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Critical heat flux modeling in water pool boiling during power transients

V.I. Deev, Htay Lwin Oo, V.S. Kharitonov, K.V. Kutsenko, A.A. Lavrukhin *

Department of Thermophysics, Moscow Engineering Physics Institute, State University, 31 Kashirskoe shosse, Moscow 115409, Russian Federation

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Abstract

This article suggests a method of the determination of main parameters and dynamic characteristics of heat transfer crisis on a surface of fast heated wall. The new physical models describing process of transition from nucleate to film boiling are presented. The results of transient critical heat flux modeling are compared with the experimental data for saturated water pool boiling under atmospheric pressure.

Keywords: Power transients; Water pool boiling; Critical heat flux; Physical models

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1. Introduction

The transition to film boiling of water on a rapidly heated surface subjected power transient is characterized by fast increase of the wall temperature that results in a damage of the construction. This transition takes a certain final interval of time t_{cr} during which the heat transfer is retained sufficiently high. The transient boiling crisis has some peculiarities, and a study of this phenomenon undoubtedly is of interest in practical and theoretical applications. Although some results have been recently obtained in this field [1–5], there is no generally accepted method for prediction of the dynamic characteristics of transient boiling crisis at various conditions. The applicability of several suggested correlations is limited to the particular data for which these correlations were worked out. This paper suggests a new method for the prediction of transient critical heat flux, which is based on the physical model developed earlier in our paper [6] as well as on experimental data for water obtained by the authors.

2. Experimental setup and procedure

A schematic diagram of the experimental apparatus used in this work is shown in Fig. 1. The basic element of experimental system was a thin wire heater from platinum (0.1 mm in diameter and approximately 25 mm long) positioned horizontally in the thermostat of about 3 l in volume with chemically treated water. The auxiliary heater arranged in a vessel of the thermostat was employed to maintain the volume of water at saturation temperature. The test platinum heater was used simultaneously as a resistance thermometer. Previous calibration of the platinum wire permitted determination of the wire temperature as a function of time at transient heating. Under conditions of our experiments, the resistance of the thermometer depended on temperature practically linearly, and a sensitivity of specific electric resistance of platinum to changing temperature $d\rho_e/dT$ was equal to $(4.0 \pm 0.2) \times 10^{-10}\ \Omega\,m\,K^{-1}$.

In the course of the experiments, the transient heat transfer under conditions of stepwise power input to the test section was investigated. To form a current pulse, the thyristor switch was used as a relay, which closed the power supply circuit of the test heater. The response time of relay was no more than 5 μs. Actuation of thyristor switch was made by TTL signals from the digital-to-analog converter of management system with the digital computer. The same

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* Corresponding author. Tel.: +7 495 3247328.
E-mail addresses: department-713@mail.ru, department-713@comtv.ru (A.A. Lavrukhin).

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Nomenclature

a	thermal diffusivity
c	specific heat capacity
d	diameter of a wire
Δh_v	latent heat of vaporization
I	electrical current
Ja	Jakob number, $Ja = c\rho\Delta T/(\rho''\Delta h_v)$
m	factor in Eq. (5)
q	heat flux
q_{cr1}	first critical heat flux at steady heating
q_h	heat load of a heater
R	electrical resistance
T	temperature
T_{sat}	saturation temperature
ΔT	liquid (wall) superheat above saturation temperature
ΔT_{cr1}	first critical temperature drop at steady heating
t	time
U	voltage
V''	vapor flow per unit area

Greek symbols

δ	thickness of two-phase boundary layer
δ_h	thickness of a heater
ρ	density
ρ''	vapor density
ρ_e	specific electric resistance
φ	void fraction

Subscripts

cal	calculated value
cr	critical value
d	departure
eb	ebullition
exp	experimental value
h	heater
mb	metastable boiling

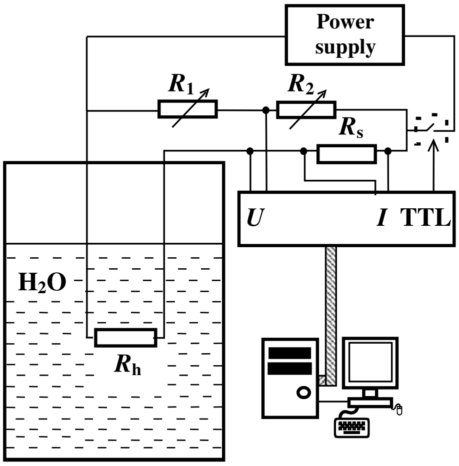

Fig. 1. Schematic diagram of the experimental setup.

signals were applied also for synchronization of instrumentation system.

