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Critical heat flux during transient boiling of water on a vertically oriented heater

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The results of an experimental determination of the critical heat flux during transient boiling of water on a steel surface due to a rapid heat release are presented. The experimental conditions were as follows: average upward water flow velocity of 0.52 m/s, initial pressure of 0.29 MPa, and liquid subcooling relative to the saturation temperature of 23, 53, and 103 K. It is shown that the influence of the surface heating rate on reaching the temperature corresponding to the onset of boiling crisis is nonlinear.

Keywords: subcooled boiling, transient boiling, critical heat flux.

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The progress in advanced energy technologies is inextricably linked to the use of high-duty heat exchange elements operating in contact with boiling working fluids. The search for the optimal balance between maximizing the density of heat fluxes and ensuring stable operation of equipment with ongoing phase transformations makes the study of critical heat fluxes (CHFs) q_{cr} under dynamic boundary conditions a pressing problem in modern thermal physics [1]. Despite extensive research in recent decades, experimental results for transient states cover only a few of the possible combinations of various conditions: properties of materials, their macro- and microgeometry, and operating parameters. The current fundamental concepts of physics of phase transformations provide a quite exhaustive description of individual mechanisms of transition to a crisis; however, the required accuracy of parameters used in theoretical models is not ensured in emergency operating conditions with their characteristic short time scales. In view of this, the problem of CHF determination in a dynamic setting with a rapid increase in temperature of the heat-transfer surface is relevant.

Experiments were carried out at the High-Temperature Circuit Multi-Access Research Center. The setup was a closed system with circulating deaerated water cooled to the required temperature (23, 53 and 103 K below the saturation temperature) [2]. The initial pressure and average water velocity were 0.29 MPa and 0.5 m/s, respectively. The heating element was a hollow steel tube through which rectified electric current of the needed power was passed in controlled pulses of a given duration. A series of experiments were carried out with different initial liquid temperatures (T_0), but the same average power release and increasing duration of heat release ($\Delta\tau$). The final surface temperature of the heater ($T_{\max}$) was measured. At low heat output in convective, bubble, or transitional heat transfer regimes, equilibrium between generated and dissipated heat was achieved, and the final temperature of the heater in experiments of various duration remained unchanged. As the power increased, equilibrium became unattainable, the fraction of the surface occupied by steam exhibited a rapid increase, and a transition to film boiling occurred. The maximum (critical) heat flux dissipated into boiling liquid was determined by finding the minimum specific power at which the temperature fails to reach a steady-state value with an increase in heating duration. The approximate error of CHF determination is 0.2 MW/m^2 and is attributable to the stochastic nature of transition to film boiling.

The data series in Fig. 1 differ in the rate of increase of the heat-transfer surface temperature, which corresponds to a certain specific heat flux of released electrical energy (W_{av}). The stabilization of surface temperature in experiments with an increasing duration of heat release means striking a balance between the supplied energy and its absorption in a cooled flow of water with a certain subcooling relative to the saturation temperature (T_{sat}). Higher levels of heat flux density are characterized by the onset of a crisis (deterioration of heat exchange) accompanied by a reduction of the possible amount of removed heat energy, which leads to an increase in surface temperature. As is known [3], the CHF depends on temperature of the coolant flow and increases significantly as it decreases. Figure 1 also demonstrates that the critical surface temperature (T_{cr}) corresponding to the transition from nucleate to film boiling increases with an increase in heat output. The formation of a vapor film was observed in certain regions (double markers (concentric) in Fig. 1) during long-term heating with a power corresponding to the CHF. Figure 1, d provides an opportunity to evaluate the influence of non-

