface, the difference does not exceed 15%. The plate was positioned such that its heat-transfer surface faced up. To decrease the influence of the heat losses, we thermally insulated one side of the experimental plate, for which purpose an adhesive layer or a rubber layer were applied on it and the plate was installed on a special

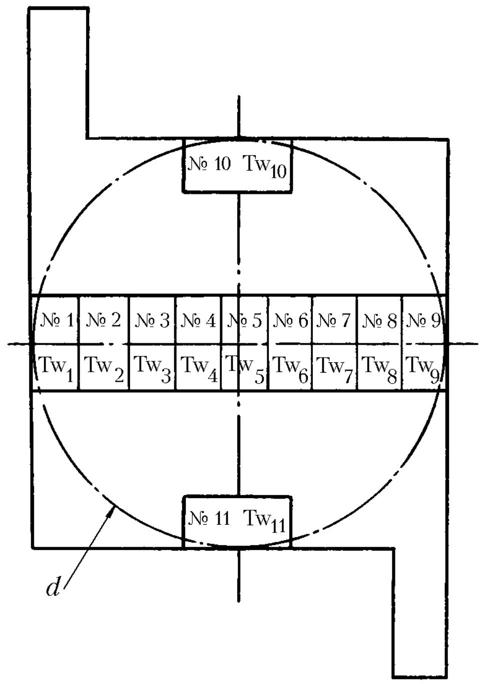

Fig. 2. Location of computational regions and thermocouples.

textolite plate. The heat losses caused by the removal of heat from the faces were estimated by the method proposed in [7].

In the course of an experiment, all the data on the change in the electric current and in the thermal state of a plate were recorded by a K12-22 mirror-galvanometer oscillograph. Since the profile of the plate was nonuniform in thickness, it was divided, in the process of calculation, into elementary parts, for which the local heat-flow density and the heat-transfer coefficients were determined by the intensity of the current and the electrical resistance. Along the diameter of the profiled part of the plate, we separated as much as 12 parts, the temperature of whose heat-transfer surface T_s was measured by caulked-in chromel-alumel thermocouples. Figure 2 shows the location of computational regions and thermocouples for a plate with a profiled part of diameter d = 90 mm. Test experiments have shown that, within the accuracy of the experiment, the error introduced by thermojunctions positioned on the heat-transfer surface of a plate exposed to a heat load exceeding the critical one is not larger than the technological spread detected in both the case of nonstationary and stationary boiling, which is due to the static nature of boiling. The heat-transfer coefficient was determined by the difference between the temperature of the surface and the saturation temperature of the heat-transfer agent. The Bi and Fo numbers estimated for the conditions of our experiments were equal to Bi $\approx$ 0.2 and Fo $\approx$ 200. Thus, because of the small thickness of the samples studied, the inequalities Bi < 1 and Fo >> 1 are fulfilled; therefore, it may be suggested that the temperature distribution over their thickness is quasistationary. The density of a heat flow was determined by the equation of thermal balance

$$q = q_e - \tilde{n}\frac{dT}{d\tau}\,.$$

(In the case where $dT/d\tau$ was determined on the basis of solution of the ill-posed problem on heat transfer by the method of iterative regulation [1], the maximum difference between the calculated and experimental values of q did not exceed 5%, which is plausible for the conditions of our experiments.) The intensity of the current flowing through a plate was determined by the voltage applied to it and its resistance. The data on the voltage drop across a sample were presented on an oscillogram. The electrical resistance of an elementary part of a plate and its total resistance were determined theoretically for definite sizes and temperatures. For this purpose, the dependence of the specific electrical resistance of the material of a sample on the temperature was determined. Since the specific electrical resistance of any material used in power engineering depends on the type of this material and the technology of its production

