PERGAMON

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

International Journal of Heat and Mass Transfer 46 (2003) 3411–3427

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Concerning the magnitude of the maximum heat flux and the mechanisms of superintensive bubble boiling

S.A. Zhukov *, S.Yu. Afanas'ev, S.B. Echmaev

Institute for the Problems of Chemical Physics, Russian Academy of Sciences, Chernogolovka, 142432 Moscow Region, Russia

Abstract

We have developed a stabilizer of the temperature of a thermoresistor wire electric heater based on a PID controller. Using this stabilizer, we investigated heat exchange of subcooled water in pool boiling. We found that on stabilization of the heater temperature up to that of the subcooled water, transition from convection to the regime of bubble boiling and vice versa occurs spontaneously and is accompanied by a jumpwise change in heat transfer. It is shown that in the regime of stable bubble boiling, the law of heat transfer is independent of the liquid temperature and the heater diameter and that the maximum heat loading may attain 50 MW/m^2, which is much above the values cited earlier in the literature. Based on the results obtained, a mechanism of implementation of bubble boiling for the regimes of a constant heat flux and a constant temperature is suggested. The assumption is made that the regime of heterogeneous vapour generation is possible only in the case of the heater constant temperature. In the regime of a stabilized heat flux on the heater, the spatially inhomogeneous regime of heat transfer is established. This regime represents a spatially distributed combination of three regimes: convective heat transfer, homogeneous boiling, manifesting itself in periodic boiling-up of overheated layers of the liquid near the surface and an unstable regime of heterogeneous vapour generation.

1. Introduction

In investigation of heterogeneous boiling, two regimes of heating are used which ensure a constant heat flux and a constant temperature of a heater [1]. It is assumed in this case that for stable bubble and film boiling the heating regimes allow one to obtain identical results, with the differences being observed only in the region of transient boiling. The overwhelming majority of experimental works were carried out with the use of the first regime of heating because of the simplicity of its practical realization.

The maintenance of a constant temperature of the heater in carrying out experiments requires overcoming appreciable technical difficulties, with a spatially inhomogeneous regime being developed on a heat-generating surface over a considerable interval of heat fluxes [10], which makes the analysis of the results obtained very difficult.

Up to the present time, mainly two techniques of maintaining temperature were used in experimental investigations under the conditions of a controlled temperature of the heater. This is the heating of the heat transfer surfaces by a condensing vapour [2] and electric heating of wire resistance thermometers by a special block for maintaining a constant mean-integral temperature [3].

Certain drawbacks are inherent in each of the techniques listed. The large heat-transfer coefficients were assumed to provide isothermal conditions on a heating element; however, the special features of the process of condensation preclude obtaining a homogeneous temperature field on the heater [4,5].

The second technique was suggested in [3,6,7] to ensure stable operation of the heater in the region of transient boiling. Electric heating of wire thermoresistors was used by Japanese researchers [8,9], but none of them paid attention to the fact that direct application of this technique to investigate the breakdown of the homogeneous regime of heat transfer and formation of alternating zones of the bubble and film regimes on the heater (the regime of mixed boiling) leads to erroneous

---

* Corresponding author. Fax: +7-96-5155420.
E-mail address: zhukov@cat.icp.ae.ru (S.A. Zhukov).

0017-9310/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0017-9310(03)00134-0

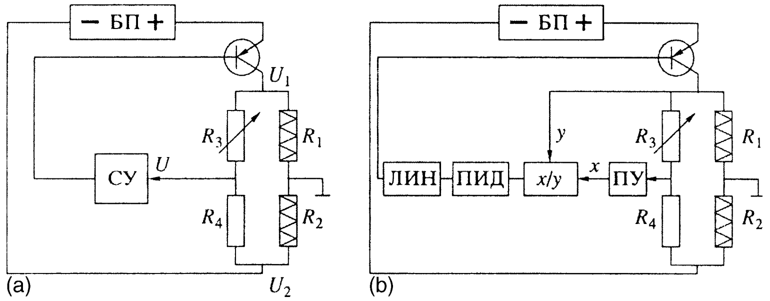

Fig. 1. (a) Schematic diagram of the resistance stabilizer based on the Wheatstone bridge, (b) schematic diagram of the stabilizer used in the present work. SU, supply unit; CS, controlling system; PID, proportional-integral-differential controller; LIN, linearizer. Key: БП = SU; ЛИН = LIN; ПИД = PID; ПУ = CU; СУ = CS.

results [10]. And, finally, recently French scientists published the results [11] of studying transient boiling which were also obtained with the use of a resistance stabilizer.

Simultaneously with [3], analogous stabilizers were developed at the Institute of Chemical Physics of the Academy of Sciences of the USSR for carrying out investigations in the field of heterogeneous catalysis [12] and kinetics of oxidation of metals [13]. Subsequently, one of the models of these stabilizers was used for studying the process of heterogeneous boiling [10], where specific features of the technique were revealed favouring the appearance of stable inhomogeneous states of the type of standing waves (dissipative structures) and the methods of the analysis of the results have been developed that make it possible to identify their formation. It was shown in that work that this stabilizer makes it possible to maintain bubble boiling stable at much higher heat fluxes than with any other technique. Moreover, the phenomenon of jumpwise transition from free-convective heat transfer to bubble boiling accompanied by a sharp increase in the heat-transfer coefficient was discovered; however, the characteristics of this stabilizer precluded its detailed investigation.

In this paper, we present the results of investigations of the process of boiling using a new model of a stabilizer of the integral mean temperature of the heater.

2. Schematic diagram of an integral mean temperature stabilizer

All of the well-known schemes of stabilization of the integral mean temperature of probes are based on the Wheatstone bridge [6–13]. The schematic diagram of one of the possible variants of the stabilizer is given in Fig. 1. Here R_1 is the heater, R_2 is a shunt, R_3, R_4 form the set-point device, CS is the control system, and PU is the power supply unit. Assuming the resistance of the probe to be dependent on the temperature in the form $R_1 = R_0(1 + \alpha\Delta T)$, where α is the temperature coefficient, R_0 is the resistance of the probe at 0 °C, and T is the temperature, it can be easily shown that the input signal for the controlling system U_{in} (the signal of bridge disbalance) is equal to

$$U_{\text{in}} = U_1(R_4\alpha\Delta T)/(R_3 + R_4)(1 + \alpha\Delta T)$$

Assuming that

$$\alpha\Delta T \ll 1, \quad A = \alpha R_4/(R_3 + R_4),$$

we have

$$U_{\text{in}} = AU_1\Delta T. \tag{1}$$

Relation (1) points to the main drawback of the system adopted, namely, its dynamic instability. If for the bridge balance it is necessary to raise the temperature of the heater, then to do this it is necessary to increase the power supplied, and this will increase the voltage U_1. Because of the thermal inertia of the heater, the rate of increase in its temperature lags behind the increase in the voltage leading to still greater unbalance. A similar situation arises also on unbalance of the bridge of opposite sign, and therefore, to avoid excitation, the response of the control system is to be limited. In other words, the regulator whose schematic is presented in Fig. 1a cannot respond adequately to rapid perturbations occurring in boiling and, consequently, cannot suppress them.

We suggested a modification of the measuring-controlling circuit to eliminate the indicated drawbacks. For this purpose, the amplified signal of the bridge unbalance was divided by the voltage U_1 with the aid of an analog circuit. Then the signal proportional to the unbalance of the temperature was supplied to a proportional-integral-differential (PID) controller, [1] linearizer (mismatch-power) and a power amplifier.

---

[1] In the experiments we used the familiar PID controller due to the absence of the well-developed mathematical model of the process and, consequently, of the optimal regulation laws.

In preparing the circuit, special attention was paid to its balancing at high frequencies, since because of the smallness of the resistances R_1 and R_2 the inductance of this arm of the bridge plays a very substantial role, and the appearance of the parasitic positive feedback imposes limitation on the transmission band and the rate of increase in the control system. For this reason, the current arm was made as possible symmetrical and, moreover, additional compensating elements were introduced into the circuit.

To increase the stability of operation in certain regimes it was foreseen in the manufactured stabilizer that it could supply the signal proportional to the magnitude of the voltage and current strength on the probe to some summing inputs of the proportional and differential part of the PID-regulator.

The block-diagram of the stabilizer which was manufactured by us is presented in Fig. 1b.

3. Description of the setup and of the measurement methods

The experiments were carried out in a glass vessel of diameter 100 mm and height 250 mm. Three copper electrodes of diameter 2.5 mm were led through a tight Teflon lad. Between these electrodes, a wire heater and a standard resistance made of manganin were soldered. The second branch of the bridge was mounted on the vessel cap, which made it possible to reduce the length of connecting wires to decrease to a minimum the parasitic inductive impedance. The heater was made of platinum wire of diameter 20, 50, and 100 μm. The length of the heater was selected so that in calculating the mean temperature of the heater one could neglect heat losses in current leads. All the results given in this work were obtained on the heaters for which the following relation holds:

$L_{\text{heater}} > 15\text{–}20\ L_{\text{therm}}$

where $L_{\text{therm}} = \sqrt{\lambda d/4\alpha}$ is the size of the zone of thermal relaxation.

Electrical measurements were made in the following way: the voltage readings from the probe and current shunt were digitized by 12-bit analog-to-digital converters (ADC), to the inputs of which the track-and-hold unit (T/H) with the fixation time uncertainty not larger than 20 ns were connected and were transmitted to a personal computer intended for primary collection of data. For one cycle of ADC, 512 values of the measured signal were recorded (for both channels) with the measurement frequency 5 kHz. The digitized electric values were recalculated in terms of temperature and power and were displayed in the form of graphical and digital information, after which ADC was started again. Thus, in the experiments the current values of the parameters of the investigated system, for example, the strength of the current and voltage (volt–ampere characteristic) or the specific heat flux and the surface temperature (boiling curve) were controlled continuously. On termination of the experiment, a copy containing the graph and protocol of the experiment was printed out.

