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SUBCOOLED LIQUID BOILING HEAT TRANSFER UNDER CONDITIONS OF STEPWISE HEAT-LOAD RELEASE

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The results of experimental investigations of the effect of liquid subcooling below the saturation temperature on boiling heat transfer under conditions of an increase in a heating load are presented. Water and TS-1 kerosene were used as heat carriers. The obtained experimental data on subcooled liquid boiling heat transfer has been generalized by an empirical relation.

The development of contemporary space-rocket technology, aircraft manufacture, and a number of branches of power engineering involves the solution of the problem of removal of a very appreciable amount of thermal energy [1]. The laws governing heat and mass transfer relate to one of the key problems in creating both the rockets themselves and their constituent parts (in the first place, propulsion systems of very high specific power). Modern engines operate in different regimes with multiple switching-on while in flight, which leads to a substantial influence of the unsteady-state operating conditions on failure-free performance of the engine [2]. For the cooling of power plants it is convenient to use boiling fuels (boiling is one of the highly intensive means of heat removal); however, the practice may meet with rapid changes in operating conditions occurring many times faster than the development of the process of boiling, including a thermal shock [3].

Investigations of boiling heat transfer under unsteady-state conditions are few in number. The influence of subcooling on heat-transfer intensity on increase in the heat flux to the surface immersed in a pool of liquid at rest has been studied much less than other problems of boiling. Below, some of the recent results of studies of unsteady-state heat transfer of water are presented, but they are adequate only for assessing the validity of the experiments carried out.

In [4], experiments were made with deaerated distilled water at atmospheric pressure in a saturated state and on subcooling below a saturation pressure of 62.2 K. The heat-flux density was increased up to 5.1 MW/m^2. It was noted that in subcooled boiling a temperature jump in the liquid is observed and that its layers close to the surface are strongly overheated, right up to the appearance of vapor bubbles.

In [5], the results of temperature measurements are presented for the surface on which water boiled under the conditions of a jumpwise increase in a heat flux. The pressure changed within the range $p = 1$–10 bar, the temperature — $\Delta T_{\text{sub}} = 0$–$70$ K. It was established that with an increase in the liquid subcooling, the time needed for warming up a test element and near-wall layers up to the saturation temperature was increased, as well as $\Delta T_{\text{st.b}}$. This leads to an increase in $T_{\max}$ and τ at which boiling is initiated.

Thus, because of a lack of experimental data, the decision was made to carry out experiments on the assessment of the influence of subcooling on boiling heat transfer. As experimental samples, pipes made from 12Kh18N9T stainless steel (real shortened fuel elements of nuclear reactors) of diameter $d_{\text{out}} = 10$ mm, wall thickness $\delta = 0.2$ mm, and operating length $l = 95$–140 mm and 12Kh18N9T stainless steel plates with $\delta = 0.5$ mm, as well as D16AT duralumin plates with $\delta = 0.58$ mm were used. Investigations were carried out with TS-1 kerosene at a pressure $p = 0.1$–0.6 MPa with subcooling $\Delta T_{\text{sub}} = 100$–$180$ K and with water at $\Delta T_{\text{sub}} = 0$–$140$ K.

The results of experiments carried out under steady-state conditions have shown that in the case of high subcoolings the vapor that released on the heater in the form of tiny bubbles and that very rapidly leaves the surface forms a finely dispersed vapor cloud around the heater. On increase in the liquid temperature, the entire surface of the

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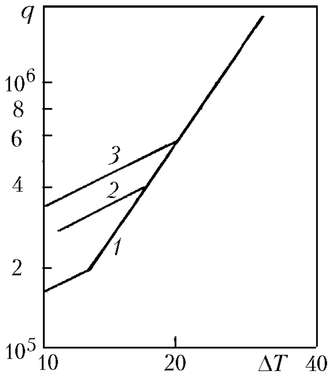

Fig. 1. Curves of water boiling under steady-state conditions for different subcoolings (superheating relative to the saturation temperature) [6]: 1) $\Delta T_{\rm sub} = 0$; 2) 14; 3) 28 K. q, MW/m^2; $\Delta T = T_{\rm w} - T_{\rm s}$, K.