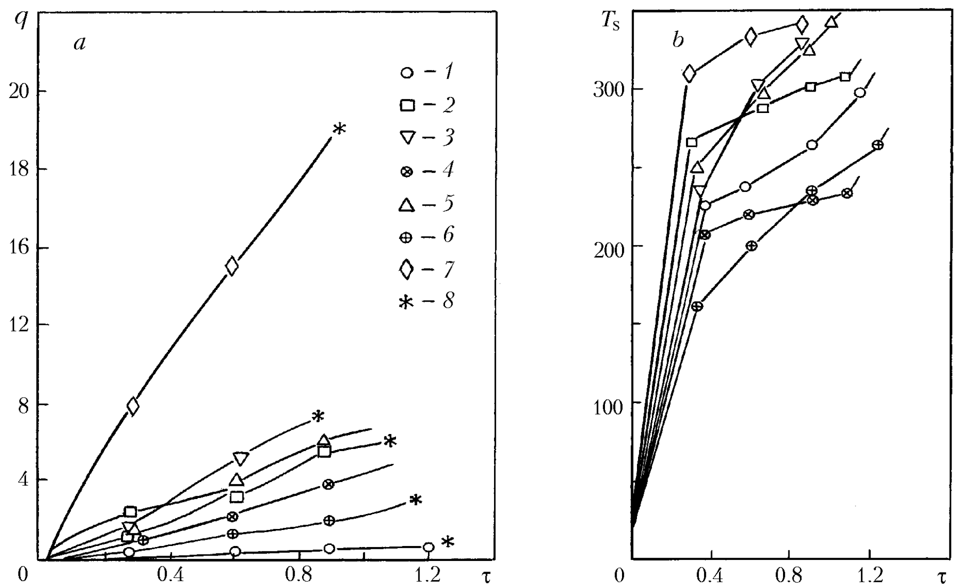

Fig. 3. Time dependence of the heat-flow density (a) and the temperature of the heat-transfer surface (b) of plates with profiled parts of different diameter: d = 90 (1, 2), 70 (3, 4), and 50 mm (5, 6); 7) plane nonprofiled plate of size 40 × 40 × 1.5 mm; 8) instant at which a plate is broken down [1 and 2); 3 and 4); 5) and 6) series of experiments with different rates of heating]. T_s, ^{o}C.

and treatment, we performed additional experiments on determination of the specific electrical resistance depending on the temperature. Our estimates show that the maximum relative error in determining the heat-flow density and the thermal pressure head do not exceed 7 and 15% respectively.

In the present work, we determined the boiling crisis by the breakdown of a sample. This method is considered as very reliable; however, the onset of crisis was additionally controlled by oscillograms of the nonstationary process (by jump-like changes in the surface temperature and in the electrical resistance). The minimum time of development of the process determined by these methods was taken as the instant of boiling crisis (the data obtained agreed, as a rule).

A plate was broken down beginning with its central part, where the heat-flow density reaches a maximum value. In our experiments, all profiled plates were broken down as a result of a change in the density of a heat load with time.

To eliminate the influence of the precipitate formation on the characteristics of nonstationary boiling, new "pure" plates were used in each experiment.

Figure 3a shows the change in the density of the heat flow in the central part of profiled plates with time to the instant of their breakdown for a number of experiments. Analysis of the dependence of the temperature of the heat-transfer surface of plates on the time at different rates of their heating (Fig. 3b) has shown that the breakdown of the plates depends not only on the maximum density of a heat flow attained in an experiment, but also on the rate of increase in a heat load.

In this connection, we made an effort to represent the data obtained in the form of the dependence $q_{cr} = f(q')$, which gave $q_{cr} = 0.867q' + 0.727$. This general dependence gives a straight line (Fig. 4a). The deviations of experimental data from the indicated dependence do not exceed 10%. The experimental point 7 was obtained for a plane plate. Note that this point was not taken into account when the dependence was approximated. However, the deviation of the experimental value from the approximation line does not exceed 3%. This points to the fact that, at a rate of heating of 20 MW/(m^2·sec), the heat-flow density distribution does not influence the critical heat-flow density.