The main part of instrumentation system was a double bridge circuit including the test heater. The resistance of the test heater R_h together with a variable resistance R_1 formed one leg of the bridge circuit and the other leg was a variable resistance R_2 and a Manganin standard resistance R_s. The latter was necessary for determination of a current through the test section. Measurements of the current and voltage across a bridge diagonal thus gave an opportunity to determine the resistance of the test heater, then to calculate its temperature and also to establish the heat generation rate.

A digital computer was used for preliminary processing data during experiments. The instantaneous electrical signals from a resistance bridge were fed to the computer through a programmed multiple differential amplifier, multiplexers and analog-to-digital converter of management system. The information obtained was figured on the display screen and recorded on a hard disk of the computer.

All measurements were made with saturated water at atmospheric pressure. Degassing of the test section was performed before each experiment; for this purpose, developed nucleate boiling on its surface was maintained not less than 5 min. After power input and measurement of all indispensable characteristics of non-steady process, the circuit of a current supply of test section was broken, and the new value of a current was set. The period between two series inputs of power was made more than 15 min that was necessary for deactivation of nucleation sites.

The relative error at measurement of time periods was less than 1%. According to the conducted estimations, the total error at determination of heat flux density was no more than 8%. The difference between the mean temperature of the platinum wire and the temperature of water was measured with inaccuracy about 2 K. The computational estimation of difference of the mean temperature from the surface temperature of the test section showed that this value in all experiments did not exceed 0.7 K.

The calculation of heat load of the test heater q_h and overheating of the platinum wire ΔT above the saturation temperature T_{sat} was conducted according to the electrical circuit shown in Fig. 1. The heat flux density $q(t)$ on a surface of the test heater was calculated by using an equation of heat balance

$$q(t) = q_h(t) - \frac{d}{4}(c\rho)_h \frac{d[\Delta T(t)]}{dt}, \tag{1}$$

where d is the wire diameter and $(c\rho)_h$ is the thermal capacity of the heater per unit volume. Under conditions of our experiments, $d(c\rho)_h/4 \approx 72 \mathrm{J\,m^{-2}\,K^{-1}}$.

3. Principal characteristics of transient at fast heating of a wall

Some representative dependences of wall superheat ΔT and heat flux q on time t under conditions of fast increase of heat load from a zero level up to a set value q_h are shown in Figs. 2–4. An analysis of the obtained experimental data demonstrates that the whole non-steady thermal process up to the moment of decreasing heat transfer owing to approach to film boiling can be presented as two consequent stages. At the first of them, the liquid on the surface of the heater does not boil, this stage lasts from beginning of heat release to the moment of liquid ebullition, which is indicated in the figures as t_{eb}. Because of a short duration of the first stage of process, the free convection in the liquid does not arise and heat is transferred from the heater to the surrounding water by transient conduction. At the second stage, nucleate boiling begins, vapor bubbles form and grow on the heated surface, and their number per unit area is continuously increased in the course of time.

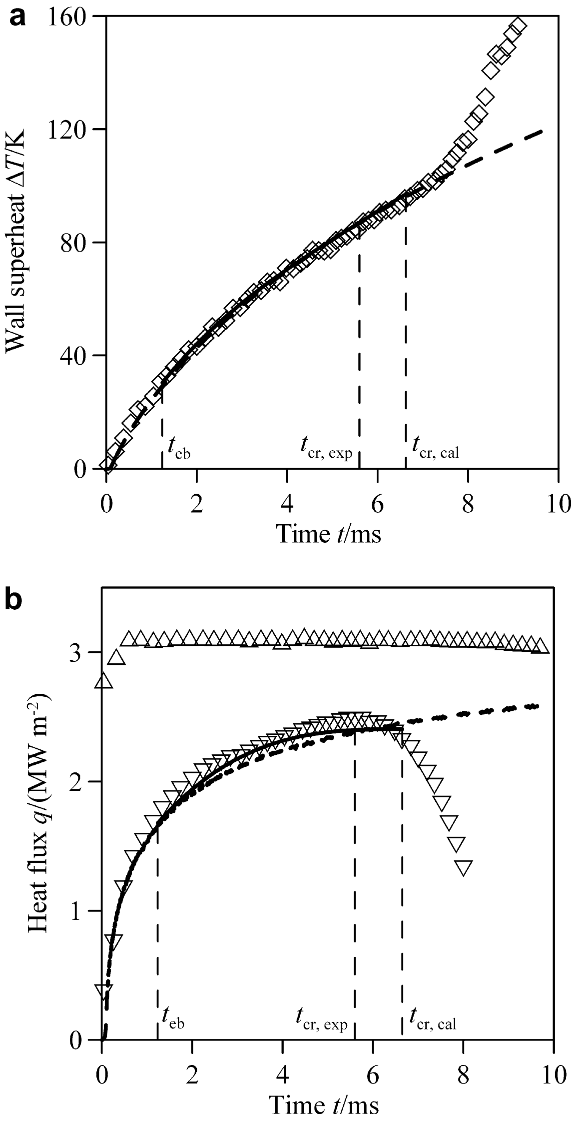

Fig. 2. The variation of wall superheat ΔT (a) and heat flux q on a heated surface (b) with time t at $q_h = 3.1$ MW m^{-2}: ◇ΔT, ∇q, △q_h – experimental data; - - - calculation by equations of conduction theory, — calculation by Eqs. (1)–(5) of the model.