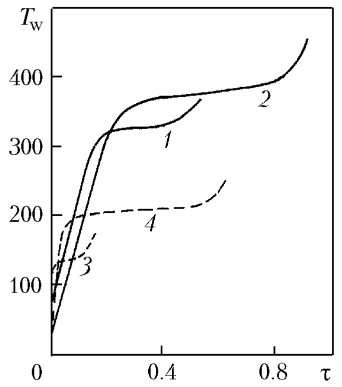

Fig. 2. Influence of liquid subcooling on the wall temperature on increase in the heat flux: 1) $\Delta T_{\rm sub} = 100$; 2) 140 K; 1, 2) TS-1 kerosene, plate with $\delta = 0.5$ mm, $q_{\rm w} = 3$ MW/m^2; 3) $\Delta T_{\rm sub} = 0$; 4) 80 K; 3, 4) water, pipe with $\delta = 0.2$ mm, $q_{\rm w} = 5$ MW/m^2. $T_{\rm w}$, °C; τ, sec.

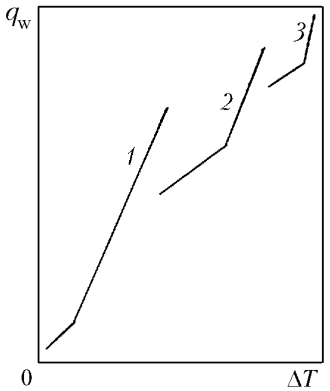

Fig. 3. Influence of liquid subcooling on heat transfer in metastable boiling under conditions of stepwise heat release: 1) $\Delta T_{\rm sub1}$; 2) $\Delta T_{\rm sub2}$; 3) $\Delta T_{\rm sub3}$; $\Delta T_{\rm sub1} < \Delta T_{\rm sub2} < \Delta T_{\rm sub3}$. q, MW/m^2; $\Delta T = T_{\rm w} - T_{\rm s}$, K.

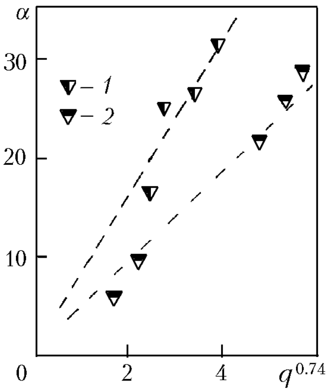

Fig. 4. Influence of subcooling on intensity of heat transfer during stepwise heat release q in the region of metastable boiling: 1) $\Delta T_{\rm sub} = 100$; 2) 170 K; 1, 2) TS-1 kerosene, $p = 0.1$ MPa. α, kW/(m^2·K); q, MW/m^2.

heater turns out to be densely covered by a layer of vapor bubbles externally resembling the mode of film boiling. Figure 1 shows the curves of water boiling under steady-state conditions [6]. It is seen that the dependences $q = f(\Delta T)$ in the field of boiling for different levels of subcooling lie on one curve when superheating of the surface is calculated relative to the saturation temperature. An increase in $\Delta T_{\rm sub}$ leads to the extension of the curve into the region of higher temperatures and heat fluxes without changing its position, i.e., heat release under the conditions of steady-state bubble boiling does not depend on liquid subcooling up to the saturation temperature.

The experimental results obtained show that with increase in subcooling under the conditions of stepwise heat release, for both water and kerosene in the region of metastable boiling there occurs expulsion of the surface temperature (Fig. 2) into the zone of elevated temperature superheatings relative to the saturation temperature. Here, neither the shape nor the material of the heating surface influenced heat transfer.

Thus, it may be stated that if the liquid subcooling does not influence the dependence of the heat-flux density on surface superheating relative to the saturation temperature (Fig. 1) in steady-state boiling, then under unsteady-state

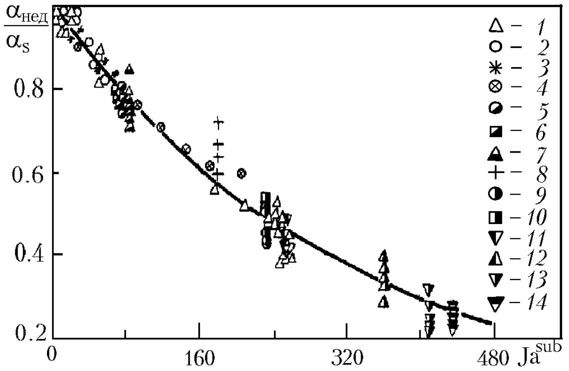

Fig. 5. Dependence of the dimensionless heat release $\alpha_{\mathrm{sub}}/\alpha_s$ on liquid subcooling below the saturation temperature $\mathrm{Ja}^{\mathrm{sub}} = c_p\rho'\Delta T_{\mathrm{sub}}/(r\rho'')$: 1) ΔT_{sub} = (3–8) K; 2) (3–33) K; 3) (23–48) K; 4) (10–58) K; 5, 6) 140 K; 7) 180 K; 8) 62.2 K; 9, 10) 80 K; 11) 100 K; 12) 140 K; 13) 160 K; 14) 170 K [1, 4, 8–10) water, p = 0.6 MPa; 2) acetone, p = 0.1 MPa; 3) ethyl alcohol, p = 0.1 MPa; 5, 6) water, p = 0.6 MPa; 7) TS-1 kerosene, p = 0.1 MPa; 11–14) TS-1 kerosene, p = 0.1 MPa; 1) 12Kh18N9T steel pipes; 2, 3) Kh18N9T steel plates [7]; 4) nickel wire [5]; 5, 9, 11, 13, 14) 12Kh18N9T steel plates; 6, 7, 10, 12) D16AT plates; 8) strip, iron-nickel alloy [4]].

