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Dynamic and structural aspects of the processes of single-phase convective heat transfer metastable regime decay and bubble boiling formation

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Abstract—This paper is concerned with the study of the mechanism underlying the formation of the bubble boiling regime on the surface of a heat generating element. Investigations are carried out on electrically heated platinum wires placed in different hydrocarbons. The process of transition from convection to boiling was induced by local disturbances in the region of metastability. It has been found that under the conditions described a self-wave-type transition process is initiated. Depending on the depth of the penetration into the metastability region, the transition process may take place in two modes—of slow and fast waves—that differ by the velocity scale and front structure. The relationships between the wave velocity and the temperature of the heating element have been obtained. Possible mechanisms of the self-wave transition process are considered. The process is found to be identical with the detonation phenomenon. The results obtained are extended to the case of steady-state bubble boiling of subcooled liquid. It is concluded that under the conditions considered the bubble boiling constitutes a poly-self-wave process, i.e. the superposition of fast and slow self-wave processes taking place simultaneously on the heater. The major conclusions are confirmed by the results of high-speed photography.

1. INTRODUCTION

THE PROBLEM of the mechanism for the initiation of the bubble boiling regime on the surface of a heat generating element, immersed in a liquid medium, superseding the convective heat transfer regime with an increase in heat loading, is one of the most important problems of the physics of boiling. It is the studies of the laws governing these transition processes that will give an answer to such fundamental questions as those concerning the existence and nature of active nucleation centres on a solid heat generating surface, the conditions of their appearance and dynamics of multiplication, and the influence of chemical and physical conditions of the surface on the rate of the bubble boiling heat dissipation.

Despite the evidence of the previous statements, the relevant literature devoted to the studies of the region of transition from convection to boiling constitutes an infinitely smaller portion compared with the studies of static trends (loading curves of boiling) in the region of developed bubble boiling. The problem of the decay of the single-phase heat transfer regime has been studied in great detail in relation to the processes in liquid layers adjacent to the surface of electrically heated wire elements in a series of works carried out by Skripov and co-workers [1]. Very much in keeping with the latter work, both methodologically and physically, are the studies of the so-called third crisis of boiling carried out by Avksentyuk and Kutateladze [2, 3]. In contrast to the former authors, the latter are primarily interested in the mode of direct transition from convection to film boiling without passing through the mode of bubble boiling. Common to both groups of researchers is the use of concepts about the leading role of homogeneous initiation of nucleation sites (homogeneous nucleation) and about the string-branched character of their multiplication in the superheated layer near the heater surface as the basic concept when analysing experimental data and constructing models of the process. The latter authors also do not leave aside the problems which have been taken up in the literature and which concern the effect of the element surface properties on the conditions of transition from convection to boiling (in particular, on the magnitude of the maximum liquid superheating); however, the heterogeneity factor is not directly included by them in the models considered.

It is also important to note for what follows that both groups of researchers develop theoretical concepts within the framework of nulmer (one-dimensional in space) models, though the experimental facts given in refs. [1–3] reveal the symptoms of spatial inhomogeneity in the decomposition of metastable regimes, i.e. the local initiation of the vapour phase and the subsequent spontaneous propagation of the new regime front over the element surface.

Based on the general ideological concepts about the class of self-wave transition processes, a hypothesis has been proposed [4] which presumes that the transition from the metastable single-phase regime to that of bubble boiling should follow the laws of the travelling wave, whereas the homogeneous decomposition

NOMENCLATURE

Bi	Biot number
d	diameter of heating element
D	size of vapour bubble
h	dimensions of vapour emulsion zone
J	strength of current
k_0	pre-exponent
L	mean distance between vapour bubbles on heating element
q	heat flux
$\bar{q}$	heat flux separating the regimes of slow and fast waves
$R(t)$	mean integral electric resistance of heating element
R	gas constant
T	temperature
T_h	temperature of heating element
T_s	saturation temperature
T_x	temperature of spontaneous loss of stability of metastable regime
T_0	temperature of liquid
u	heating element voltage
V	self-wave velocity.

occurring simultaneously over the whole surface of the element should be regarded as a highly improbable phenomenon. Moreover, it was claimed that the physical mechanisms of feedback and transport of the process in space that keep control over the motion of the new regime front will be essentially different from the thermal mechanism of wave transitions between bubble and film boiling [5]. The proposed hypothesis [4] was qualitatively confirmed by direct experiments carried out with the use of the technique of local initiation of the transition process. The high velocities of the waves of the single-phase regime decomposition, which were observed experimentally, suggested the use of the cavitational mechanism as a possible mechanism for the initiation and transport of nucleation sites along the surface of the element in realization of the given type of the autowave process. (The assumption concerning the cavitational effects being responsible for the origination of a vapour phase in a superheated liquid film were also advanced in ref. [3].)