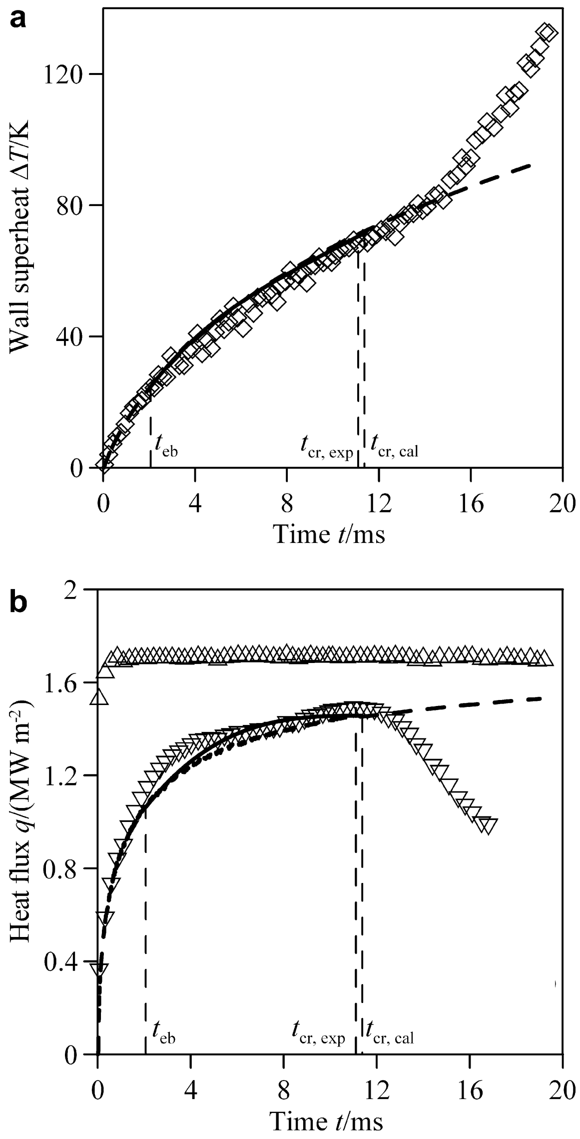

Fig. 3. The variation of wall superheat ΔT (a) and heat flux q on a heated surface (b) with time t at $q_h = 1.7$ MW m^{-2} (the marks are the same as in Fig. 2).

If a step power input exceeds one corresponding to the critical heat flux at steady heating q_{cr1}, this nucleate boiling regime is metastable and finishes by formation of a stable vapor film on the heated surface. It causes a fast increase of the wall temperature in the course of time due to decreasing heat transfer coefficient. Thus, the heat flux transmitted to the liquid also decreases (crisis of heat transfer). In the case of high levels of step power input, after a

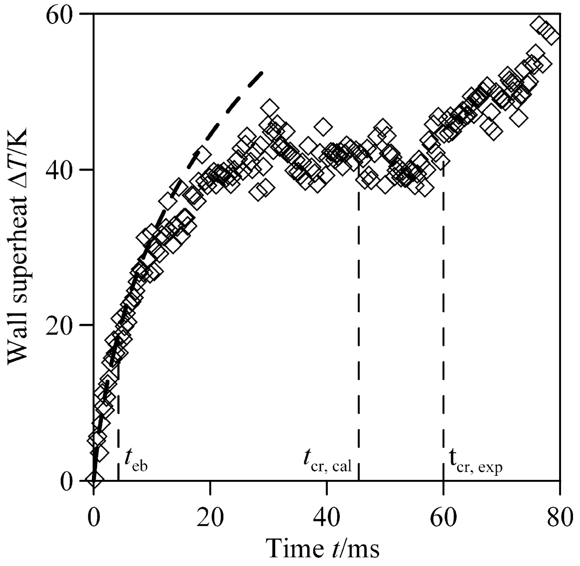

Fig. 4. The variation of wall superheat ΔT with time t at $q_h = 0.8$ MW m^{-2} (the marks are the same as in Fig. 2).

lapse of the critical time interval t_{cr}, a maximum of q is seen clearly on the curves based on experimental data (see Figs. 2 and 3). The duration of the second stage, which is completed by merging vapor bubbles in a stable film, in the given paper is denoted as t_{mb}. Thus, the critical time interval t_{cr} from the moment of step power input up to coming film boiling represents the sum of intervals t_{eb} and t_{mb}. Moreover, the values of the heat flux and the wall superheat, corresponding to the moments of liquid ebullition and boiling crisis, also represent the significant parameters determining the non-steady thermal processes, which occur on the fast heated surface. A consistent technique of calculation of these parameters is given below.