The accuracy of the measurement of the current and voltage was 0.04%. To extend the range of measurements by ADC, a precision voltage divider was used.

4. Experimental conditions

The experiments were carried out according to the following scheme: at a constant temperature of the liquid (20 or 100 °C) and minimum strength of the current the initial resistance of the probe was measured. Then the liquid was heated up to the needed temperature with the aid of an additional heater or was cooled by a cooling coil. The temperature of the probe was increased up to the occurrence of crisis [2] which was fixed by the change in the character of the signal on a control oscillograph, by the drop in the power on the heater and by the change in the tone of sound which accompanies the process of boiling. After this the temperature was decreased and the boiling curve reversed. As a rule, this procedure was carried out several times to refine the critical values of the process parameters.

Preparation of the liquid. Distilled water was the working liquid. Before the beginning of each experiment it was boiled for 30–40 min in a working vessel with the assembly put inside, which ensured good reproducibility of results.

5. Results of experiments

The phenomenon of jumpwise occurrence of the regime of bubble boiling was observed at small subcooling of the liquid below the saturation temperature, therefore the first results were obtained for the case of boiling of subcooled liquids.

---

[2] Under the conditions of operation with a resistance stabilizer the boiling crisis sets up on a small local portion of the heater and leads to the development of a stable inhomogeneous regime on it. The greater part of the heater is in the bubble boiling regime, whereas on the remaining portion of size from fractions of millimeters to several millimeters (depending on the heater diameter and the liquid temperature) there is a film boiling regime. Since the stabilizer maintains the whole probe at a mean temperature, the heating in the zone of the film regime is not very high (even for cold water it does not exceed 200–300 °C) and the heater does not breakdown (for more details about the special features of stationary states of the heater in this regime see [10]).

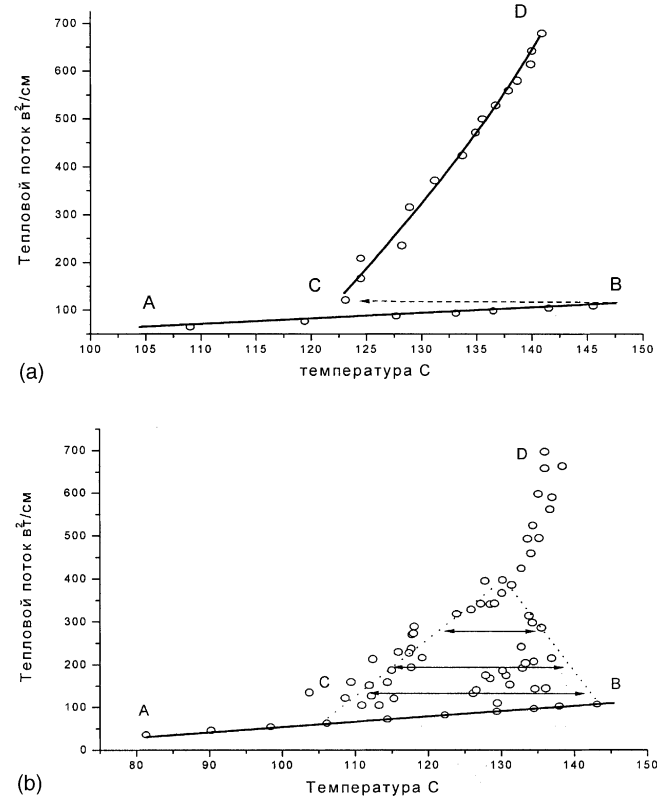

Fig. 2. The distilled water boiling curve ($T_{\mathrm{liq}} = 20$ °C) on a platinum wire of $d = 0.1$ mm at a constant heat flux. AB, the branch of free-convective heat transfer; BC, boiling-up; CD, bubble boiling. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C.

Figs. 2a and 3 present the curves of boiling [3] of distilled water on a platinum wire of diameter 100 μm at the liquid temperature 20 °C. The first curve was obtained in the mode of the stabilization of the current passing through the heater (the analog of the $q = \mathrm{const}$ regime) and the second in the regime of stabilization of the integral mean temperature ($T = \mathrm{const}$ regime). In both cases, the experimental points in the figures represent the time-averaged values (the averaging time is 3 min).

The first to attract attention in analyzing the curves presented is the control of critical phenomena in both regimes. Transition from free-convective heat transfer to bubble boiling occurred by a jump on attainment of the critical value of the parameter which is used for controlling (temperature or heat flux). However, the consequences of the development of these phenomena are essentially different. In the first case, the transient process is accompanied by a decrease in the temperature of the heater with a constant heat flux temperature (transition BC, Fig. 2) and is ended with bubble boiling characterized by the presence of irregular fluctuations of the heater temperature (Fig. 2b). In the second case, with the heater temperature being constant, there occurs a considerable increase in heat transfer (transition along the BD arrow, Fig. 3). In both regimes of control, the reverse transition is also observed from the regime of vapour formation to the regime of free convection, but while in the first case this transition is associated with disappearance of the last bubble from the heater surface, in the second case the boiling ceases instantly and simultaneously over the entire surface.

The most interesting results were obtained in the region of heat fluxes close to a maximum heat flux. The first to be mentioned is the great difference in the values of the heat fluxes attained in the experiment. While the supply of the load in the regime $q = \mathrm{const}$ ensures stable operation up to $q = 700$ W/cm^2 (Fig. 2), [4] the applica-

---

[3] Here and hereafter only a portion of the boiling curve is given which includes the branches of bubble boiling and of free-convective heat transfer.

[4] In different experiments, the crisis occurred in the interval of heat fluxes 300–700 W/cm^2, i.e., the given value of the critical heat flux (700 W/cm^2) is close to the maximum values observed in the experiments.

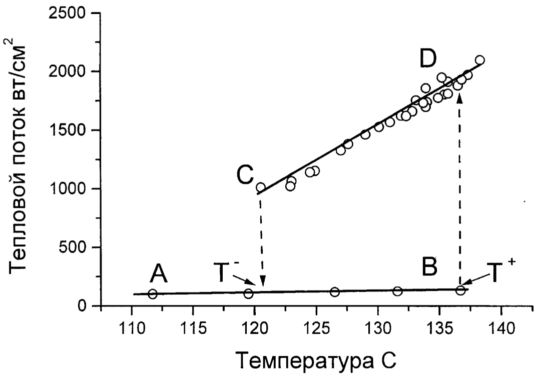

Fig. 3. Distilled water boiling curve ($T_{\text{liq}} = 30$ °C) on a platinum wire of diameter 0.1 mm at a constant temperature of the heater. AB, branch of convective heat transfer; BD, boiling-up; CD, bubble boiling branch. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C.

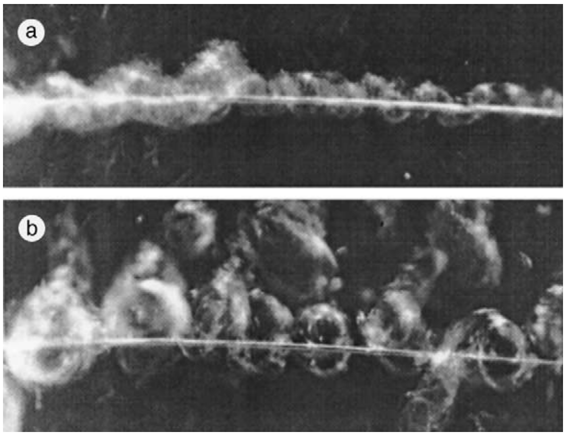

Fig. 4. Bubble boiling. Regime $R = \text{const}$, $d = 0.1$ mm, $T_{\text{liq}} \approx 70$–80 °C.

tion of the resistance stabilizer made it possible to attain three times higher heat fluxes (Fig. 3) for an absolutely stable boiling.

The second is the essential difference in the laws of heat transfer. While in the case of heat flux stabilization the function $q = q(T)$ can be approximated by the power-law dependence (Fig. 2a), then in maintaining the temperature of the heater constant the heat flux is linearly connected with temperature. The change in the laws of heat transfer influences the character of the process of vapour generation. At $q = \text{const}$, boiling is ordinary in character; it was described not once in many works, while in stabilization of temperature a fundamentally different picture is observed. At large subcoolings, vapour generation occurs in the form of fine bubbles which depart with a high velocity from the surface and around the heater they form virtually symmetric finely dispersed vapour cloud, the characteristic dimensions of which exceed tens of millimeters. Externally the regime observed is more like a film regime of boiling, while the sonic effects accompanying boiling are especially intense. Some notion about the differences in the character of bubble boiling is given by Fig. 4, which presents the photographs obtained in the regime of $R = \text{const}$.

The transformation of the boiling curve with a change in the degree of subcooling of the liquid is shown in Fig. 5. It is seen that an increase in subcooling caused the bubble boiling branch to extened to the side of higher and higher superheatings and heat fluxes not changing its position relative to the branch of free-convective heat transfer. Thus, it was found that the law of heat transfer in the bubble regime is independent of the degree of liquid subcooling below the saturation temperature.

To investigate the influence of the heater diameter on the regularities of vapour generation, experiments were carried out on wires of diameters 50 and 20 μm. The results obtained point to the fact that a qualitatively similar character of the dependence $q = q(T)$ is retained in the entire range of the investigated diameters. The revealed quantitative differences consisted in a certain change in the temperatures of the beginning (T') and termination (T) of bubble boiling and in the magnitude of the critical heat flux. The boiling curves for the 20-μm filament are presented in Fig. 6; Fig. 7 presents the graph which generalizes the results of several experiments in the course of which the diameters of the heater and the degree of liquid subcooling were varied. It follows from Fig. 7 that in experiments with a temperature stabilizer in all the cases the bubble boiling branch remains linear with a constant inclination angle.