heat release with increase in subcooling the curve $q = f(\Delta T)$ is displaced to the region of higher surface superheatings (Fig. 3). This is attributed, first, to the considerable superheating of the near-wall liquid layer before the activation of the nucleation sites and, second, to the difference in the character of the growth of vapor bubbles under steady- and unsteady-state heating conditions.

Figure 4 presents a generalization of the experimental data obtained for TS-1 kerosene and water without accounting for the effect of subcooling in the form of the empirical dependence $\alpha \sim q^{0.74}$. The experimental data presented demonstrate a strong dependence of the heat-transfer coefficient in the region of metastable boiling with stepwise heat release on liquid subcooling below the saturation temperature. The intensity of heat transfer with increase in liquid subcooling decreases and, naturally, the neglect of this fact is inadmissible.

An analysis of various elementary functions has shown that to take into account the influence of liquid subcooling on heat-transfer intensity $\alpha_{\mathrm{sub}}/\alpha_s$ the exponential function $b^{f(\Delta T_{\mathrm{sub}})}$ is the most suitable. The Jakob number $f(\Delta T_{\mathrm{sub}}) = \mathrm{Ja}^{\mathrm{sub}} = c_p\rho'\Delta T_{\mathrm{sub}}/(r\rho'')$, where the superheating is replaced by subcooling, seems to be an appropriate exponent. A comparison between the experimental data for $\alpha_{\mathrm{sub}}/\alpha_s = b^{\mathrm{Ja}_{\mathrm{sub}}}$ has shown that the dimensionless complex $(\rho' - \rho'')/\rho'$ can serve as the base of the power. Figure 5 presents the dependence $\alpha_{\mathrm{sub}}/\alpha_s = ((\rho' - \rho'')/\rho')^{\mathrm{Ja}_{\mathrm{sub}}}$ obtained.

CONCLUSIONS

1. Experimental investigations of boiling heat transfer under conditions of an increase in the supplied heat flux for kerosene and water under conditions of different subcoolings and pressures have shown a substantial difference in unsteady-state heat transfer for saturated liquid and that subcooled below the saturation temperature. For a subcooled liquid, one does not observe an explicit developed boiling, whereas for a saturated liquid an explosive incipience of boiling is typical.

2. The influence of subcooling is suggested to be taken into account in the form of a certain function of the Jakob number. A comparison of experimental data with calculation demonstrates a satisfactory agreement.

NOTATION

b, base of the exponential function; c_p, specific heat, J/(kg·K); d_{out}, outer diameter of the pipe, mm; l, working length of the pipe, mm; p, pressure, MPa; q, heat-flux density, W/m^2; q_{w}, density of the heat flux from the wall, W/m^2; r, vapor-generation heat, J/kg; T, temperature, K; ΔT, temperature drop; K; ΔT_{sub}, subcooling of liquid below the saturation temperature, K; $\Delta T_{\text{in.b}}$, drop between the temperatures on incipience of boiling and saturation, K; $T_{\max}$, temperature of the start of boiling, K; T_{s}, saturation temperature, K; T_{w}, wall temperature, K ($^{\text{o}}$C); α, heat-transfer coefficient, W/(m^2·K); α_{s}, heat-transfer coefficient on increase in the heat flux at saturation temperature, W/(m^2·K); α_{sub}, heat-transfer coefficient on increase in the heat flux in the case of subcooling below the saturation temperature, W/(m^2·K); δ, test sample wall thickness, mm; ρ, density, kg/m^3; τ, time, sec; $\text{Ja} = c_p\rho'\Delta T/(r\rho'')$, Jakob number; $\text{Ja}^{\text{sub}} = c_p\rho'\Delta T_{\text{sub}}/(r\rho'')$, Jakob number. Superscripts: sub, subcooling; $'$, liquid; $''$, vapor. Subscripts: max, maximum value; p, at constant pressure; s, saturation; w, parameters on the wall; out, outer surface; sat, saturated state; in.b, incipience of boiling.

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