4. Calculation of ebullition parameters

In considered models of transient boiling crisis, liquid superheat at the wall relative to the saturation temperature, ΔT_{eb}, and the heat flux from the wall to the liquid, q_{eb}, in an instant of ebullition t_{eb} will be used as the parameters describing ebullition of the liquid. The liquid superheat at ebullition ΔT_{eb} generally depends on many factors, such as value of step input in heat generation, pressure, liquid subcooling relative to the saturation temperature and rate of heat input to the heated wall. Properties of the heated surface (roughness and wettability) also play a significant role during vapor bubble nucleation on the solid surface. The correlation between the heat flux in an instant of ebullition q_{eb} and the liquid superheat ΔT_{eb} in relation to the saturation temperature can be developed by using the known experimental data for water under atmospheric pressure [7–14] presented in Fig. 5.

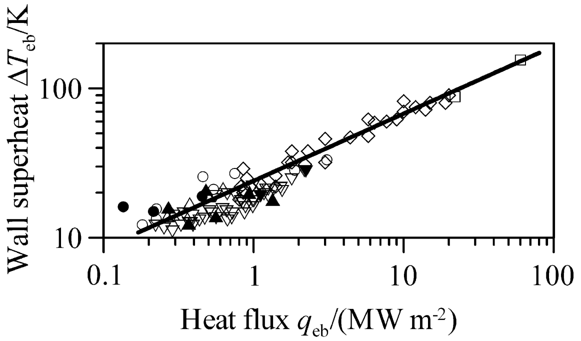

Fig. 5. The relation between wall superheat ΔT_{eb} above the saturation temperature and heat flux q_{eb} on a heated surface at ebullition of saturated and subcooled water under atmospheric pressure: ▼ [7], ○ [8], ▲ [9], ● [10], ∇ [11], △ [12], ◇ [13], □ [14] – experimental data; — Eq. (2).

Fig. 5 shows that, despite a rather broad variety of conditions of the experiments, all set of the presented data in the range of heat fluxes from 10^5 up to 10^8 W m^{-2} on the average (with inaccuracy ±25%) can be described by the equation suggested in the paper [13]:

$$\Delta T_{eb} = 0.048 q_{eb}^{0.45} \qquad (2)$$

At the definite law of heat release in the heater of the known shape with the given sizes and properties, the calculation of the first stage of non-steady thermal process (conduction in a quiescent fluid surrounding the heater) does not introduce the special difficulties. Thus, from the joint solution of equations of transient conduction recorded for a heated wall and a fluid, it is possible to define the wall superheat and heat flux on the wall surface at any moment of time. Using the correlation (2) between these parameters at the moment of water ebullition, one can find then the values of t_{eb}, ΔT_{eb} and q_{eb}. If the relations $\Delta T(t)$ and $q(t)$ are known, it is possible also to compute their derivatives on time and in particular the derivative $q'(t_{eb}) = \mathrm{d}q(t_{eb})/\mathrm{d}t$ necessary for further calculations. The examples of calculations of conduction regimes for a case of our heater are given in Figs. 2–4. The good agreement of the computational and experimental data corresponding to the time period 0–t_{eb} is visible.

5. Calculation of crisis parameters

The main parameters describing crisis of heat transfer at non-steady heating of a wall are the critical values of heat flux and temperature drop, q_{cr}, ΔT_{cr}, and also the time period t_{cr} from beginning of heat release in the heater till the moment when nucleate boiling is replaced by film boiling. Our experimental data demonstrate different nature of metastable nucleate boiling of water at high and moderate levels of power input. When heat flux density transferred in a liquid significantly exceeds (approximately in one and a half, two times) the value of q_{cr1} (see, for example, Figs. 2 and 3), the transient crisis of heat transfer takes place for a rather small period during which vapor bubbles growing on a heated surface have no time to achieve the departure size. The moment t_{cr} corresponding to originating crisis of metastable nucleate boiling in these cases can be determined as time at which the heat flux on a heated surface reaches the maximum value. Further, we consider this value as a critical heat flux q_{cr} at transient heating. If the value of step heat flux is close to critical heat flux for the conditions of steady heating q_{cr1}, the transition to film boiling can take a lot of time (several tens, hundreds or thousands of milliseconds). Thus, the vapor bubbles have time to depart many times from each center on the surface of the heater where nucleation takes place. In those cases, the heat flux density on the heated surface during all period of metastable nucleate boiling on the average is practically equal to a heat load q_{h} generated in the heater. In the moment t_{cr} the fast increase of temperature of the heated wall starts.