The present paper constitutes a development of earlier work [4] and is focused on the solution of the following problems:

(a) elucidation of the effect of the type of liquid systems on the qualitative character of autowave transitions from convection to boiling;

(b) quantitative study of the dynamic laws governing these transition processes under the conditions of their artificial initiation by local disturbances;

(c) study of the structure of the decomposition wave front in order to reveal the specific features of the transition from a finely-dispersed vapour phase state in the initial stage of decomposition (nucleation period) to its macrostate in the form of a vapour-storing bubble held by the surface (in the steady-state boiling regime);

(d) study of the wave front structure in order to reveal the surfaces of generation of acoustic (cavitational) effects, zone of their appearance in space with respect to the heating element surface, and of the stages of their action.

2. CHOICE AND SUBSTANTIATION OF EXPERIMENTAL TECHNIQUE

The range of problems posed in this work dictated the choice of the objects of study. Investigations were carried out in the processes of boiling on electrically heated metal filaments in liquid media subcooled below their saturation temperatures.

The use of thin wire elements, isothermal over their cross-section, simplified the pattern studied and reduced it to a one-dimensional scheme with the predominant orientation of the process only along one coordinate, i.e. along the filament axis. Moreover, the wire heating element was used simultaneously as a heat probe and as such made it possible to carry out oscillographic measurements of the wave velocity of the single-phase regime decomposition according to the technique developed earlier [5].

Liquid subcooling is essential for the creation of the required temperature ranges on surface elements (or heat load ranges) within which there exists the metastable heat transfer regime characterized by a sufficient stability to arbitrary decomposition. It should also be noted that subcooled boiling is distinguished by a lowered level of hydrodynamic and thermal noise, which creates favourable conditions for measurements and visual observations of all the successive stages of the transition process: local decomposition of the single-phase regime in a superheated layer, propagation of the decomposition front over the element, coalescence of the finely dispersed phase into one vapour bubble held by the surface, its departure, rise and destruction in the cold liquid medium.

Different liquid hydrocarbons selected from the paraffin series (heptane, hexane), from the series of saturated aromatic compounds (benzene, toluene) and also from the series of limiting oxygen-containing hydrocarbons (ethyl alcohol, acetone) were used in experiments. The liquid media selected differed not only by boiling temperatures (from 56°C (acetone) to 115°C (toluene)), but also by parameters such as the dipole moment (the first two groups are non-polar fluids, the third group is represented by polar fluids).

Experiments were carried out in a rectangular $100 \times 55 \times 100\ \text{mm}^3$ cuvette made from optical quartz glass. A coil exchanger was installed inside the cuvette so that the temperature of the liquid medium could be kept constant. A 5–7 cm long wire heating element was immersed into the liquid in a horizontal position and was orientated in the cuvette along the major axis of its cross-section. This permitted visualization and high-speed cine-photography of the process through plane wall-windows of the cuvette. The investigation was carried out mainly on 50, 100 and 120 μm diameter platinum probes. Control experiments were performed with elements made of nickel wire.

The system of electric power supply to the heat generating element permitted the observation of the transition processes of three different regimes of heat flux control in time: direct current regime ($J(t) =$ const.), constant voltage regime ($u(t) =$ const.) and the regime of constant resistance of the element ($R(t) =$ const.). The speed of response of the current and voltage stabilizers used constituted 10^{-4} s at an accuracy of stabilization of 10^{-2}%, whereas the speed of response of the resistance stabilizer was 10^{-2} s at an accuracy of 1%. The value of the regime of heat supply in the studies of boiling processes was discussed earlier [6]; more details on corresponding heat sources are given in that work. The role of the above-indicated regime factor is also important for solving the problems of the present work as illustrated below on specific examples.

The initiation of the process of decomposition of the metastable homogeneous regime of heat transfer from a solid surface to a liquid medium was achieved by means of the introduction of a local disturbance that caused the local superheating of the element. Along with the gas-jet technique [5], use was also made in the present work of a finer technique to excite the transition process. It rests on the use of an additional wire heater orientated normally to the axis of the main heater and located in the immediate vicinity of it. The additional heater is fed from the independent source. On having raised the heat load in this heater to the level corresponding to a stable boiling on it, one can easily excite the local decomposition of the metastable regime on the element studied. This regime propagated over the whole surface of the heater.