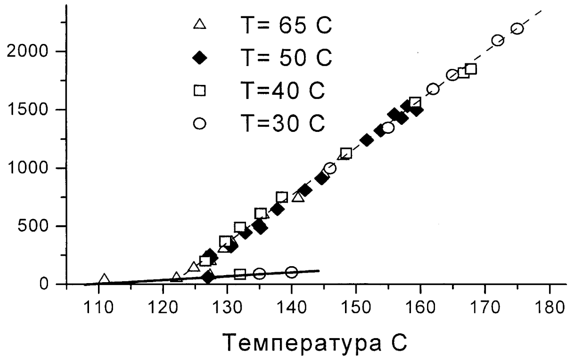

Fig. 5. Branch of bubble boiling at different liquid temperatures. Water, heater of $d = 0.1$ mm; the liquid temperature $T = 65$, 50, 40, and 30 °C. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C.

Of great interest is the study of the kind of transition characteristics of the process of the incipience and termination of bubble boiling which contain important

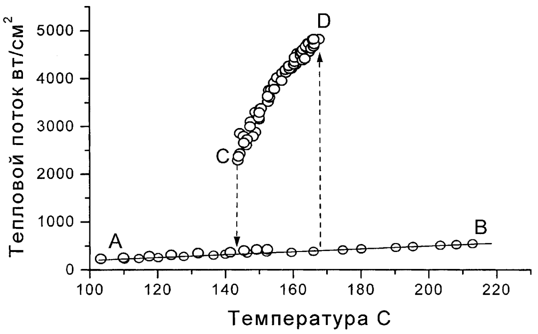

Fig. 6. The form of the boiling curve for the heater of $d = 0.02$ mm, $T_{\text{liq}} = 20$ °C. The regime of a stabilized temperature. AB, convection; CD, stable bubble boiling. Points in the figure relate to different experiments. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C.

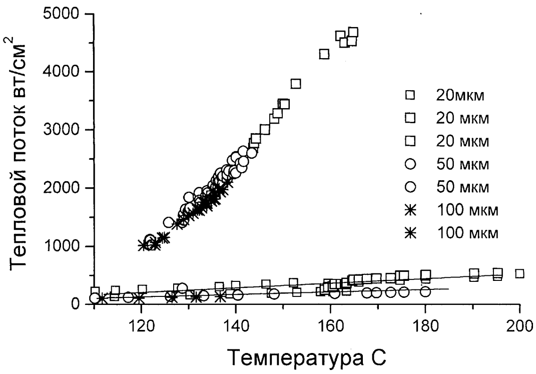

Fig. 7. Dependence of the heat flux on the heater temperature (boiling curve) for different diameters of the heater and the liquid temperatures. $T_{\text{liq}} = 20$–60 °C. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C; мкм = μm.

information on the nature of active centers, laws of their multiplication, and their demise. However, according to the data given in [14,15], the decay of metastability and transition from convection to bubble boiling always occurs in the form of a self-wave process, which does not allow one to apply traditional methods for analyzing the characteristics of the establishment of boiling. As to the reverse transition (from bubble boiling to convection), its self-wave nature has not been proven. In the present work, we obtained the results of investigations of a reverse transition. It appeared that boiling terminates spontaneously, with the time of transition to the convective branch of heat transfer not exceeding 200 μs. We have failed to elucidate the dependence of the duration of transition on the heater temperature (Fig. 8). In some experiments, after the attainment of the convective regime of heat transfer a sudden jumpwise increase in the power with subsequent relaxation to the regime of convective heat transfer of duration ≈0.1 s was observed (Fig. 8b).

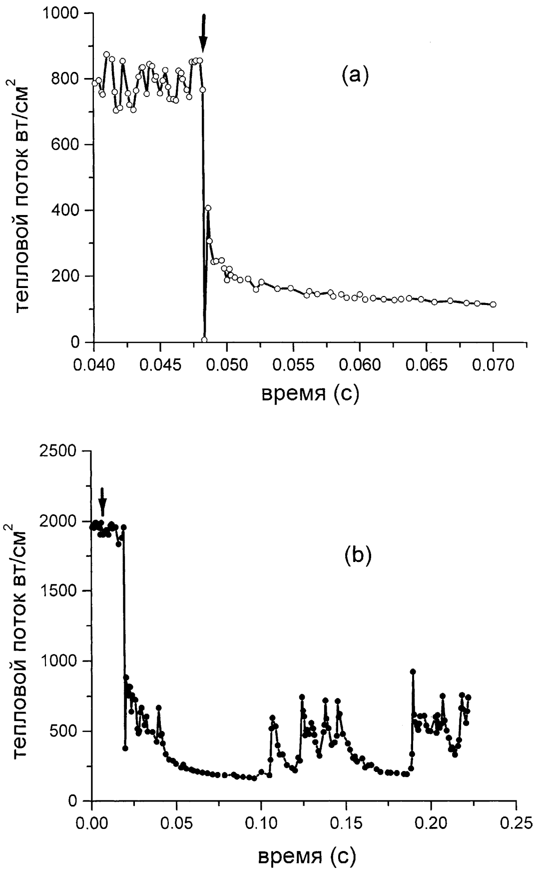

Fig. 8. Oscillogram of transition from bubble boiling to convection, $d = 50$ mm, (a) $T_{\text{liq}} = 40$ °C, (b) $T_{\text{liq}} = 80$ °C. The arrow denotes the moment of the assignment of $T = T^-$ on the heater. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; время = time.

With increase in the temperature of the liquid and its approach to the saturation temperature, the difference $T^- - T^+$ (Figs. 3, 5–8) decreases and the earlier distinct jumps between stationary regimes gradually disappear and the heat flux virtually ceases to depend on the temperature. In a narrow temperature range (≈2 °C) irregular jumps of heat power (Fig. 9) from the values typical of convective heat removal to maximum ones are observed. A similar behavior of the heater could be seen on heaters of different diameters.

The character of change in the critical values of the bubble boiling parameters depending on subcooling and the heater diameter is shown in Figs. 10 and 11. It is seen from the figure that both the critical heat flux and the critical temperature increase with liquid subcooling and with a decrease in the heater diameter, whereas the temperature of termination of boiling (T) remains vir-

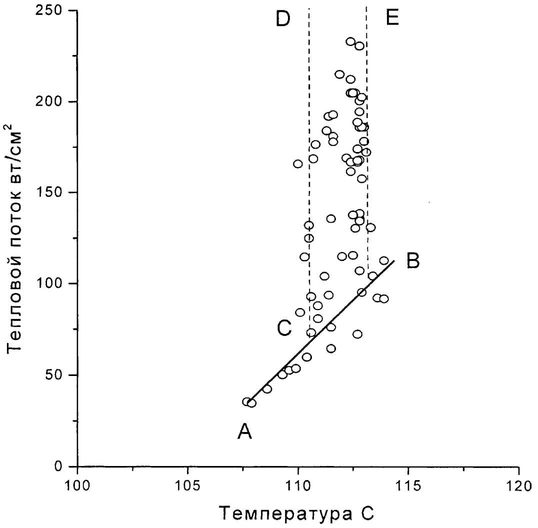

Fig. 9. The form of the boiling curve in the regime $R = \text{const}$ for water at the saturation temperature, $d = 0.05$ mm. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C.

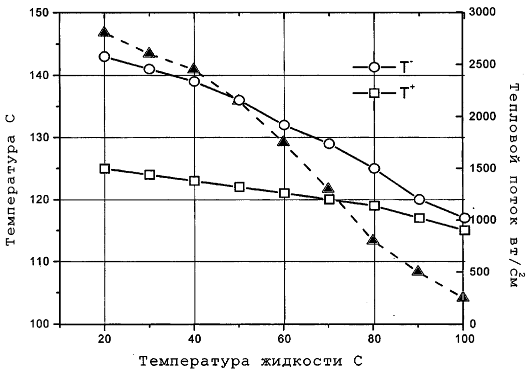

Fig. 10. Dependence of the critical heat flux, critical temperature and the temperature of the cessation of boiling (T^-) on the liquid temperature, $d = 0.05$ mm. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C; температура жидкОСТк С = liquid temperature, °C.

tually insensitive to liquid subcooling. This fact supports the data presented in Fig. 5 and indicates that the region of the nonuniqueness of stationary states is expanded as subcooling increases.

The interest in the physics of boiling and in the problem of the effect of the process of the vapour generation of the gas dissolved in the liquid is traditional. The most interesting regularities confirming this effect and observed in our experiments are presented in Figs. 12 and 13.

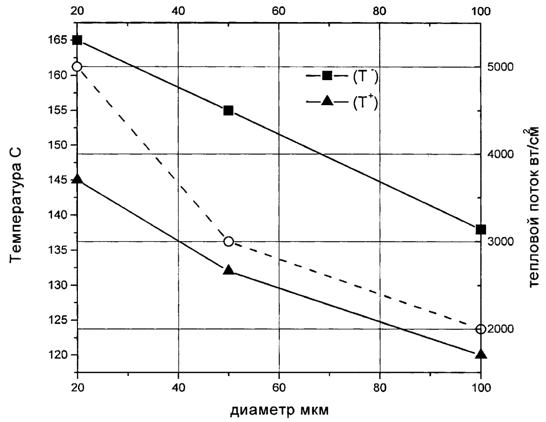

Fig. 11. Dependence of the critical heat flux, critical temperature and the temperature of the cessation of boiling (T^-) on the heater diameter. Key: Тепловой поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C; диаметр мкм = diameter, μm.