The considerable difference in time scales, during which the process of metastable nucleate boiling occurs at high and moderate values of step power input, causes the different nature of heat transfer crisis on the heated surface. In our opinion, in the former case (high loads), the crisis comes as a result of merging vapor bubbles in a stable vapor film directly on the heated surface. In the latter case (moderate loads), the crisis is connected with limiting saturation of two-phase boundary layer by vapor. In view of the marked features of crisis coming at the different levels of the step power input, two approaches to calculation of critical parameters are considered below.

If the transition to film boiling takes place for period smaller than the time of growth of vapor bubbles on a heated surface before their departure from it (high heat loads), for determination of the time interval t_{cr} it is possible to use the equation from our paper [6]

$$\int_{t_{\mathrm{eb}}}^{t_{\mathrm{cr}}} q(t)\left[1-\cos\left(\frac{\pi}{2}\cdot\frac{t-t_{\mathrm{eb}}}{t_{\mathrm{cr}}-t_{\mathrm{eb}}}\right)\right]\mathrm{d}t = k\Delta h_{\mathrm{v}}\rho'' f(Ja)\sqrt{a(t_{\mathrm{cr}}-t_{\mathrm{eb}})}, \tag{3}$$

where $q(t)$ is the heat flux transferred from the heated surface to the liquid; $k \cong 1.12$; $f(Ja)$ is the function of the Jakob number. At development of Eq. (3), it was supposed that the module of vapor bubble growth could be calculated by using the known formulas for steady boiling when the values ΔT and Ja do not change in the course of time.

To determine the moment of merger of vapor bubbles in a vapor film t_{cr} by means of Eq. (3), it is necessary to know, firstly, the dependence of heat flux q on time t and, secondly, some average value of wall superheat ΔT which can be used in calculation of the criterion Ja. Apparently in general case, the relations $q(t)$ and $\Delta T(t)$ are either to be obtained from the solution of conjugated problem of heat transfer both in the heater and in the liquid or to be established on the basis of the experimental data. The consistent theoretical analysis of the process of heat transfer in a boiling liquid is rather difficult now. However, there is an opportunity to apply to the solution of the problem an approximate approach, in which only the most common properties of functions $q(t)$ and $\Delta T(t)$ are taken into consideration. As to density of heat flux on a heated surface, for this function over the period of time t_{mb}, the following equalities should be fulfilled: $q(t_{\mathrm{eb}}) = q_{\mathrm{eb}}$; $q'(t_{\mathrm{eb}}) = q'_{\mathrm{eb}}$; $q'(t_{\mathrm{cr}}) = 0$. Accordingly, the relationship between the heat flux and time is represented as a polynomial

$$q(t) = (q_{\mathrm{cr}} - q_{\mathrm{eb}})\left[(\xi-2)\left(\frac{t-t_{\mathrm{eb}}}{t_{\mathrm{mb}}}\right)^3 + (3-2\xi)\left(\frac{t-t_{\mathrm{eb}}}{t_{\mathrm{mb}}}\right)^2 + \xi\left(\frac{t-t_{\mathrm{eb}}}{t_{\mathrm{mb}}}\right)\right] + q_{\mathrm{eb}}, \tag{4}$$

where $q_{\mathrm{cr}} = q(t_{\mathrm{cr}})$ is the transient critical heat flux; $\xi = q'_{\mathrm{eb}}t_{\mathrm{mb}}/(q_{\mathrm{cr}} - q_{\mathrm{eb}})$. In the case of a thin cylindrical heater, it is enough to determine the average wall superheat ΔT relative to the saturation temperature. It can be found as a function of time from the equation of heat balance (1). But if a heater is massive, it is necessary to solve the equation of transient conduction in the heater with the boundary condition (4).

For the solution of the problem in accordance with the suggested approximate method, the value of transient heat flux q_{cr} in expression (5) should be known. One of the ways of determination of this value is usage of the connection between q_{cr} and ΔT_{cr} that can be obtained from the following consideration. In the region of large values of q_{cr}, the intensity of heat transfer at metastable nucleate boiling, as seen in Figs. 2 and 3, is very close to the level of heat transfer by means of transient conduction. Then, from the solution of the conjugated problem of conduction in the system consisting of the cylindrical heater with the heat source $q_{\mathrm{h}}(t)$ and the quiescent liquid, it is possible to find the relations $q(t)$ and $\Delta T(t)$. After that with usage of Eq. (3), the moment of time t_{cr} is determined and therefore the values q_{cr}, ΔT_{cr} and the period t_{mb} are evaluated. In our calculations, the law of vapor bubble growth from paper [15] was used and the numbers Ja were determined by values ΔT that were equal to integral average temperature drops multiplied by 0.7. The relation between q_{cr} and ΔT_{cr} calculated in this way at large heat fluxes is represented in Fig. 6 by broken line. In the same figure, our experimental data are presented for all investigated range of q_{cr}.