Figure 4b and c shows the dependences of the heat-transfer coefficient, determined at a boiling temperature of 160^{o}C in the central broken-down part of a plate, on q_{cr} and q'. The generalized expression has the form α_{cr} = (1.5

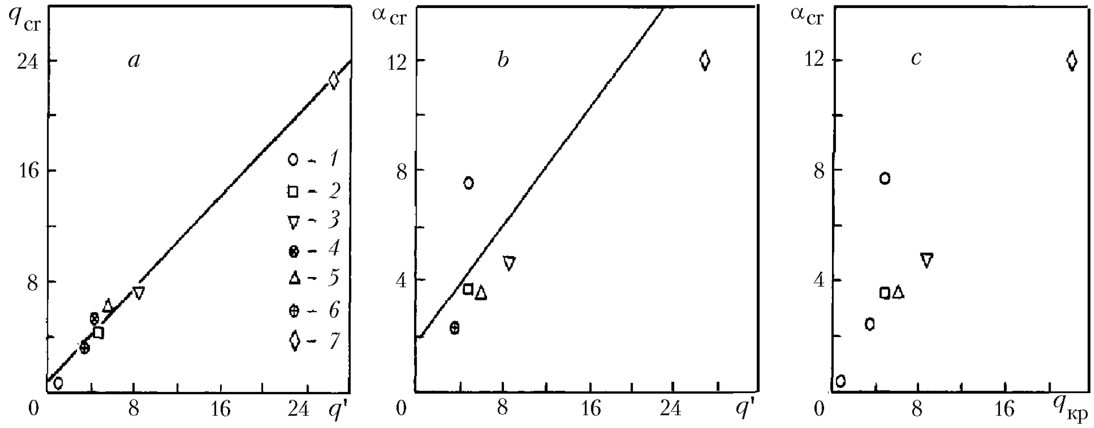

Fig. 4. Dependence of the critical heat-flow density (a) and the heat-transfer coefficient (b) on the rate of thermal loading and dependence of the heat-transfer coefficient on the heat-flow density at the instant of boiling crisis (c). The designations are identical to those in Fig. 3.

$+0.52q')\cdot 10^{-2}$. The dependence (presented in Fig. 4b) agrees with the experimental data worse than the above-indicated analogous dependence; in this case, the deviations of certain results from the straight line reach 20%. The result obtained for the plane plate differs from the approximation dependence by 24%.

Since a deviation of experimental data from the calculated one of not larger than 15% is considered as a good result in the case of nonstationary heat exchange and generally cannot ever on even be obtained, no matter what the dependence in investigating the boiling crisis, our results can be considered as satisfactory.

CONCLUSIONS

1. It has been established that an important factor influencing the heat-transfer coefficients is the rate of heating.

2. It has been shown that, at a rate of heating of higher than 20 MW/(m^2·sec), the heat-flow density distribution does not influence, within the limits of accuracy of the experiment, the process of heat transfer.

3. Empirical dependences of the critical heat-flow density and the critical heat-transfer coefficient on the rate of heating of samples have been obtained.

NOTATION

a, thermal diffusivity, m^2/sec; Bi = $\alpha\delta/\lambda$, Biot number; c, specific heat capacity of the material of a plate per unit of its area, J/(kg·K·m^2); d, diameter of the profiled part of a plate, mm; $dT/d\tau$, rate of change in the overheating of a heater relative to a liquid, K/sec; Fo = $a\tau/\delta^2$, Fourier number; q, density of a heat flow, MW/m^2; q_{cr1}, first critical density of a heat flow, MW/m^2; q_{cr}, first nonstationary critical density of a heat flow, MW/m^2; q_e, specific electrical power, MW/m^2; $q' = dq/d\tau$, rate of increase in the heat load, MW/(m^2·sec); α, heat-transfer coefficient, kW/(m^2·K); α_{cr}, heat-transfer coefficient corresponding to a nonstationary crisis of boiling, kW/(m^2·K); δ, thickness of a plate, mm; λ, heat-conductivity coefficients, W/(m·K); τ, time, sec; τ_{cr}, instant of time at which the boiling crisis happens, sec. Subscripts: cr, critical; e, electrical; s, surface.

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