

Transient boiling crisis of cryogenic liquids

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Abstract

This paper introduces a new physical model of boiling crisis under rapid increase of power on the heated surface. The calculation of the time interval of the transition to film boiling in cryogenic liquids was carried out depending on heat flux and pressure. The obtained results are in good agreement with known experimental data.

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1. Introduction

Internal pulse heating is possible in some objects that are cooled by cryogenic liquids, for example, in superconducting coils. To conduct a careful analysis, two important questions have to be answered: what minimal pulse heating in coil will result in quench process? How long will it take after the heat up occurs, and what maximal quantity of energy will be transmitted to coolant?

It is most convenient to follow the principal patterns of transient heat processes by comparing two boundary cases of changing heat flux q : stepwise power input ($dq/dt \rightarrow \infty$) and quasi-stationary conditions ($dq/dt \rightarrow 0$). The minimal value of q at which boiling crisis under the stepwise condition occurs is called minimal transient critical heat flux $q_{cr,tr}^{\min}$ [1]. In experiments [2–4] the values of $q_{cr,tr}^{\min}$ obtained for liquid nitrogen at atmospheric pressure fell by a factor of 2–3 in comparison with q_{cr1} , but $q_{cr,tr}^{\min}$ for liquid helium were equal to q_{cr1} .

Stepwise power input leads to consistent change of heat transfer mechanisms: first of all, transient conduction changes on metastable nucleate boiling and, then, film boiling. At $q > q_{cr,tr}^{\min}$ there is an interval of time t_{cr} during which the heat transfer is rather high. Therefore, the knowledge both of the value t_{cr} and of parameters, which this value depends on, deserves attention.

2. The analysis of boiling crisis conditions at transient heating

Let us consider the conditions, when the transition to film boiling may take place at q less than q_{cr1} . For cryogenic liquids superheat for the onset of nucleate boiling approximates the limiting value ΔT_{lim} corresponding to homogeneous nucleation. If the value of heat input q_1 is varied between values of q_{cr1} and q_{cr2} , then on steady boiling curve (Fig. 1) a metastable state of the examined system may be presented by point 1. At the higher values of applied power, when $q_2 > q_{cr1}$, the state of system would be shown by point 2. In the first case, regime of metastable boiling will change to stable regime of either nucleate or film boiling. In the second case, only transition to film boiling is permitted.

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Nomenclature

a	thermal diffusivity
c	specific heat capacity
E	energy per unit area of the heated surface
Δh_v	latent heat of vaporization
Ja	Jakob number, $Ja = c\rho\Delta T/(\rho''\Delta h_v)$
n	nucleation site density
p	pressure
q	heat flux
q_{cr1}	first critical heat flux
q_{cr2}	second critical heat flux
$q_{cr,tr}^{min}$	minimal transient critical heat flux
R	vapor bubble radius
s_v	heating surface part occupied by vapor
ΔT	liquid (wall) superheat about saturation temperature

t	time
t_1	birth time of vapor bubble

Greek symbols

λ	thermal conductivity
ρ	density
ρ''	vapor density

Subscripts

ac	accumulated
cr	critical value
eb	ebullition
ev	evaporation
lim	limiting value
mer	merging
tr	transient

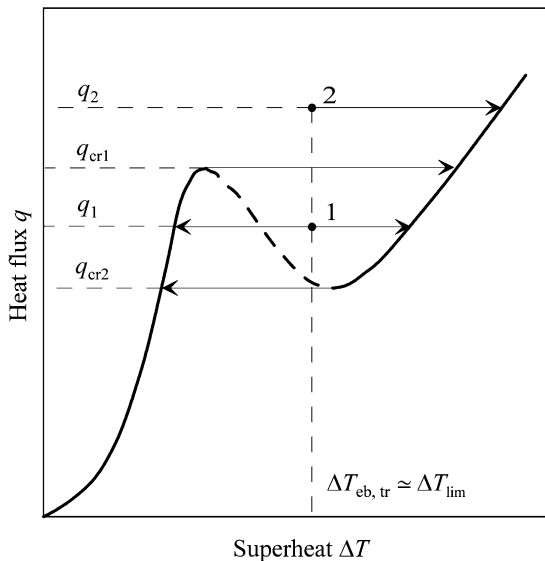


Fig. 1. Typical steady boiling curve and possible change of heat transfer regimes at stepwise power input.