At low heat loads, the experimental data considerably deviate from the curve calculated on the base of the conduction equation, that is connected with change of the mechanism of heat transfer at $q_{\mathrm{cr}} \approx q_{\mathrm{cr1}}$. To describe the relation between q_{cr} and ΔT_{cr} in a wide range of the above parameters, it is offered to use an interpolation formula

$$q_{\mathrm{cr}} = q_{\mathrm{cr1}}\exp\left(m\frac{\Delta T_{\mathrm{cr}} - \Delta T_{\mathrm{cr1}}}{\Delta T_{\mathrm{cr1}}}\right) \tag{5}$$

By the corresponding selection of a factor m, this formula provides smoothly varying transition from values of the critical parameters at steady heating (q_{cr1}, ΔT_{cr1}) to the values of these parameters at input of large heat loads. For

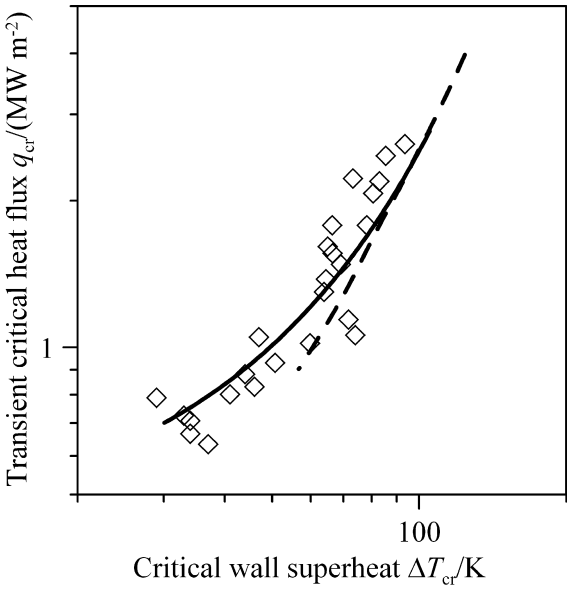

Fig. 6. Effect of critical wall superheat ΔT_{cr} on transient critical heat flux q_{cr}: ◇ experimental data; - - - calculation by using Eq. (3) and the relations $q(t)$, $\Delta T(t)$ obtained from solving the conjugated problem of conduction; — Eq. (5) with $m \approx 0.53$.

example, according to the data of our experiments at $q_{cr1} = 0.7$ MW m^{-2}, $\Delta T_{cr1} = 30$ K, $m \approx 0.53$ was found.

The complete system of Eqs. (1)–(5) allows to determine not only the values of the basic characteristics of boiling crisis but also to describe dynamic relations $q(t)$ and $\Delta T(t)$ observed in the experiments at the high levels of non-steady heat release in the heaters. With the purpose of comparison with the experimental data, the results of calculations of these relations by our method are shown in Figs. 2 and 3 as continuous lines. The good agreement of the computational and the experimental data is visible.

At moderate heat loads ($q_{cr} \geqslant q_{cr1}$), the heat transfer from the heater during a considerable period takes place under the conditions when there is an intensive vaporization in superheated layer of the liquid adjacent to the heated wall. The growing vapor bubbles after reaching definite size are periodically torn off from the heated surface and leave the two-phase boundary layer. The void fraction φ of this layer in the non-steady process continuously increases due to originating new centers of nucleation. The heat transfer crisis occurs when φ becomes close to unit. In this case, for calculation of duration of metastable boiling stage, it is offered to use an approach, which is similar to that presented in paper [4].

Let us assume that the two-phase boundary layer has a thickness δ of an order of departure diameter of a vapor bubble. Then the characteristic time of evaporation of the liquid in the neighborhood of each nucleation site is equal to an average time of vapor bubble growth up to departure size t_d. In this situation, variation of the void fraction of the two-phase boundary layer in the course of time can be described by a heat balance equation

$$\Delta h_v \rho'' \delta \, d\varphi(t) = [q(t) - \Delta h_v \rho'' V''(t)] dt, \tag{6}$$

where $V''(t) = \varphi(t)\delta/t_d$ is the vapor flow that forms on a unit area of the heated surface and leaves the two-phase boundary layer. Substitution of the above quantity into Eq. (6) gives a differential equation, which allows to determine the void fraction of the boundary layer as a function of time:

$$\Delta h_v \rho'' \delta \frac{d\varphi(t)}{dt} = q(t) - \frac{\Delta h_v \rho'' \delta}{t_d} \varphi(t) \tag{7}$$

Transition to the limiting case of steady-state conditions, when $q_{cr} = q_{cr1}$, gives the value $\delta \approx q_{cr1} t_d / (\Delta h_v \rho'')$. After substitution of δ, integrating Eq. (7) results in expression, which allows to find from the condition $\varphi(t_{cr}) = 1$ the duration of metastable boiling stage t_{mb} before heat transfer crisis:

$$q_{cr1} t_d \exp\left(\frac{t_{mb}}{t_d}\right) = \int_{t_{eb}}^{t_{eb}+t_{mb}} q(t) \exp\left(\frac{t - t_{eb}}{t_d}\right) dt \tag{8}$$

