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Boiling crisis in cryogenic fluids during unsteady heat supply

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ABSTRACT

Boiling of cryogenic fluids is an important problem in superconductor technology, which becomes emergent in case an accidental, short-term and unsteady heating impulse appears. Here the process deviates from a standard scenario, approaching the crisis at lower heating. The present paper sheds light into the matter, aiming at the theoretical determination of the minimum critical heat flux required for the crisis to occur in the impulse mode. An analytical expression for the heat flux is derived and validated with the experiments on boiling in liquid nitrogen. Finally, a sensitivity study was performed looking at the influence of pressure, heater size and type of the fluid on the process.

1. Introduction

Nucleate boiling of cryogenic fluids during fast, unsteady heat supply may deviate from the conventional scenario. In this situation, as demonstrated in Pavlenko and Chekhovich [1], Surtaev et al. [2], Walunj and Sathyabhama [3], Deev et al. [4], the crisis of nucleate boiling appears at a heat flux significantly lower than the first critical heat flux q_{cr1}, which is observed during quasi-stationary heating. Here we term this point, $q_{cr,min}$, as a minimum heat flux during the crisis of nucleate boiling at the condition of a short-term impulse heat supply. Mapping the boiling curve further towards film boiling, originated at the second critical heat flux q_{cr2}, it is possible to formulate the inequality:

$$q_{cr1} \geqslant q_{cr,\,min} \geqslant q_{cr2}. \tag{1}$$

As it follows from Deev et al. [4], for a short-term unsteady heating, one may assume the transition to film boiling to occur when the energy E_{acc}, accumulated in the thermal boundary layer prior to boiling onset, overcomes the energy E_f, required for the formation of a stable vapour film:

$$\Psi = \frac{E_{acc}}{E_f} > 1, \tag{2}$$

$$E_{acc} \approx \frac{\pi}{4} \cdot \frac{\lambda^2}{a} \cdot \frac{\Delta T_{lim}^2}{q_{cr,min}}, \tag{3}$$

$$E_f \approx r \cdot \rho'' \cdot D, \tag{4}$$

where λ is the thermal conductivity of liquid, a is the thermal diffusivity, ΔT_{lim} is the superheat limit [5] (the limiting excess temperature for nucleate boiling to occur), r is the latent heat, ρ'' is the density of saturated vapour, D is the departure diameter of vapour bubble [6]. When the condition from Eqs. (3) and (4) is satisfied, a stable vapour film is formed at the heater.

Making use of both inequalities (Eqs. (3) and (4)), it is possible to identify the scenario followed by a thermal system upon the unsteady heat supply. Both of them require quantification of the minimum critical heat flux. Determination of $q_{cr,min}$ potentially contributes into ongoing development of modern theory of boiling, finding, in addition, practical applications in the design and operation of superconductor cooling systems.

Hence in the present study we present experimental results on boiling of liquid nitrogen at different heating conditions, which are further followed by an extensive theoretical analysis aimed in the extraction and analytical prediction of the desired parameter.

2. Experiment

The experimental system involved in the present study was partially described in our previous work [7]. The set-up consisted of the thermally insulated cylindrical vessel (10 L by volume, 12 cm internal diameter) with liquid nitrogen which was pressur-

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ized by purpose in the interval from 1 to 4 bar. A platinum wire with the diameter $d = 100$ μm and length $l = 26.9$ mm was located horizontally in the bulk of the fluid and used as the heating element. The wire was mounted between two copper terminals by using a soldering technique.

The wire was simultaneously employed as a thermistor, which sensitivity $d\rho_e/dT$ was defined as $(4.3 \pm 0.3)\cdot 10^{-10}\ \Omega$ m/K in the temperature interval 77–300 K. Fig. 1 presents a typical boiling curve for liquid nitrogen recorded during our experiments at the pressure of 3 bar and quasistationary variation of the heat flux. Hysteresis of the boiling curve, discussed elsewhere [8], is clearly seen in the figure.

The short-term power impulse was supplied to the heater through a thyristor with the response time of less than 1 μs, the absolute uncertainty of the time measurement was of equivalent order.

The heat flux captured by liquid nitrogen was determined balancing the heat flux q_g, generated by electrical current, and the actual amount of heat remaining in the heater:

$$q(\tau) = q_g(\tau) - \frac{d}{4}\cdot(c\rho)_h\cdot\frac{d\Delta T(\tau)}{d\tau}, \qquad (5)$$

where $(c\rho)_h = 1.86\cdot 10^6$ J/(m^3·K) is the volumetric heat capacity of the heater, ΔT is the excess temperature of the heater relative to liquid (superheat), and τ is time. Eq. (5) is derived assuming a uniform temperature profile over the entire heating surface.

The combined uncertainty analysis performed for the key process parameters, returns 5% relative error for q_g, 10% for $\Delta T(\tau)$ and 15% for $q(\tau)$.