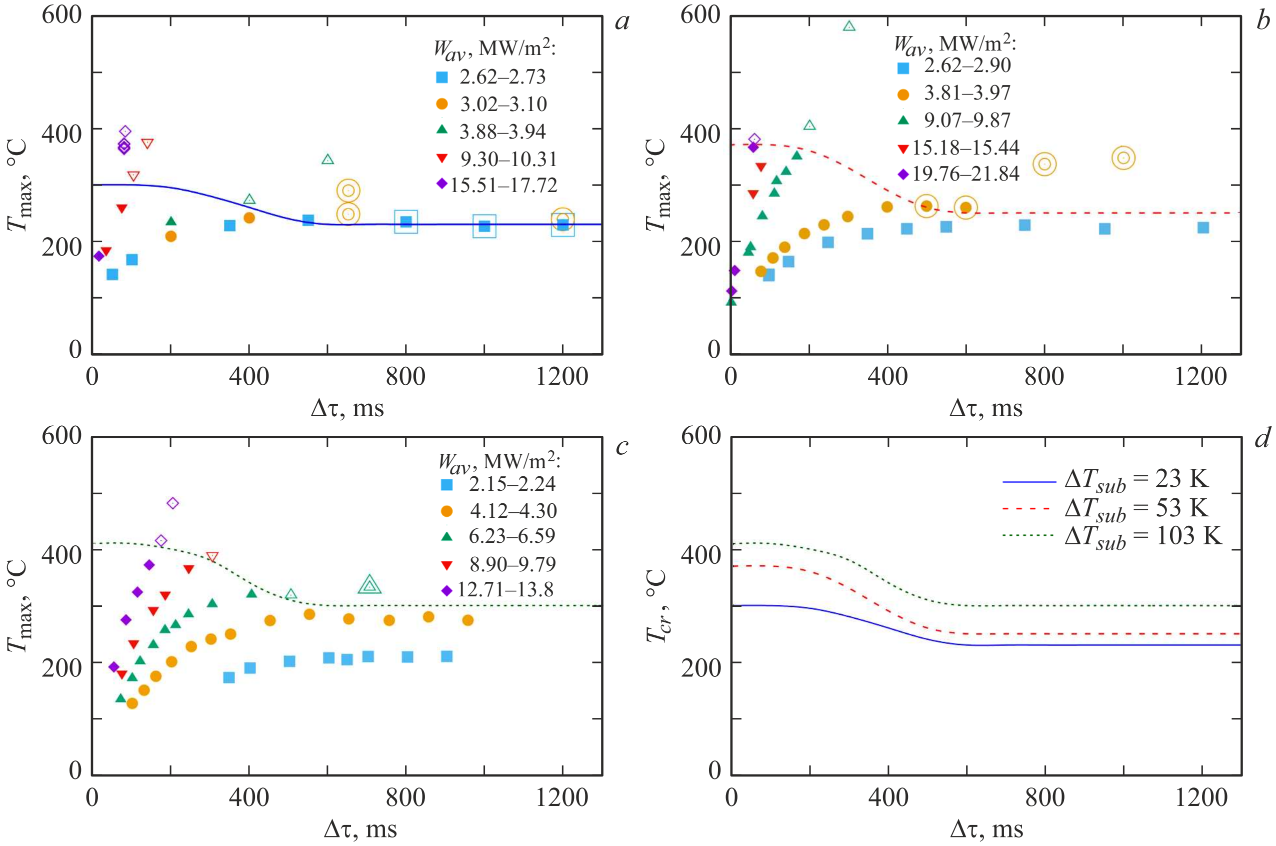

Figure 1. Heat-transfer surface temperature reached under transient heating with different heat-release durations and specific heat fluxes of the released electrical energy (W_{av}, MW/m^2) at a flow subcoolings $\Delta T_{sub} = 23$ (*a*), 53 (*b*), and 103 K (*c*). (*d*) Comparison of critical temperatures for different subcooling levels (lines in*a*–*c*). Markers: filled — nucleate boiling; open — fully developed film boiling; concentric (double) — local film boiling (CHF).

stationarity on the transition between boiling regimes: the bubble one, which is established at a surface temperature below T_{cr}, and the film one, which is characterized by the complete vanishing of wetted surface following the merger of steam bubbles and agglomerations. Note that with a heating duration exceeding 0.5 s, the onset of film boiling is observed at certain constant values of surface temperature. These temperature values depend on the level of liquid subcooling relative to the saturation temperature ($\Delta T_{sub} = T_{sat} - T_0$) and the rate of increase of the surface temperature. An increase in heating rate of the heat-transfer surface is accompanied by a nonlinear influence of the initial temperature on the transition temperature. Specifically, the difference in T_{cr} temperature between experiments with a subcooling of 53 and 103 K decreases significantly with an increase in heater power release. This observation may be interpreted as the possibility of existence of a certain limiting time of transition between bubble and film boiling regimes that is set by thermal processes and phase transitions.