As it was marked already, under the considered conditions the heat flux density on the heated surface q in each instant practically is equal to the heat load q_h generated in the heater and, therefore, $q_{cr} \approx q_h$. That is why, if the law of heat release in the heater is known, it is not difficult to find from Eq. (8) the time interval t_{mb}. Then, taking into account the liquid ebullition stage, the moment of heat transfer crisis beginning t_{cr} can be determined as the sum of t_{eb} and t_{mb}. From the comparison of the results predicted according to the suggested method with our experimental data represented in Fig. 4, one can see a satisfactory agreement of the computational and the experimental data. For calculating the value of t_d in Eq. (8), the correlations presented in papers [15,16] were used. For the case of our experiments with saturated water under atmospheric pressure, this time was approximately equal to 20 ms.

The important characteristic of heat transfer crisis under non-steady conditions is the quantitative correlation between the heat flux on the heated surface and the moment of crisis occurrence. The experimental data shown in Fig. 7 clearly demonstrate different character of

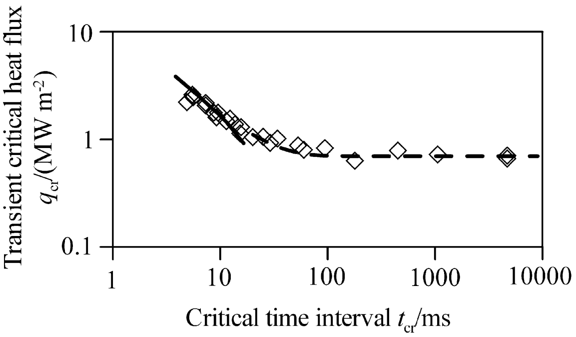

Fig. 7. Comparison of the presented models with the data of the authors: ◇ experimental data; — the model based on Eqs. (1)–(5); - - - the model with using Eq. (6).

correlation between the values q_{cr} and t_{cr} at the high and the moderate heat loads.

In accordance with the above assumptions about the different mechanisms of crisis of metastable nucleate boiling at the large and the moderate values of q, the comparison of the results of calculations performed by using the presented here physical models with the experimental data was conducted separately for two ranges of t_{cr}. As can be seen from Fig. 7, the model based on Eqs. (1)–(5) describes satisfactorily the $q(t)$ relation in the region $t_{cr} < 20$ ms; while at $t_{cr} > 20$ ms, it is possible to use the model with Eq. (8).

Analyzing a phenomenon of heat transfer crisis under the conditions of non-steady heat release in the heater, the authors of papers [2,9] examined the relation between the critical heat flux and the parameter describing the rate of the heat load variation. So in experiments [9], the crisis of non-steady boiling of water on the surface of plate-type heaters from nickel of the different thickness ($\delta_h = 0.01$, 0.05 and 0.1 mm) was studied. The heat generation rate in the test section was increased linearly in time in accordance with the law $q_h = 1.16 \times 10^6 (t/t_0)$, where t_0 is the time constant or the "ramp-period". In the experiments [2], heat release in the platinum wire of diameter 1.2 mm was changed according to the exponential law $q_h = 4.5 \times 10^3 \exp(t/t_0)$. The minimum value of time constant t_0 was 1.5 ms in the paper [9] and it was equal to 5 ms in the paper [2]. The comparison of the transient critical heat fluxes calculated by using the models presented in this paper with the data [2,9] is shown in Fig. 8 with coordinates q_{cr}, t_0. The quite satisfactory agreement of the computational and the experimental data is observed.