3. Experimental results

Figs. 2–5 document a temporal history of the heater excess temperature ΔT, generated q_g and captured by liquid nitrogen heat flux q for different system pressures and heating regimes: quasistationary in (Figs. 2 and 4) and impulse (Figs. 3 and 5). Experimental results are compared with the numerical model, formulated for the problem of unsteady thermal conduction to the fluid making use of the Neumann boundary conditions. The simulations were carried out in FlexPDE, advancing in time with 1 μs step with the use of adaptive mesh refinement. The critical parameters of interest were defined at a moment where the experimental results started to experience notable deviations from the numerical solution. Analysing the figures, it is possible to detect some of the typical features of considered heating scenarios. The conventional, quasistationary heating, illustrated in Figs. 2 and 4, takes place when the heat flux, transferred to the liquid, overcomes $q_{cr,min}$ insufficiently. In this case, the monotonous rise of the excess temperature gets to a local maximum τ_{eb}, which corresponds to the onset of nucleate boiling, further, the parameter remains constant (or slightly reduces), and, after a relatively long time τ_{cr}, grows again due at the onset of film boiling. The critical superheat $\Delta T(\tau_{cr}) = \Delta T_{cr}$ follows the inequality $\Delta T_{cr} \le \Delta T_{lim}$, and the generated heat flux $q_g \approx q$ at this moment.

The second scenario takes place when q overcomes $q_{cr,min}$ sufficiently. It can be seen in Figs. 3 and 5 that the excess temperature ΔT is continuously increased and $q(\tau)$ approaches a local maximum at τ_{cr}. The maximum $q(\tau_{cr}) \equiv q_{cr}$ is an unsteady critical heat flux which corresponds to $\Delta T_{cr} \approx \Delta T_{lim}$, and τ_{eb} is close to τ_{cr}. The dependence of ΔT on time for $\tau > \tau_{cr}$ is of low-grade power-law type as $q_g > q$. It is useful to note that thermal response time of the heater for $\tau \approx \tau_{cr}$ is negligible so ΔT_{cr} determination is not influenced by thermal inertia of the wire.

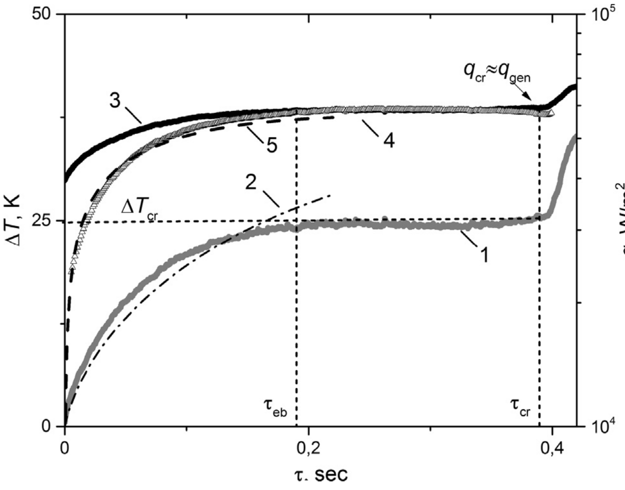

Fig. 2. Excess temperature (1), generated (3) and captured (4) heat flux as a function of time at 1 bar ($T_s = 76.8$ K). Quasistationary heating. Experimental results are compared with the numerical solution for superheat (2) and heat flux to the fluid (5).

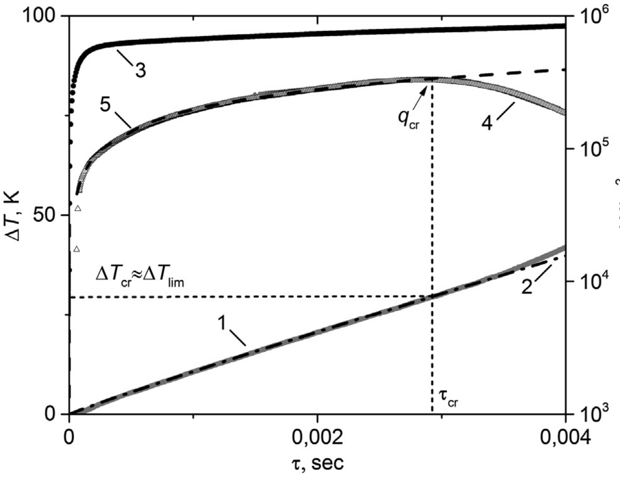

Fig. 3. Excess temperature (1), generated (3) and captured (4) heat flux as a function of time at 1 bar ($T_s = 76.8$ K). Impulse heating. Experimental results are compared with the numerical solution for superheat (2) and heat flux to the fluid (5).

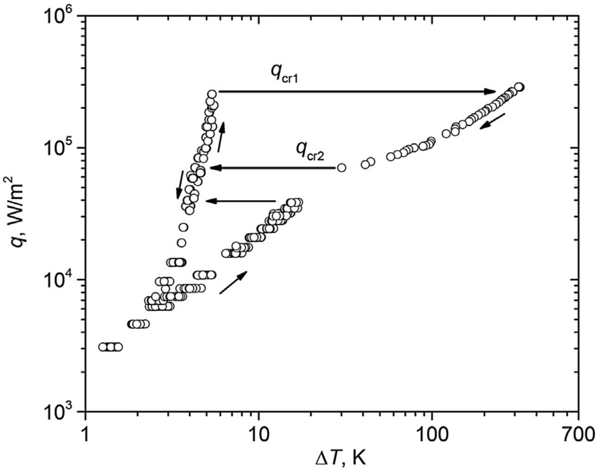

Fig. 1. Boiling curve for liquid nitrogen at $p \approx 3$ bar.