Several dependences were used for comparison with theoretical values. One of them is the well-known Kutateladze formula for CHF during boiling of a liquid subcooled relative to the saturation temperature [3]:

$$q_{cr} = 0.14r\sqrt{\rho''}\sqrt[4]{\sigma g\Delta\rho}\left(1+0.1\left(\frac{\rho'}{\rho''}\right)^{3/4}\frac{\Delta i}{r}\right), \qquad (1)$$

where $\Delta\rho = \rho' - \rho''$, $\Delta i = i' - i(T_0)$, $r = i'' - i'$, σ is the coefficient of surface tension, and g is the gravitational acceleration. Here, ρ' and ρ'' are the densities and i' and i'' are the enthalpies of liquid and vapor phases saturated at a given pressure, respectively. The almost linear nature of dependence (1) on the initial liquid subcooling is worthy of note. In contrast, the Tong's formula adapted in [4] characterizes a more complex nature of influence of the initial temperature

$$q_{cr} = r(\rho w)(0.27 + 5.93 \cdot 10^{-2}p)\Psi \mathrm{Re}^{-0.5}, \qquad (2)$$

where p is expressed in MPa, $\mathrm{Re} = \frac{\rho w D}{\mu}$ is the Reynolds number, ρw is the mass flow rate, D is the effective channel diameter, and μ is the viscosity. Parameter Ψ is a generalization in the form of a piecewise-defined function of mass vapor content x:

$$\Psi = \begin{cases} 1, & x < -0.1775, \\ 0.825 - 0.986x, & -0.1775 < x < 0. \end{cases} \qquad (3)$$

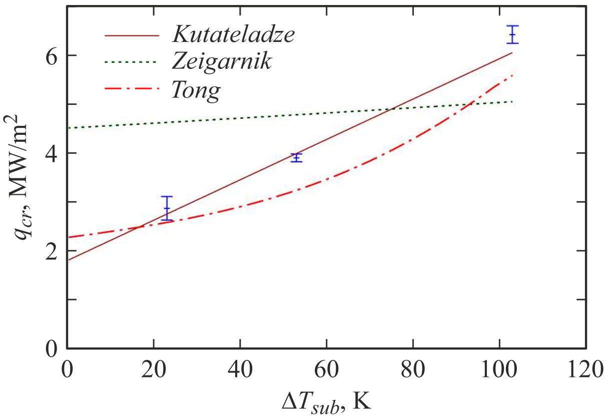

Figure 2. CHF plotted versus the level of flow subcooling relative to the saturation state.

Several series of experimental data presented in [5] demonstrate the nonlinear nature of dependence of q_{cr} on ΔT_{sub}; however, the lack of a pronounced local minimum, which is replaced by mere flattening, at low mass flow rates was noted. The dependence of the critical heat flux on liquid subcooling is defined as follows:

$$q_{cr} = A + B(\rho w)\Delta T_{sub}. \tag{4}$$

Here, q_{cr} is expressed in MW/m^2 and empirical coefficients A and B depend on the heater diameter. At a diameter of 12 mm, $A = 4.5\,\mathrm{MW/m^2}$ and $B = 1.05 \cdot 10^{-5}\,\mathrm{MJ/(kg \cdot K)}$. A comparison of the results of calculation by formulae (1), (2), and (4) with the experimental data (Fig. 2) for the steady-state regime (heating time in excess of 500 ms) reveals that formula (1) provides the best theoretical prediction. It should be noted that, for vertically oriented surfaces, the critical heat flux density is typically lower than the value predicted by Eq. (1), which was derived for horizontal surfaces [6]. Nevertheless, in our experiments with transient boiling of a subcooled water flow on a vertical cylindrical heater, the measured CHF was close to the theoretical value given by Eq. (1), i.e. it was significantly higher than the CHF typically observed for vertical surfaces under steady-state conditions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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