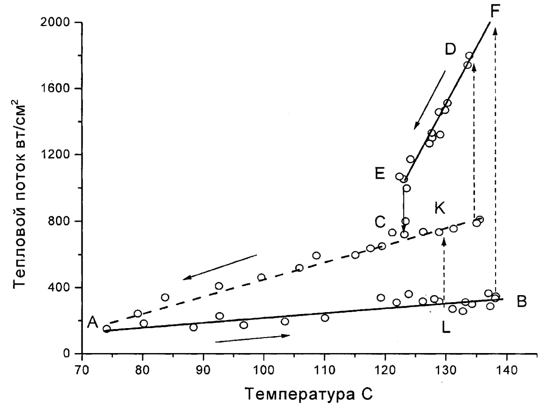

Fig. 12. The form of the boiling curve obtained with the use of the heater temperature stabilizer for water containing dissolved air; ALB, the branch of free-convective heat transfer; GHC and ACK, intermediate branches of bubble boiling; EDF, branch of stable bubble boiling. The heater diameter is 20 mm. Key: Тепловой поток = heat flux; ВТ = W/cm^2; температура С = temperature, °C.

Fig. 12 presents the boiling curve obtained with the heater temperature stabilizer in an un-degassed water. A characteristic feature of heat transfer of this liquid is the existence of different laws of heat exchange in the region of bubble boiling, which manifested itself in the existence of two branches of stationary states. The following jumpwise transitions were observed in the experiments: at high values of the initial superheating, the boiling-up led to the attainment of the branch with maximum heat transfer (transition BF) and at lower values, to the

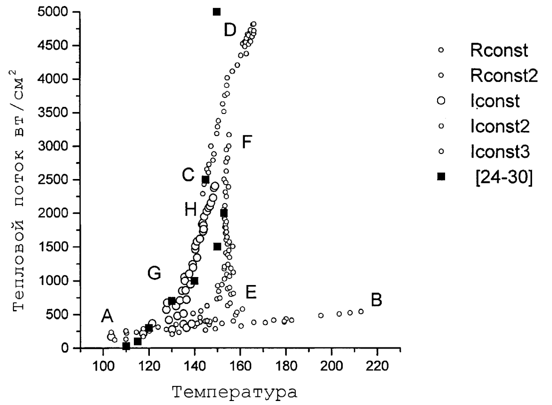

Fig. 13. The form of the experimentally observed curve of boiling of water saturated with air in the regime of controlling the heater by the heat flux. The heater diameter is 50 μm. Key: Тепловой поток = heat flux; ВТ = W/cm^2; температура С = temperature, °C.

transition to the branch of intermediate states (transition LK). The vapour formation ended in a jump, with the transition from the upper branch always terminating on the branch of intermediate states. The inclination angle and the depth to which the branch ACK enters into the region of low temperatures (below 100 °C) were entirely determined by the degree of liquid saturation with a gas.

In the case where the heater was fed from a current source, the influence of the dissolved gas on heat transfer manifested itself in the displacement of the boiling curves to the region of lower temperatures (Fig. 13). The behaviour of the boiling curve obtained after long boiling of the liquid and its rapid cooling to room temperature is unusual. As is seen from the figure, above the region of oscillations (Fig. 13, curve 2) the bubble boiling branch steeply goes upward, virtually vertically. This behaviour persists until the stationary bubble boiling branch is attained, following which crisis phenomena develop. For rather a short interval of time (≈15–30 min) the FE curve moves to the side of low temperatures and begins to coincide with the curve GH.

6. Discussion of the results obtained

Before we start the discussion, we summarize some intermediate results. Thus, it was found experimentally that under the conditions of the heater temperature kept constant, boiling of a subcooled liquid in a certain interval of the heater temperature occurs in the mode of bubble boiling characterized by extremely high intensity of heat transfer. The appearance and disappearance of this regime undergoes a critical stage. In the entire range of the existence of this regime, the heat flux depends linearly on the temperature head. Transition to a regime of a constant heat flux leads to the appearance of a traditional curve of boiling.

It is convenient to begin the discussion of results from the analysis of the experimentally obtained volt–ampere characteristics of the heater. Fig. 14 depicts the volt–ampere characteristic of the element operating in the mode of power sustainment ($I = \text{const}$ regime) and Fig. 15 presents the same in the mode of sustainment of the heater temperature ($R = \text{const}$ regime). (Recall that the corresponding curves of boiling are given in Figs. 2 and 3). As is seen, the curves $I = f(U)$ presented in Figs. 14 and 15 have both common and different features.

We will begin consideration of the special features from the volt–ampere characteristic of the element

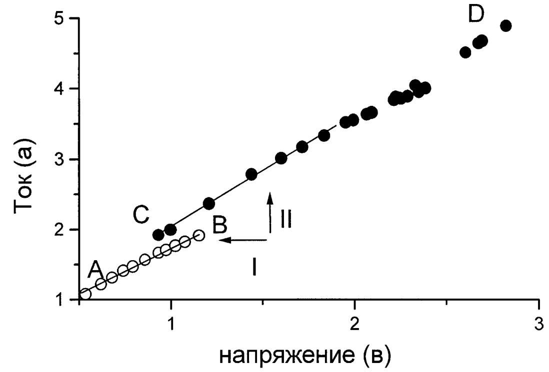

Fig. 14. The volt–ampere characteristic of the wire heating element. The regime of load supply $I = \text{const}$. AB, branch of free-convective heat transfer; CD, branch of bubble boiling. I, II, direction of possible transitions. Key: Ток (а) = current (A); напряжеНие = voltage (V).

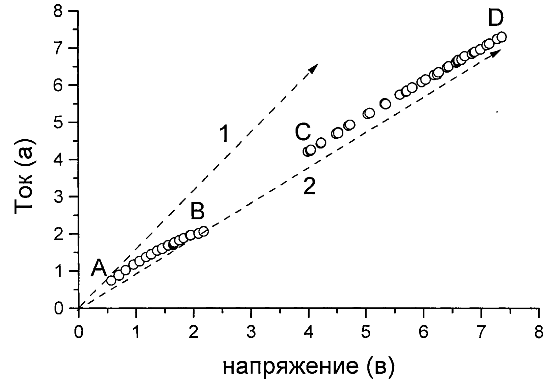

Fig. 15. The volt–ampere characteristic of the wire heating element. The regime of load supply $R = \text{const}$. AB, bransc of free-convective heat transfer; CD, branch of bubble boiling. (1, 2) loading curves for different temperatures $T_2 > T_1$. Key: Ток (а) = current (A); напряжение = voltage (V).

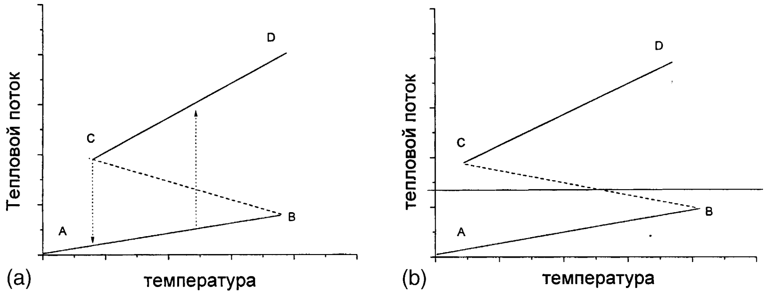

Fig. 16. (a) The qualitative form of the boiling curve. In the experiment the conditions maintaining the heater temperature constant are implemented. (b) Diagram of the stationary states of the heater. In the experiment the conditions of a constant heat flux are given. Key: Тепловой поток = heat flux; температура = temperature.

connected to the integral-mean temperature stabilizer. The typical form of the volt–ampere characteristic under these conditions is given in Fig. 15. For subsequent analysis it is important to bear in mind that the control regime sustains the given resistance of the probe constant in time. Taking into account that $R = U/I$, we may conclude that in the plane of the coordinates U–I for any value of R there will correspond the loading straight line emanating from the coordinate origin with the inclination angle tangent U/I.

First of all, we pay attention to the fact that the experimentally obtained current–voltage dependence is discontinuous, i.e., there is a region of parameters in which the system investigated does not have stable stationary states, and this determines the behaviour on change in the temperature.

An increase of the initial temperature leads to a decrease in the inclination angle of the loading straight line relative to the abscissa axis. In this case, the representing point (the point of intersection of the loading straight line with the branches of the stationary states) displaces along the line AB from the point A to the point B. At the point "B" the branch of free-convective heat transfer becomes unstable, and on attainment of this branch there occurs a jumpwise transition to the upper branch of stationary states (the bubble boiling branch) accompanied by an appreciable increase in heat transfer.

In reverse motion (decrease in the heater temperature), the representing point moves along the CD line up to the point C at which the bubble boiling regime becomes in turn unstable and one experimental transition to the convective heat transfer branch is observed.

The volt–ampere characteristic of the wire element placed, e.g., into an inert gas medium is a weakly nonlinear monotonically increasing function. The special features revealed in the experiments can be due only to the presence of boiling on its surface. Thus, under the conditions of constant temperature of the heater for the process of heterogeneous vapour generation there corresponds a discontinuous form of the boiling curve characterized by the presence of the region of nonuniqueness of stationary states (Fig. 16a). [5]

Let us consider the volt–ampere characteristic of the element connected to a source of stabilized current. We note that the function $I = I(U)$ depicted in Fig. 16a also contains a singularity in the form of a discontinuity, pointing to the existence of a temperature jump during boiling-up (see Fig. 2, transition BC). The qualitatively similar dependence $I = I(U)$ results in the case where the supply of the heater occurs in the regime of control by the voltage ($U(t = \text{const})$) with the only difference that in this control regime the transition to the bubble boiling branch follows the line of constant voltage (Fig. 14, transition 11).