The transition to film boiling regime at $q_{cr2} < q < q_{cr1}$ will occur if the accumulated energy in the thermal boundary layer E_{ac} is larger than E_{ev} , which is required for forming vapor film on the heated surface. In this case, the additional heating is not required and appearance of vapor layer will lead to transition to film boiling regime. Let us estimate the correlation between E_{ac} and E_{ev} under stepwise heat flux input to the liquid from a flat heater with negligible heat capacity. Assuming that δ_v is a characteristic size of the forming vapor layer that is of the order of vapor bubble departure diameter, we have

$$E_{ac} = \frac{\pi}{4} \lambda \rho c \frac{\Delta T_{lim}^2}{q}; \quad E_{ev} = \rho'' \Delta h_v \delta_v. \quad (1)$$

The ratio E_{ac}/E_{ev} as a function of the relative value of applied heat flux q/q_{cr1} for saturated nitrogen and helium at atmospheric pressure is shown in Fig. 2. The values required for calculations were derived from [5].

From Fig. 2 one can see that for nitrogen, E_{ac} in the region $q_{cr2} < q < q_{cr1}$ is much larger than E_{ev} . Under these conditions the accumulated energy at the thermal boundary layer will cause intensive nucleation that re-

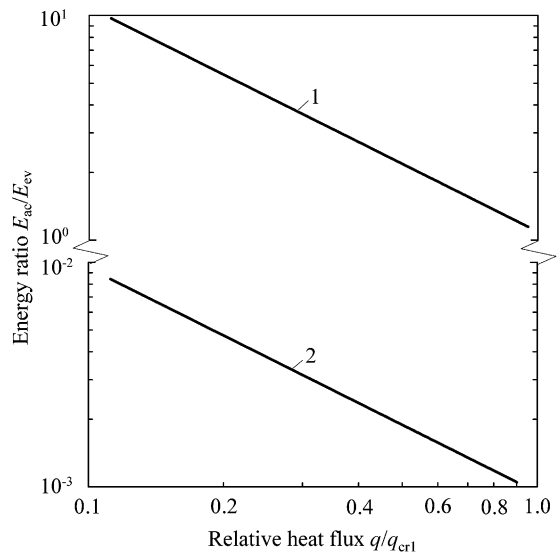


Fig. 2. The relationship between E_{ac} and E_{ev} for a flat heater immersed into liquid nitrogen (1), liquid helium (2) at atmospheric pressure.

sults in quick forming of vapor film. In this case transient critical heat flux will be less than q_{cr1} . This transition to film boiling may be classified as the type of crisis, which Skrypov [6] has termed “thermodynamic crisis”. For saturated helium, E_{ac} is less than E_{ev} . Consequently, the crisis of heat transfer cannot come immediately. In order that the bubbles could grow up enough and coalesce into vapor film, the heat must additionally arrive from heating wall. The experiments [7] show that if heat flux is smaller than q_{cr1} the wall superheat after spontaneous boiling of helium, at first, sharply decreases and, then, reaches steady level. Due to this reason, the value of critical heat flux at transient heating of helium cannot be less than steady value, and thus $q_{cr,ti}^{min}$ coincides with q_{cr1} .

3. The model of critical time interval

Let us consider the transient heat process until the beginning of film boiling as consistently replacing each other stages. The first stage is a stage of transient conduction lasting until the moment of liquid ebullition. The second stage is the stage of growing and merging of vapor bubbles on the heated surface. Crowding of bubbles and their coalescence prevent from liquid flow toward the surface and, as a result, if the heat flux is rather high, crisis of heat transfer occurs when a continuous vapor film is formed on the heated surface. Therefore, the critical interval of time t_{cr} is the sum of time intervals of the first and second stages $t_{cr} = t_{eb} + t_{mer}$.