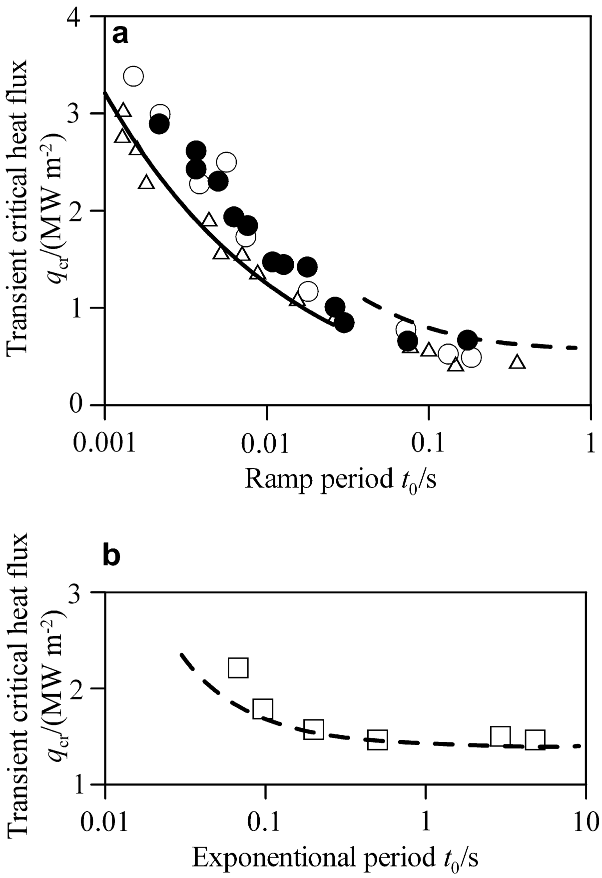

Fig. 8. Comparison of the presented models with the data of the other authors: data [8] for plate heaters of different thickness δ_h, mm: △ 0.01; ● 0.05; ○ 0.1 (a); □ data [2] (b); — the model based on Eqs. (1)–(5) at $\delta_h = 0.05$ mm; - - - the model with using Eq. (6).

6. Conclusion

The suggested method of calculation allows to describe dynamic characteristics of transient heat transfer crisis at pool boiling of saturated water under atmospheric pressure. This method can be used to determine the parameters of boiling crisis for different heaters and for various laws of heat release.

Acknowledgement

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References

[1] H. Kawamura, R. Tachibana, M. Akiyama, Heat transfer and DNB heat flux in transient boiling, in: Proceedings of the Fourth International Heat Transfer Conference, vol. 5. Paris – Versailles, 1970, pp. B3.3.

[2] A. Sakurai, M. Shiotsu, Transient pool boiling heat transfer, Part 2: boiling heat transfer and burnout, Transactions of the American Society of Mechanical Engineers, Series C, J. Heat Transfer 99 (1977) 554–560.

[3] A. Serizawa, Theoretical prediction of maximum heat flux in power transients, Int. J. Heat Mass Transfer 26 (1983) 921–932.

[4] Yu.M. Pavlov, V.I. Babich, A calculation of heat transfer crisis at fast heat flux increasing on the surface during boiling, Teploenergetika 2 (1987) 8–11 (in Russian).

[5] K.O. Pasamehmetoglu, R.A. Nelson, F.S. Gunnerson, Critical heat flux modeling in pool boiling for steady-state and power transients, Transactions of the American Society of Mechanical Engineers, Series C, J. Heat Transfer 112 (1990) 1048–1057.

[6] V.I. Deev, V.S. Kharitonov, K.V. Kutsenko, A.A. Lavrukhin, Transient boiling crisis of cryogenic liquids, Int. J. Heat Mass Transfer 47 (2004) 5477–5482.

[7] M.W. Rosenthal, An experimental study of transient boiling, Nucl. Sci. Eng. 2 (1957) 640–656.

[8] H. Lurie, H.A. Johnson, Transient pool boiling of water on a vertical surface with a step in heat generation, Transactions of the American Society of Mechanical Engineers, Series C, J. Heat Transfer 84 (1962) 217–224.

[9] F. Tachibana, M. Akiyama, H. Kawamura, Heat transfer and critical heat flux in transient boiling, (I) an experimental study in saturated pool boiling, J. Nucl. Sci. Technol. 5 (1968) 117–126.

[10] H.A. Johnson, Transient boiling heat transfer to water, Int. J. Heat Mass Transfer 14 (1971) 67–82.

[11] A. Sakurai, M. Shiotsu, Transient pool boiling heat transfer, Part 1: Incipient boiling superheat, Transactions of the American Society of Mechanical Engineers, Series C, J. Heat Transfer 99 (1977) 547–553.

[12] L. Nghiem, H. Merte, E.R.F. Winter, H. Beer, Prediction of transient inception of boiling in terms of a heterogeneous nucleation theory, Transactions of the American Society of Mechanical Engineers, Series C, J. Heat Transfer 103 (1981) 69–73.

[13] J. Ebrardt, Ph. Vernier, Optical measurement of water superheat near a rapidly heated wall at atmospheric pressure, in: Proceedings of the Seventh International Heat Transfer Conference, vol. 4. München, 1982, pp. 479–484.

[14] K.P. Derewnicki, Experimental studies of heat transfer and vapour formation in fast transient boiling, Int. J. Heat Mass Transfer 28 (1985) 2085–2092.

[15] D.A. Labuntsov, V.V. Yagov, To problem about growth rate of vapor bubbles at boiling, Trudy MEI 268 (1975) 3–15 (in Russian).

[16] S.S. Kutateladze, I.I. Gogonin, Growth rate and departure diameter of a vapor bubble at saturated liquid boiling under natural convection conditions, Teplofizika Vysokih Temperatur 17 (4) (1979) 792–797, in Russian.