In contrast to the case considered above, the volt–ampere characteristic of the element fed from a current source has no "forbidden" regions. Over the entire range of currents and voltages (outside the nonuniqueness region) the function investigated remains to be smooth and continuous. Thus, except for the point B a stable operation of the heater is to be observed in the experiments at any currents, which contradicts the experimental results. It is known that the process of boiling-up ends up with the establishment of irregular fluctuations of the heater temperature which also are retained on considerable increase in the heat load. (In Fig. 2a the region of fluctuations is absent, since it presents the time-averaged values. When instantaneous values of temperature are laid off on the graph, for each heat load in the experiment there corresponds the range of measured temperatures (Fig. 2b).)

---

[5] Restoring the form of the boiling curve by using the volt–ampere characteristic of the heating element, we assumed that all the points of the heater surface are equally capable of vapour generation, i.e., we excluded the possibility of the existence of nonuniform distribution of boiling centers over the surface, thus assuming that the heater relates to the class of concentrated systems.

It seems that the special features revealed by analysis in the behaviour of the considered curves can be explained if we assume that the boiling curve in the region of transition from free-convective heat transfer to bubble boiling has really a discontinuous form with the nonuniqueness of stationary states.

Let us analyze the results obtained in this work from these standpoints. Let us try to imagine a possible mechanism of the implementation of heterogeneous boiling with different means of controlling a fuel element.

When carrying out experiments with a stabilizer on the heater, evidently, a process of heterogeneous vapour generation is implemented without any other regimes of heat transfer. In what follows, this regime of heat transfer will be called the stable regime of bubble boiling, whereas the term unstable bubble boiling will be referred to the regime of heat transfer implemented on the heater when $q = \text{const}$. It follows from the data presented in Figs. 5 and 7 that heat transfer in the bubble boiling regime is independent either of the liquid temperature or of the degree of subcooling, or of the heating element diameter, that is, of this traditional parameters for the boiling process and is described by the single dependence $q = q(T)$. The fact of observation of critical phenomena points to the fact that bubble boiling exists only in a certain temperature interval and the form of the volt–ampere characteristic of the heater confirms the homogeneity of the regime observed.

The temperature interval of the existence of bubble boiling is limited from above by the value of the critical temperature; the lower boundary seems to be determined by thermodynamic and kinetic restrictions imposed on the process of heterogeneous formation of bubble nuclei.

Thus, the boiling curve in the temperature region $T < T_{\mathrm{cr}}$ must have the form depicted in Fig. 16a. It is seen from the figure that in the experiments a transition to a bubble regime occurs not on attainment of the unstable point (spinodal), but substantially earlier, i.e., it is assumed that the critical phenomena have a self-wave character.

In the $q = \text{const}$ regime, the presence of the discontinuous boiling curve lead to the case which graphically is depicted in Fig. 16b. Between the branches of stationary states and the loading straight line there is the sole intersection point which is located on the branch of unstable states. [6] Since the investigated system is kept by a controlling device on the straight line corresponding to a conditions of a constant heat flux, the selected regime of control must lead to stabilization of the unstable regime. It is seen from the figure that the mechanism of heterogeneous vapour generation in the developed regime of heater operation cannot be realized until the increase in the heat load makes the heater attain the branch of stable boiling. On the branch of unstable states, vapour generation on the surface is insignificant leading to the overheating of the liquid layers adjacent to the heater surface. At the heater temperatures exceeding the saturation temperature, the overheated layer becomes metastable and in it the possibility of exciting the process of homogeneous nucleation appears. [7] The vapour formed relieves the overheating of the liquid, and the stage of its heating begins again. Thus, in the regime of controlling the power ($q = \text{const}$) the zones of volumetric (homogeneous) boiling must occur near the heater.

The foregoing physical picture of boiling can be observed in its full extent only for an absolutely homogeneous surface, i.e., for the case when the heater behaves as a concentrated system. For actual heat generating elements this condition is not satisfied, therefore the existence of the above-described processes on them must be accompanied by the establishment of a spatially inhomogeneous regime when on the heater there simultaneously exist spatially separated zones of different heat transfer regimes. However, the presence, of the zones of boiling-up of the superheated liquid near the heater surface must remain to be the characteristic feature of this regime. Thus, boiling occurring on a heat-generating surface under the conditions of a constant heat flux is not a self-maintained regime, but represents a spatially distributed combination of three regimes, that is, of free-convective heat transfer, periodic boiling-up of superheated layers of liquid near the surface and of unstable heterogeneous vapour generation.

As a direct proof of the reality of the proposed mechanism we can consider the results of works [14,15] in which the presence of homogeneous stages in a stationary bubble regime was recorded in several ways, including direct filming.

A number of indirect proofs of the proposed mechanism are presented in the results of this work, in particular, the fact of the existence of the region of fluctuational instability in the regime $q = \text{const}$ (Figs. 2b, 13). In accordance with the above-given notions, the occurrence of self-fluctuations of the heater temperature occurs in a rigid manner due to the attainment of the

---

[6] This situation was considered earlier in [16], where, on the basis of the similarly analyzed phenomenon with the well-studied case of operation of a neon lamp with an identical volt–ampere characteristic [17], a conclusion was drawn that with this regime of control relaxational vibrations must arise in the system which involve both stationary states. However, a more attentive analysis of the situation proved the uncorrectness of the above analogy.

[7] The specific mechanism underlying the incipience of nuclei, in particular, the question whether it is purely homogeneous or there are heterogeneous stages in it, is not considered at the present time for lack of experimental data.

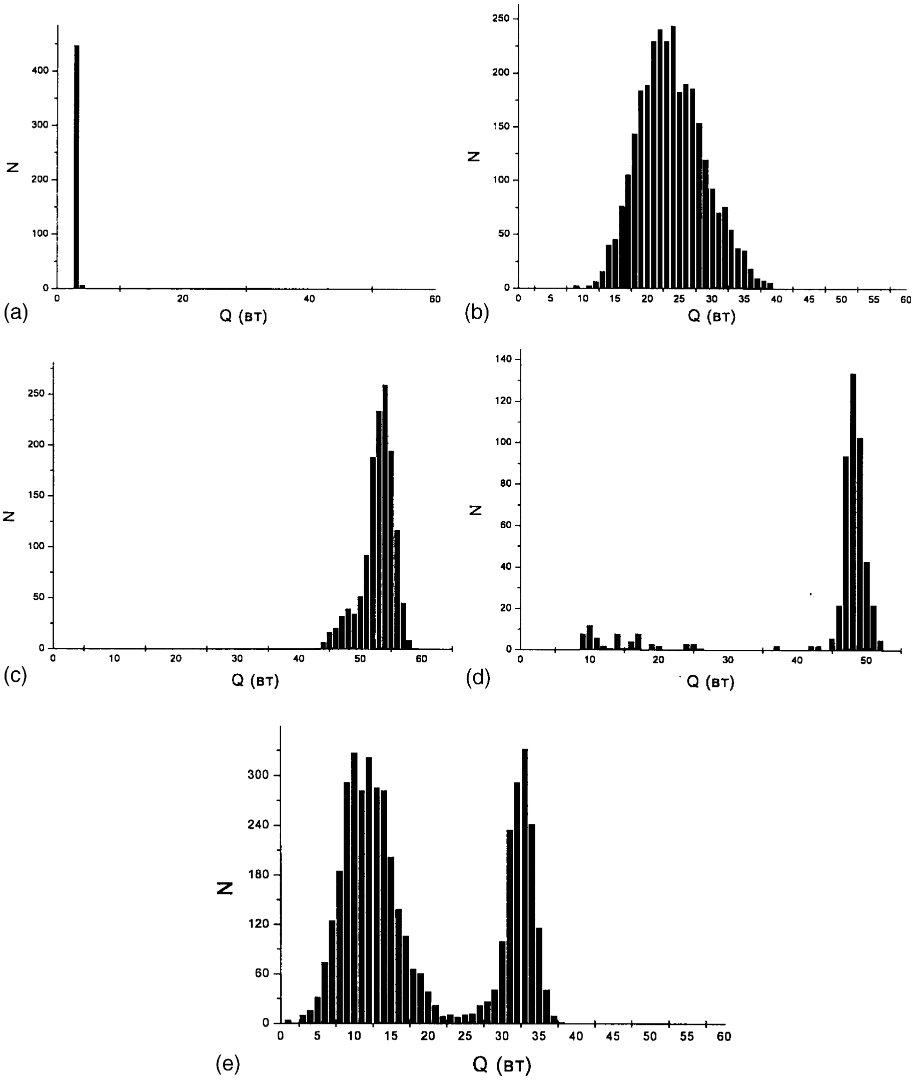

Fig. 17. The histogram of the distribution of power in the regime $R=\text{const}$: (a) free convection; (b) bubble boiling, (c) same at the load close to the critical; (d) beginning of the formation of the mixed boiling regime; (e) mixed boiling regime. Key: Bт = W.

branch of unstable boiling. Their amplitude is the greatest near the branch of convective heat transfer and decreases gradually with increase in the heat load. On attainment of the regime of stationary boiling [8] the fluctuations smoothly disappear. The value of the heat load at which they disappear is equal to the value of the minimum heat flux measured in the experiments with the heater temperature stabilization.