At the stage of heating until the ebullition temperature, the interval of time t_{eb} can be found by solving the equation of transient conduction for semi-infinite massive of liquid. For flat heater with constant density of heat flux at the wall, t_{eb} is determined by the formula

$$t_{eb} = \frac{\pi}{4} \lambda c \rho \frac{\Delta T_{eb}^2}{q^2}, \tag{2}$$

where ΔT_{eb} is a superheat of liquid at onset of boiling on the wall, which is approximately equal to ΔT_{lim} .

It is considered in the suggested model that, on the second stage of transient boiling, the growth of vapor bubbles and their coalescence with each other take place before the time of bubble departure. As it was established in experiments [8,9] with helium, this happens if applied power exceeds ≈ 1.5 times the critical heat flux. Under this condition, E_{ev} turns to be somewhat smaller than the values that were used for calculations of the dependencies shown in Fig. 2.

For calculation of the second stage duration, it is necessary to give the laws of vapor bubble growth and of nucleation site density. Perhaps, the most widely used correlations for the rate of bubble growth are those of Plesset and Zwick [10] and of Labuntsov [11]. According to the model [10], in asymptotic period the growth of

vapor bubble is governed by transferring heat to bubble surface from surrounding overheated liquid. In the model [11] it is assumed that heat is immediately transmitted to growing vapor bubble from the heated surface nearby to the basis of a bubble. Both models lead to identical dependence of vapor bubble radius on time such as

$$R(t) = f(Ja) \sqrt{a(t - t_1)}, \tag{3}$$

where t_1 is the birth time of vapor bubble and $f(Ja)$ is the function of the Jakob number. The kind of this function depends on the accepted model, namely $f(Ja) \sim Ja$ [10] and $f(Ja) \sim Ja^{0.5}$ [11]. As it is shown in [5], the calculation $R(t)$ by the model of Plesset and Zwick brings to satisfactory agreement with experimental data for cryogenic liquids in the range of Jakob numbers from 5 to 60 when $f(Ja)$ is given by

$$f(Ja) = 1.35Ja. \tag{4}$$

The indicated range of Jakob numbers conforms to the growth of vapor bubbles in liquid nitrogen.

In the case of boiling helium, the Jakob numbers are substantially smaller and varied in the range $0.15 < Ja < 5$. For this range, it is recommended [5] to use the following dependence:

$$f(Ja) = 4.77Ja^{0.37}. \tag{5}$$

By determining the nucleation site density, we suppose that quantity of vapor bubbles, which arise in the superheated layer of liquid nearby the wall on the unit of surface area per unit of time, is proportional to portion of surface, which is free from vapor. The probability of appearance of nucleation centers on each free part of the heated surface is assumed to be the same. Thus, the number of active sites per unit surface area as a function of time may be expressed by the following equation:

$$n(t) = \int_0^t P_0 [1 - s_v(t_1)] dt_1, \tag{6}$$

where $s_v(t_1)$ is a portion of the heated surface occupied by vapor to the moment of time t_1 and P_0 is the normalization factor, which value is determined by condition $s_v(t_{mer}) = 1$ at the moment of heat transfer crisis. We shall consider that the surface area occupied by vapor may be defined as the sum of projections of diametrical cross-section of all vapor bubbles growing in the superheated boundary layer. Thus, we have

$$s_v(t_1) = \pi [f(Ja) \sqrt{a}]^2 \int_0^{t_1} n(t_2) dt_2. \tag{7}$$

After substitution of (7) in expression (6) one gets integral equation for nucleation site density, the solution of this equation is

$$n(t) = \sqrt{\frac{P_0}{\pi [f(Ja) \sqrt{a}]^2}} \sin \left[\sqrt{\pi [f(Ja) \sqrt{a}]^2 P_0 t} \right]. \tag{8}$$

From condition of normalization it follows that $P_0 = \pi/4[f(Ja)\sqrt{a}]^2 t_{\text{mer}}^2$. After substituting this value in expression (8) one can obtain

$$n(t) = \frac{1}{2[f(Ja)\sqrt{a}]^2 t_{\text{mer}}} \sin\left(\frac{\pi}{2} \frac{t}{t_{\text{mer}}}\right). \quad (9)$$