One other proof of the validity of the proposed mechanism of subcooled boiling follows from the analysis of Figs. 17 and 18 which represent histograms of the distribution of power and temperature on the probes operating in the regimes $R=\text{const}$ (Fig. 17) and $I=\text{const}$ (Fig. 18). In the figures N is the number of realizations. It is seen that for each means of control there corresponds a characteristic form of the distribution curve which reflects the special features of the mechanism of boiling of the given operation regime of the heater.

For the case $R=\text{const}$ in the region of free-convective heat transfer the fluctuations of the heater temperature are insignificant and slight changes in the power are needed for their compensation (Fig. 17). In transition to the regime of stable bubble boiling (Fig. 17b) the form of the function of power distribution does not undergo a

---

[8] On some heaters it was possible to attain the lower boundary of stable bubble boiling even in the mode of a constant heat flux.

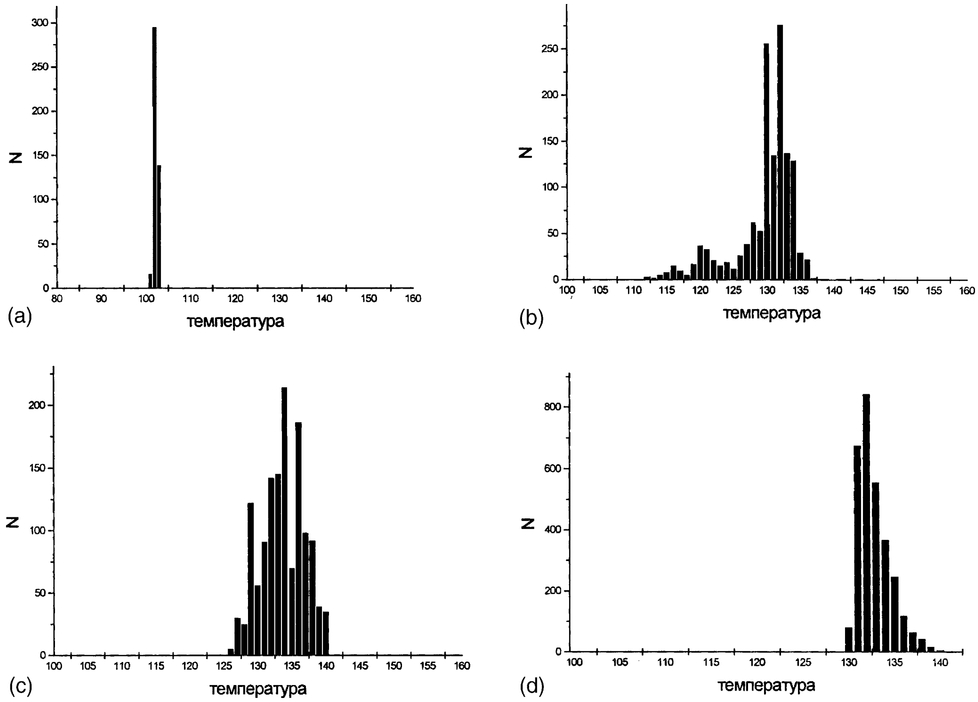

Fig. 18. Histograms of the distribution of the heater temperature in the regime $I = \text{const}$; (a) free convection; (b) bubble regime after boiling-up; (c) bubble boiling regime near the branch of stable boiling; (d) bubble boiling near the critical heat flux. Key: температура = temperature.

qualitative change; however, a small expansion of the power interval is observed which is required to stabilize the regime. We note that the curve obtained closely resembles the curve of normal distribution.

With a further increase in the temperature and approach to the value of T_{cr} (Fig. 17c) the distribution curve becomes asymmetrical due to the broadening of the "cold end". The indicated feature reflects the changes in the character of the processes occurring on the heater, namely, in the process of boiling dangerous superheatings occur, and in order to prevent them, the stabilizer must periodically reduce the power. On further increase in the temperature (Fig. 17d and e), the distribution becomes bimodal and reflects the probability of the existence of different regimes of boiling on the heater: a bubble one and partially a film one.

Let us analyze the distribution of the heater temperature for the case $q = \text{const}$. It is seen from Fig. 18a that the histogram of temperature distribution in a free-convective regime of heat transfer corresponds to the histogram of power distribution in the regime $R = \text{const}$, whereas qualitative differences are observed in the region of unstable bubble boiling (Fig. 18b). In this regime the spectrum is broadened greatly due to the appearance of lower and lower values of temperatures. As follows from the above-described mechanism of boiling, in this regime fluctuations of the heater temperature are determined by the appearance of the zones of homogeneous boiling-up of a liquid on the heater surface. A further increase in heat load and approach to a critical heat flux leads to the appearance of a large number of "hot" perturbations, and the distribution curve first tends to become symmetrical (Fig. 18c) and then displaces to the region of high temperatures (Fig. 18d). The increase in the frequency of the appearance of dangerous perturbations ends by the appearance of a film boiling wave.

Thus, analysis of the histograms confirms the above assumptions about the mechanisms of bubble boiling of a subcooled liquid.

To get direct confirmation of the results obtained, we carried out experiments the aim of which was to confirm the predicted behaviour of a point heater on the branch of unstable states (Fig. 16b). The experimental method was used developed earlier to investigate the kinetics of heterogeneous-catalytic reactions [18] which made it possible to obtain a model of a point system on decrease in the length of the heater. When the size is smaller than the length of thermal relaxation, an inhomogeneous temperature profile is formed on the heater because of the presence of heat losses to the current loads. In this case, the maximum temperature will be attained in a narrow zone at the center of the filament where the principal processes occur. Precisely this zone was used as a special very small heater. The experiments were carried out in an assembly which made it possible to decrease the length of the heater to about 1 mm. The calculations of the maximum temperature of the probe were not carried out, therefore the results given below are of qualitative character. The heater operated in the regime $I = \text{const}$.

At a small value of the heat flux on the "point" heater, just as in a fuel element of normal size, the mode of free-convective heat transfer was established. On increase in the heat flux, it was replaced by a stable self-fluctuational regime. The self-fluctuational regime of heat transfer had a rigid origin. The observed fluctuations at a fixed value of the current had constant frequency and amplitude. An increase in loading led to an inertialess change in their frequency. As an illustration, Fig. 19 presents some of the obtained thermograms of self-fluctuations. As is seen, they have a distinct relaxational character. The period of fluctuations is composed of the following stages: AB, heating of the liquid; BC, the stage of vapour generation in a superheated boundary layer and cooling of the liquid to the saturation temperature. We note that the fluctuations were stable and preserved their shape and frequency for a long time (for tens of minutes).

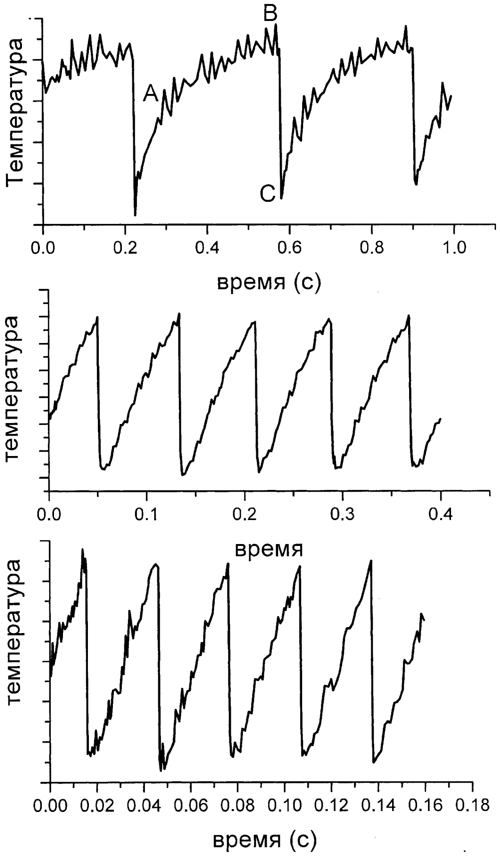

Fig. 19. Thermograms of a self-fluctuational operational regime of a "point" heating element. Key: температура = temperature; время (с) = time (s).

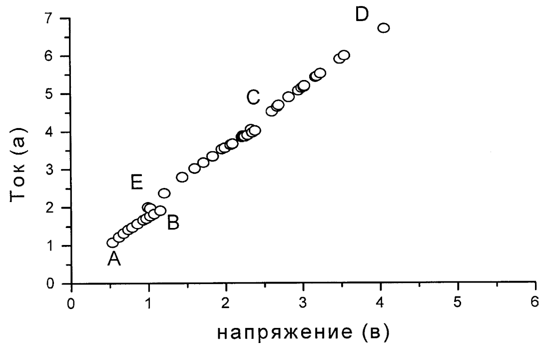

Fig. 20. The volt–ampere characteristic of the heating element operating in a gas-saturated water in the regime of temperature stabilization. The boiling curve corresponding to this case is presented in Fig. 13. Key: Ток (а) = current (A); напряжение = voltage (V).

Within the framework of the developed notions about unstable boiling it is possible to explain the mechanism of the effect of the gas dissolved in the liquid on the process of heterogeneous boiling. As follows from the physical model, the formation of gas bubbles in the stage of superheating of the boundary layer must cause active evaporation of the liquid in them [19]. This will lead to a decrease in superheating and, consequently, will favour the decrease and complete suppression of the "bursts" of homogeneous vapour generation because of the increase in the centers of gas and vapour release. Thus, the saturation of the liquid with a gas must lead to an increase in the stability of the bubble boiling regime.