Let us now consider at first the case when vapor bubbles grow in the superheated liquid due to the expense of energy accumulated in thermal boundary layer. Using the model of Plesset and Zwick (Eqs. (3) and (4)) for energy spending on evaporation until the moment of coalescence of vapor bubbles, one gets the following expression:

$$\begin{aligned} E_{\text{ev}} &= \rho'' \Delta h_v \int_0^{V(t_{\text{mer}})} n(t) dV(t) \\ &= 2\pi\rho'' \Delta h_v [f(Ja)\sqrt{a}]^3 \int_0^{t_{\text{mer}}} n(t)(t_{\text{mer}} - t)^{0.5} dt, \end{aligned} \quad (10)$$

where $V(t_{\text{mer}})$ is the volume of vapor formed on unit surface area of a heating wall. Taking into account (9), it follows from Eq. (10) that

$$E_{\text{ev}} = \pi\rho'' \Delta h_v f(Ja)\sqrt{a}I\sqrt{t_{\text{mer}}}, \quad (11)$$

where $I = \int_0^1 (1-x)^{0.5} \sin(\pi x/2) dx \cong 0.358$. Using the result obtained, it is interesting to define the relation of time intervals t_{eb} and t_{ev} . Having in mind that in the case of $q = \text{const}$ $E_{\text{eb}} = qt_{\text{eb}}$ and t_{eb} is expressed by Eq. (2), excluding q , we shall find $t_{\text{eb}}/t_{\text{ev}}$ which is finally as follows:

$$\frac{t_{\text{eb}}}{t_{\text{mer}}} = 4\pi I^2 \left[\frac{f(Ja)}{Ja} \right]^2 \left(\frac{E_{\text{ac}}}{E_{\text{ev}}} \right)^2. \quad (12)$$

After substituting Eq. (4) in (12), usual calculations allow to get the following expression suitable for numerical evaluation:

$$\frac{t_{\text{eb}}}{t_{\text{mer}}} \cong 3 \left(\frac{E_{\text{ac}}}{E_{\text{ev}}} \right)^2. \quad (13)$$

In view of the data presented in Fig. 2, the achieved results show that at stepwise power input the time of nitrogen ebullition is considerably higher than the time of growing of the vapor bubbles until their coalescence into vapor film. Thus, in this case the time interval t_{eb} practically on the whole determines the moment of transient boiling crisis t_{cr} in condition when applied heat flux $q > q_{\text{cr,tr}}^{\text{min}}$.

To determine the duration of the metastable boiling stage for liquid helium when $E_{\text{ac}} \ll E_{\text{ev}}$, let us write the heat balance equation in the following form:

$$\begin{aligned} qt_{\text{mer}} &= 2\pi\rho'' \Delta h_v [f(Ja)\sqrt{a}]^3 \int_0^{t_{\text{mer}}} n(t)(t_{\text{mer}} - t)^{0.5} dt \\ &+ q \int_0^{t_{\text{mer}}} [1 - s_v(t)] dt, \end{aligned} \quad (14)$$

where the second term at the right part in this expression is the heat transfer on free from vapor area of the heated surface and $f(Ja)$ is given by Eq. (5). Using the expressions (7), (9) and (14), one can find the time of the vapor bubbles growing until moment of crisis

$$t_{\text{mer}} = \left[\frac{\pi^2 I}{\pi - 2} \rho'' \Delta h_v f(Ja)\sqrt{a} \right]^2 \frac{1}{q^2} \quad (15)$$

and then applying Eq. (2) the relationship between t_{eb} and t_{mer} as follows:

$$\frac{t_{\text{eb}}}{t_{\text{mer}}} = \frac{(\pi - 2)^2}{4\pi^3 I^2} \left[\frac{Ja}{f(Ja)} \right]^2. \quad (16)$$

The calculation based on the correlation (16) shows, that in the range of Ja numbers corresponding to Eq. (5), the time of liquid boiling incipience is negligible in comparison with time of the vapor bubbles growing until the moment of crisis. Therefore, unlike liquid nitrogen, t_{cr} for helium is fully determined by the process of heat transfer, which occurs in the metastable stage of nucleate boiling.