Analyzing Fig. 13, we may see that the boiling curve for the liquid saturated with a gas is characterized by a much smaller amplitude of temperature fluctuations in the range of loads of interest for us in comparison with a degassed one. The experimentally observed displacement of the boiling curve to the region of lower and lower temperatures also gets its explanation. Fig. 20 depicts the volt–ampere characteristic of the heating element operating in the mode of $R = \text{const}$. As we can see, the presence of a dissolved gas in the liquid has led to the appearance of a new branch of stationary states which is located in the formerly "forbidden" region of the parameters. Being aware of the "imaginary nature" [9] of

---

[9] Speaking of the "imaginary nature", we bear on mind the fact that it absolutely formally entered into the diagram of stationary states of the process of vapour generation, since actually it is the characteristic of quite a different process, viz., of liquid degassing.

this branch, we pay attention to the fact that its appearance has substantially changed the situation for the $R = \text{const}$ regime. Now, at a fixed temperature of the heater the system will be stable everywhere. It is seen from the figure that the new regime must be characterized by lower temperatures of the heater.

We note that according to the revealed mechanism, the saturation of liquid by a gas in experiments with a "point" heating element, led to the loss of the reproducibility of the form and frequency of vibrations.

At the end of this discussion we consider the description of one other experiment, the statement and the prediction of the results of which follow from the developed physical model of bubble boiling. Its idea is understandable from the following considerations.

It is well known that even near the point of crisis the main amount of heat from the heater is removed in the regime of free convection. Theoretical estimates [20] and direct measurements [21] show that only several percents of the total amount of heat evolved on the heater are spent directly on vapour generation. In our opinion, one should consider with caution the numerous data pointing to the strong dependence of heat transfer in bubble boiling on the intensity of forced convection [22]. The controversy between the experimental data and physical representations are removed if we assume that in the works cited the regime of bubble boiling was not attained; they investigated the laws governing the unstable regime in which, as we think, vapour generation really plays an insignificant role. Thus, in the experiment undertaken we ment, on the one hand, to prove the independence of heat transfer on the branch of bubble boiling on the liquid medium velocity, and, on the other hand, to show the strong dependence of heat transfer on the intensity of forced motion on the branch of unstable boiling.

The experiments were carried out on the setup described above. The forced motion of liquid was created with the aid of a magnetic stirrer with a regulated rate of rotation. The results are presented in Fig. 21 and fully correspond to the initial assumptions.

Pool boiling is characterized by the ABCFD curve. The branches of free convection (AB) in the regimes $R = \text{const}$ and $I = \text{const}$ coincide. In the regime $R = \text{const}$, at the point B there was a jump to the FD branch of a stable bubble boiling. In the $q = \text{const}$ regime in the CF region unstable boiling was observed with the amplitude of temperature fluctuations of the order of 15 degrees, and at a load of about 500 W/cm^2 there was a crisis.

In creating forced motion of liquid, the convection branch moved to the region of higher heat fluxes. The EF line corresponds to the maximum rate of blowing. At a lower velocity the convection branch occupied an intermediate position between AB and EF. Near the point F the branch of forced convection EF passed over into the branch of stable bubble boiling FD, with the crisis occurring at a load of about 1700 W/cm^2.

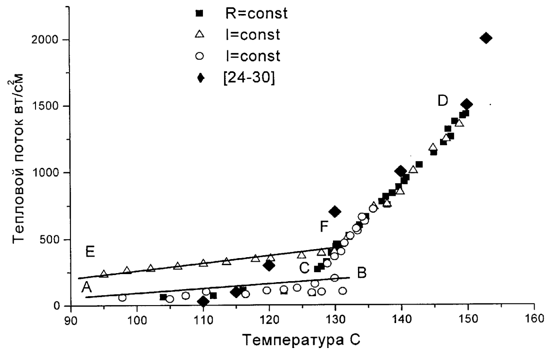

Fig. 21. The boiling curve for the case of pool boiling and forced motion of liquid. ABCFD, pool boiling; CF, unstable boiling, $q = \text{const}$ regime; FD, branch of stable boiling, $R = \text{const}$ regime; EF, forced convection at the mixer rotation speed 400 rpm; FD, stable bubble boiling in the $q = \text{const}$ regime with liquid agitation. (1) $R = \text{const}$; (2, 3) $q = \text{const}$, according to [25–30]. Key: Тепловои поток = heat flux; Вт/см^2 = W/cm^2; температура С = temperature, °C.

The results obtained have confirmed, on the one hand, the initial assumption about the independence of heat transfer in the regime of stable bubble boiling on the intensity of forced convection. On the other hand, they made it possible to conclude that the stabilizations of unstable bubble boiling can be attained not only by changing the regime of control, but with the aid of forced convection.

The results qualitatively similar to those presented in Fig. 22 were earlier observed in boiling of water in heated tubes [22]. Over the initial section of the tube a strong dependence of the intensity of heat transfer on the liquid flow velocity was observed and then a regime

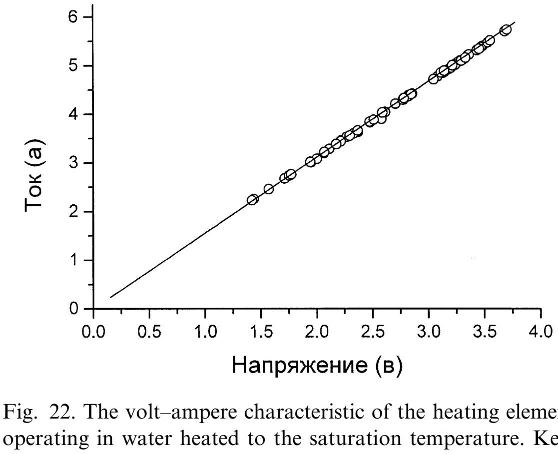

Fig. 22. The volt–ampere characteristic of the heating element operating in water heated to the saturation temperature. Key: Ток (а) = current (A); напряжение = voltage (V).

of "developed boiling" was established which is characterized by a high coefficient of heat transfer on which the liquid velocity does not exert a noticeable effect. The physical processes determining these two, as was considered earlier, fundamentally different types of boiling seem to be identical. To explain the existence of the regime of unstable bubble boiling of metals, an analogous mechanism of the appearance of the factors destabilizing heat transfer was suggested in [23].

In conclusion we note that the inferences made in this work may be extended to the case of boiling not only of subcooled water. In all of the liquids investigated by the authors, viz., in water, acetone, ethyl alcohol, benzene, toluene, heptane and hexane a qualitatively similar form of the curve of boiling was observed. The only condition for its appearance is the subcooling of liquid below the saturation temperature. The physical sense of the requirement is not very clear for us. Possibly, it is associated with a sharp change in the conditions of growth of vapour bubbles in a saturated liquid or is the consequence of such changes in the form of the boiling curve, when the laws of control used become inefficient. To explain the latter assumption, Fig. 22 shows the volt–ampere characteristic of a heater in the liquid heated up to the saturation temperature (the curve itself is presented in Fig. 9). It is seen from the figure that after the beginning of boiling all the experimental points lie virtually along a single straight line. This means that the stabilizer, which in the experiment maintains the prescribed angle of inclination of the loading straight line, is unable to control the process and at the given temperature the heater can be at any point belonging to this straight line. The indicated special feature can be associated with both the narrowness of the hysteresis loop for the liquids at the saturation temperature and the possible degeneration of critical phenomena at this temperature. The answer to this question must be the subject of further investigations.

7. Conclusions

1. It has been proved that the replacement of the regime of controlling the heater by means of a constant heat flux by the regime of constant temperature leads to the increase in the critical heat flux on wire heating elements placed in a subcooled water by a factor of 20–50 in comparison with the literature data.
2. The laws of heat transfer on the revealed branch of boiling are independent of the heater diameter, degree of liquid subcooling, and of the intensity of forced convection.
3. In the regime of control of the heater which ensures the constancy of its temperature, the existence of the branch of stable bubble boiling is revealed, the appearance and disappearance of which passes through a critical stage on attainment of certain temperatures by the heater.
4. It is proved that in the regime of control of the heater by the heat flux in the entire range of heat loads attainable in the experiment the establishment of the stable stationary regime of bubble boiling cannot be ensured. On extended heaters the heat transfer occurs in the form of a spatially inhomogeneous regime which represents a combination of three regimes: the free convective regime, the regime of homogeneous nucleation periodically occurring near the heater surface and degenerated regime of heterogeneous vapour generation.

Acknowledgements

The authors express their gratitude to the Russian Fundamental Research Foundation for financial support, grant nos. 95-02-04334, 97-02-16996 and 01-02-1723.

Appendix A

The present work was sent to the Office of the International Journal of Heat and Mass Transfer in 1996. However, the proofs of the adopted paper were lost in mailing. The work was restored and revised in 2000. During this time new results were obtained related directly to the problems considered, among which of greatest interest, in our opinion, are the data on investigation of microbubble emission boiling (MEB).

For the first time, information on the new regime of heat transfer discovered in boiling of a subcooled liquid moving near the heat generating surface appeared in the beginning of 1980 in Japan journals. Almost 10 years the publications related to microbubble emission were very short and were published only in the Japan language. From the 1990s onwards, the data on this regime began to appear in the publications of international conferences and journals [24–30]. The main results can shortly be formulated in the following way:

- if a cold water is blown with a high velocity (up to 2 m/s) along a plane heat generating surface, then in the region of the existence of a transient regime, heat transfer does not decrease, but rather increases with temperature;
- the regime of the microbubble emission boiling is realized if the flow is directed along the tangent to the surface or along the normal from it;
- the obtained temperature dependences of the heat flux are not monotonic. Based on this, some researchers separate the regimes into two subregimes: calm

and stormy (according to the sound effects accompanying them);
- for the stormy regime and for the calm one it is possible to isolate characteristic frequencies in the sonic region of the spectrum;
- it has been suggested that the microbubble emission boiling is associated with the formation of scale, but this was rejected. No new hypotheses have been advanced up to now.