4. Comparison with experimental data

In our experiments [4] crisis of heat transfer at transient boiling of liquid nitrogen was investigated on the surface of platinum wire with diameter $d = 0.1$ mm. The wire was heated by passing a stepwise pulse of electric current through it. The average temperature of the wire was determined by means of using the consequent change of wire electric resistance. The wire was placed in a pool of saturated liquid at atmospheric pressure either horizontally or vertically. For comparison with the presented model we used the results only of those experiments when the heat load was changed by a jump from a zero level. Under such conditions, at the moment of crisis the wire temperature was close to the limiting value corresponding to homogeneous nucleation. The value of minimal critical heat flux $q_{\text{cr,tr}}^{\text{min}}$ was nearly to 7×10^4 W m⁻².

In Fig. 3 the experimental data [4] are compared with the results of calculation of the time period, after which overheat of the wire at fixed power input achieves the limiting value $\Delta T_{\text{lim}} = 33$ K. The solid curve in this figure was computed by transient conduction theory [12]. Assuming the wire to have heat capacity but no resistance to heat conduction, the relationship between the power generated within a wire and its overheat, with time of heating as a parameter, can be presented as follows:

$$q_{\text{h}} = \frac{\pi^2}{8} \frac{\lambda \Delta T_{\text{lim}} K_{\text{cp}}^2}{d} \left[\int_0^\infty \frac{1 - \exp(-\mu^2 Fo_{\text{eb}})}{\mu^3 (\xi^2(\mu) + \zeta^2(\mu))} d\mu \right]^{-1}, \quad (17)$$

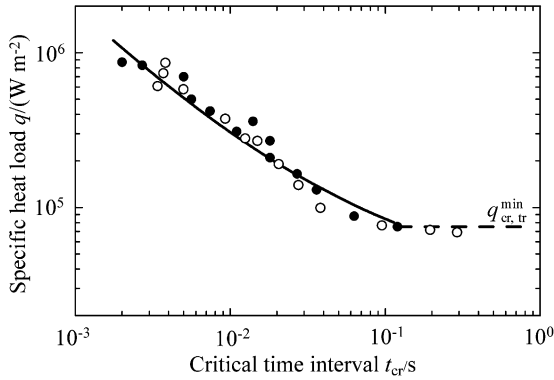


Fig. 3. Transient boiling crisis in liquid nitrogen on the surface of platinum wire at stepwise power input under conditions of atmospheric pressure: ○ horizontal orientation of the heater; ● vertical orientation; — calculation by Eq. (17); --- minimal transient critical heat flux.

where q_h is the specific load of a heater (or power generation per unit area of wire surface), $K_{cp} = (c\rho)_h/c\rho$ is the ratio of heat capacity of a heater and a liquid, $\xi(\mu) = \mu J_0(\mu) - (2/K_{cp})J_1(\mu)$, $\zeta(\mu) = \mu Y_0(\mu) - (2/K_{cp}) \times Y_1(\mu)$, and $Fo = 4at_{eb}/d^2$ is the Fourier number. As it is seen from Fig. 3, experimental and calculated data confirm the earlier made conclusion that for nitrogen $t_{cr} \approx t_{eb}$.

In our other experiments [8] the transient boiling crisis at stepwise power input was studied on the surface of brass ribbon with the size $65 \times 4 \times 0.05$ mm immersed in a pool of liquid helium. One of the ribbon sides (65×4 mm) had a contact with helium, another side was thermally isolated. The ribbon was heated by passing electric current through it. For measurement of the ribbon surface temperature, the miniature fast – response film germanium resistance thermometer was used. In these experiments, in particular, the dependence of critical heat flux on orientation of test heater in the gravity field and also the influence of helium saturation pressure on critical time interval in the range $40 \div 200$ kP ($p/p_{cr} \approx 0.18 \div 0.88$) were studied.

Fig. 4 shows the experimental data [8] for atmospheric pressure and $q \geq 1.5q_{cr1}$ together with the calculated results of critical time interval by the suggested model. (For the tested heater depending on its orientation in the gravity field the value of q_{cr1} was varied from 2.9×10^3 to 5.7×10^3 W m⁻².) As it can be seen from this figure, the orientation of the heater in the considered cases practically does not have influence on critical time interval. The correlation between q and t_{cr} may be described as

$$q = C t_{cr}^{-0.5} \tag{18}$$

In the case of $t_{cr} \approx t_{mer}$ this dependence fully corresponds to Eq. (15) of the model, if $C = (\pi^2 I / (\pi - 2))$

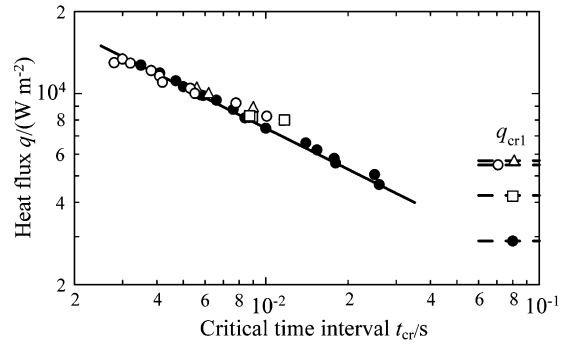


Fig. 4. Transient boiling crisis in liquid helium on the surface of brass ribbon at stepwise power input under conditions of atmospheric pressure: Δ \square horizontal orientation of the heater (heat transfer surface facing upward, downward, located vertically, respectively); \circ vertical orientation; — calculation by the suggested model; --- stationary critical heat flux.

$\rho'' \Delta h_c f(Ja) \sqrt{a}$. The calculation of C in (18) at the helium parameters corresponding to atmospheric pressure gives the value $C_1 \approx 750$ W s^{0.5} m⁻². The comparison of predicted and experimental data is presented in Fig. 4. Good agreement is observed.

As it follows from analysis of experimental data, the value of C varies with changing saturation pressure. The influence of pressure p on coefficient C is shown in relative coordinates in Fig. 5, where data from [8,13] and

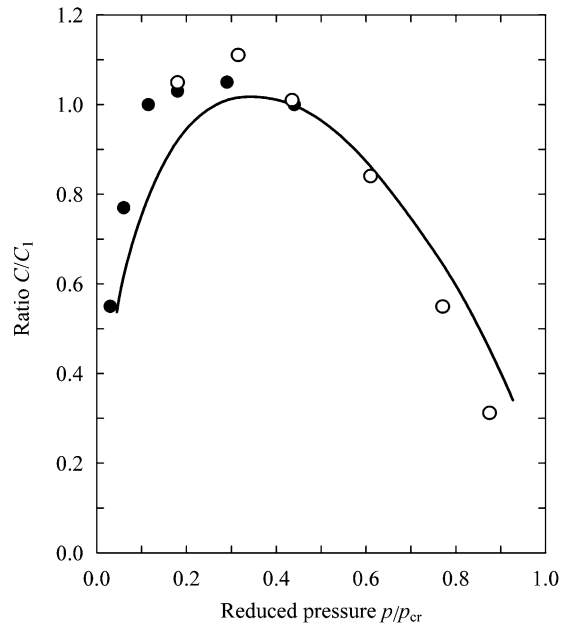


Fig. 5. The influence of saturation pressure on coefficient C in Eq. (18): \circ experimental data [8]; \bullet the data [13]; — calculation by the suggested model.

also results of calculation according to our model are presented. As it is demonstrated, this model rather satisfactorily describes the dependence of coefficient C and so of critical interval of time t_{cr} on pressure.

5. Conclusion

A spontaneous boiling crisis in liquid nitrogen at transient heating with $q < q_{cr1}$ is explained by considerable heat energy, which is accumulated in liquid before its ebullition. In the case of liquid helium, for lack of such energy reserve the heat transfer crisis at stepwise power input occurs not at once, and the delay time of transition to film boiling is determined by the duration of the metastable nucleate boiling stage. The calculation of this stage by the presented model allows to determine the critical time interval.

The authors hope to develop this model so that it was possible to apply it to water in the next paper.

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