The external signs of the manifestation of microbubble emission boiling given in [24–30] completely coincide with the signs of developed boiling described in the present work. Moreover, the results given in Fig. 21 can be considered as the proof of the identity of these two regimes. We recall that this figure presents the data of the experiment proving that the branch of developed boiling can be attained at any regime of control if forced convection is organized in the system.

Figs. 12 and 21 present the comparison of our data on heat exchange obtained under the conditions of subcooled pool boiling and the data taken from [24–30]. It is seen that the points corresponding to the stormy regime branch virtually completely coincide with our results. As to the calm regime, then proceeding from the photographs and descriptions of this regime given in [25,27], we may assume that it is a spatially inhomogeneous regime composed of a regime of developed boiling and, probably, a film regime. This kind of the structure was repeatedly observed in our experiments, however, the points corresponding to it were not represented in the figures due to the fact that the mixed regimes of boiling cannot be put onto the boiling curve, for details see [10].

In conclusion, we present some of our new results relating to investigation of the mechanism of developed boiling. Studying the initial stages of the incipience of the bubble regime, we managed to isolate the mechanism which, as we think, provides so high heat fluxes. We found that in a supre-heated metastable liquid destruction of convective mechanism of heat transfer occurs via the formation of an ensemble of submerged microjets directed from the heater surface into the liquid. The formation of the jets is associated with local destruction of a metastable overheated boundary layer and for this reason at the bottom of each of the jets there is an oscillating zone of destruction of the metastable state (Fig. 23c, A) similar to that which was observed by us in the experiments on a short filament. Three types of the manifestation of instability were singled out in the experiments. Formation of an oscillating local zone of destruction not leading to formation of a jet (Fig. 23, 2a, 3, 4, 4a, D) is related to the first type. The second type includes the zones leading to the formation of defocused jets (Fig. 23, 1a, B). And, finally, the third type includes the zones which form distinctly focused jets capable of penetrating a liquid at the distance of tens of diameters (Fig. 23, 1, 2, C). All the three types are dynamic structures and easily go over into one another with time or when the conditions of the experiment change. The velocity of the liquid can be evaluated from the length of the track which is left by the bubbles formed in the jet. It appeared that this velocity attains several meters per second. Thus, near the heater located in a large volume and connected with the resistance stabilizer, high-power convective flows commensurable with those considered in [24–30] may form under certain conditions.

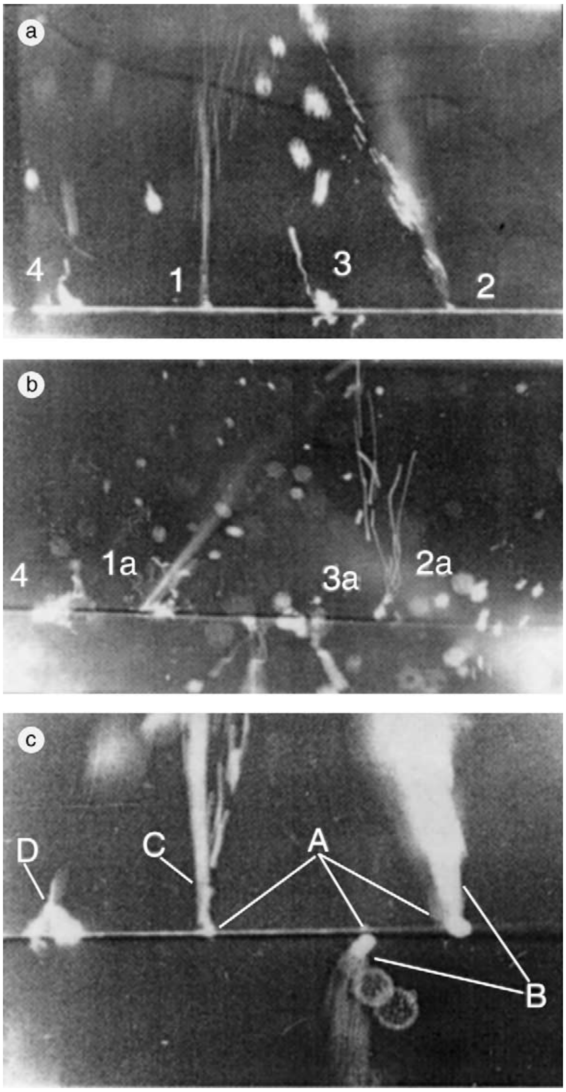

Fig. 23. The photograph of the initial stages of the formation of the developed boiling regime. For explanation, see the text.

References

[1] S.S. Kutateladze, Heat Transfer in Condensation and Boiling, Mashgiz, Moscow, 1952;
Fundamentals of the Heat Transfer Theory, fifth ed., Atomizdat, Moscow, 1979.

[2] J.W. Westwater, J.G. Santangelo, Ind. Chem. Eng. 47 (1955) 1605.

[3] W.C. Peterson, M.G. Zaalouk, A.J. Goetze, J. Franklin Inst. 285 (1968) 285.

[4] M.A. Styrikovich, G.M. Polyakov, Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk 5 (1951) 652.

[5] A.S. Perkins, J.W. Westwater, AIChEJ. 2 (1956) 471.

[6] W.C. Peterson, M.G. Zaalouk, A.J. Goetze, Nucl. Eng. Design 44 (1977) 163, 58 (1980) 57.

[7] W.C. Peterson, M.G. Zaalouk, Trans. ASME 4 (1974) 90.

[8] A. Sakurai, M. Shiotsu, Heat Transfer 4 (1974) 81.

[9] A. Sakurai, M. Shiotsu, Trans. ASME 4 (1977) 44.

[10] S.A. Zhukov, V.V. Barelko, Int. J. Heat Mass Transfer 26 (1983) 269–275.

[11] M.C. Duluc, M.X. Francois, J.P. Brunet, Int. J. Heat Mass Transfer 39 (1996) 1758–1762.

[12] L.B. Mashkinov, Yu.E. Volodin, V.V. Barelko, L.N. Gal'perin, Prib. Tekh. Eksp. 3 (1975) 269.

[13] Yu.M. Grigor'ev, Application of filaments for studying the kinetics of high-temperature interaction of metals with gases. Combustion Processes in Chemical Technology and Metallurgy, Preprint of the Dept. of the Inst. of Chem. Physics, Chernogolovka, 1974.

[14] S.A. Zhukov, V.V. Barelko, Dynamic and Structural Features of the Processes of Decay of a Metastable Regime of Single-phase Convective Heat Transfer and Bubble-boiling Formation, Preprint of the Dept. of the Inst. of Chem. Physics, Chernogolovka, 1987.

[15] S.A. Zhukov, V.V. Barelko, Int. J. Heat Mass Transfer 35 (1992) 759–775.

[16] S.A. Zhukov, V.V. Barelko, A.G. Merzhanov, Int. J. Heat Mass Transfer 24 (1980) 47–55.

[17] A.A. Andronov, A.A. Vit, S.E. Haikin, Theory of Vibrations, Fizmatgiz, Moscow, 1959.

[18] S.A. Zhukov, V.V. Barelko, Dokl. Akad. Nauk SSSR 229 (1976) 655–660.

[19] P.A. Pavlov, The Dynamics of Boiling-up of Heavily Superheated Liquids, Sverdlovsk, 1996.

[20] F.C. Gunter, F. Kreith, Photographic study of bubble formation in heat transfer to sub-cooled water, Jet. Prop. Lab. Progr. Report, CIT, 1950 pp. 4–120.

[21] A.P. Burdukov, G.G. Kuvshinov, V.E. Nakoryakov, Special features of heat transfer of s subcooled liquid in pool bubble boiling at subatmospheric pressures, in: S.S. Kutateladze (Ed.), Heat Transfer in Boiling and Condensation, Novosibirsk, 1998, pp. 94–118.

[22] L. Tong, Boiling Heat Transfer and Two-Phase Flow, Izd. Mir, Moscow, 1969.

[23] V.I. Subbotin, D.N. Sorokin, D.M. Ovechkin, A.P. Kudryavtsev, Natural Convection Boiling Heat Transfer of Metals, Izd. Nauka, Moscow, 1969.

[24] S. Inada, Y. Miyasaka, R. Izumi, M. Kobayashi, Bull. JASME 25 (1982) 1085–1092.

[25] Y. Hirono, R. Shimada, S. Kumagai, T. Takeyama, JSME Int. J. 30 (1987) 1282–1287.

[26] Y. Hirono, R. Shimada, S. Kumagai, T. Takeyama, Techn. Reports of the Tohoku University, vol. 52, 1988, pp. 149–165.

[27] R. Kubo, S. Kumagai, Bubble growth and collapse frequency in microbubble emission boiling performing heat flux, in: Proceedings of the 1st International Conference Transp. Phenom. in Progressing, Honolulu, Hawaii, 1992, pp. 867–878.

[28] R. Kubo, S. Kumagai, Occurrence and stability of microbubble emission boiling-stormy and calm regimes, in: Proceedings of the 10th International Heat Transfer Conference, vol. 5, 1994, pp. 99–104.

[29] S. Kumagai, K. Kawabata, T. Katagari, R. Shimada, Temperature and pressure fluctuation associated with bubble motion in microbubble emission boiling, in: Proceedings of the 11th IHTC, Kyongju, Korea, vol. 2, 1998, pp. 279–284.

[30] S. Kumagai, T. Uhara, T. Nakata, M. Izumi, Void fraction behaviour in the vicinity of the surface in microbubble emission boiling, in: Proceedings of the 5th ASME/JSME Joint Engineering Conference, San Diego, California AJTE 99-6430, 1999, pp. 1–8.