The initial information for the quantitative study of the laws that govern the autowave rearrangements of the metastable regime of the heating element operation was provided by its volt–ampere characteristic. The changes in time of the current and voltage on the heater were recorded by means of self-balancing potentiometers, digital voltmeters with printout and oscillographic facilities. According to the electrothermographic technique [5], the rate of the autowave process (v) developing on the metallic wire (temperature-sensitive resistor) and accompanied by the change in its temperature regime is the value proportional to the rate of change in the electrical resistance of such a probe ($v(t) \propto \mathrm{d}R(t)/\mathrm{d}t$). The temperature of the heating element drops in transition from convective heat transfer to boiling. It is precisely this fact which ensured the necessary conditions for the use of the thermal signal (electrothermography) for measuring the speed of the decomposition wave which, generally speaking, is a process of non-thermal nature. The majority of the results given below have been obtained when 10^{-2} cm diameter probes were used. The thermal inertia of such probes determined experimentally under conditions of convective heat transfer in the liquid media indicated lies within the range from 10^{-3} to 10^{-4} s. The estimated value of the characteristic width of the thermal front obtained from the ratio $d/\sqrt{(Bi)}$ (Bi is the well-known Biot parameter) is approximately equal to 10^{-1} cm. From this it follows that the application of the electrothermographic technique allowed the measurements of the running wave velocities to be carried out up to the values of order $10^3\ \text{cm s}^{-1}$ without distortions.

The most preferable regime for controlling the supply of heat load to the element is the direct current regime. It ensures the realization of the measuring signal of maximum strength, i.e. the attainment of the maximum sensitivity of the measuring circuit. Moreover, with $J(t) =$ const. the processing of the measured data is simplified, since under these conditions the function $R(t)$ is proportional to the electrogram of $u(t)$ measured directly in the experiment.

The elucidation of the specific features of the different stages of the transition process was carried out with the help of a motion-picture camera operating at a speed of 4000 frames s^{-1} with a five-fold magnification of the image. This speed provided the possibility for studying the details of the decomposition of the structure at wave velocities up to $1\text{–}5 \times 10^3\ \text{cm s}^{-1}$.

3. STATIC LOADING CURVES: THE REGIONS OF EXISTENCE OF METASTABLE FUEL ELEMENT OPERATION REGIMES

Before entering into the study of the dynamic aspects of the process of spontaneous transition from single-phase convection to nucleate boiling, it was necessary to obtain information on the laws governing the stationary heat conduction in both stable and metastable regimes. Among the major problems of this initial stage of the study were: (1) the problems of the existence, width and position of the boundaries of the metastable convective regime region; (2) the dependence of the limiting thermal load of spontaneous metastable state decomposition on the mode of the element powering; (3) the effect of the degree of liquid subcooling on the location of the metastable region; (4) the change in the qualitative form of the loading curves with a change in the physical properties of the fluid medium. The discussion of these problems will be made on the example of the data obtained for the system 'platinum wire–toluene'. Qualitatively identical trends are typical of all the above-named fluids from the series of saturated and aromatic hydrocarbons. The specific features characteristic of oxygen-containing compounds (acetone, ethanol) will be given special examination at the end of this section.

The stationary loading characteristic of the element made of a 10^{-2} cm diameter platinum wire and placed in the toluene medium with $T_0 = 20^\circ C$ is presented in Fig. 1 in the plane of the parameters 'heating element temperature–heat dissipation rate'. The load characteristic is composed of three branches. The branch 'abe' corresponds to the single-phase free-convective heat transfer regime, and heat transfer at each point of this branch is described by a single law coinciding with that obtained in ref. [7]. This regime is stable and is the only one possible over the segment 'ab', whereas over the segment 'be' it becomes metastable and capable of going over into the regime of stable nucleate boiling (the transition to the state lying on the branch 'bc') if there exists a rather strong local disturbance.

When the element is powered from a constant current source, the metastable regime preserves its stability against spontaneous decomposition up to the loading approximately corresponding to the point 'd'. At large loadings, $q > q_d$, the amplitude of self-disturbances of the system becomes sufficient to induce spontaneous transition to the boiling regime (the transition along arrow 'I'). The life-time of the metastable state decreases exponentially with distance from q_d.

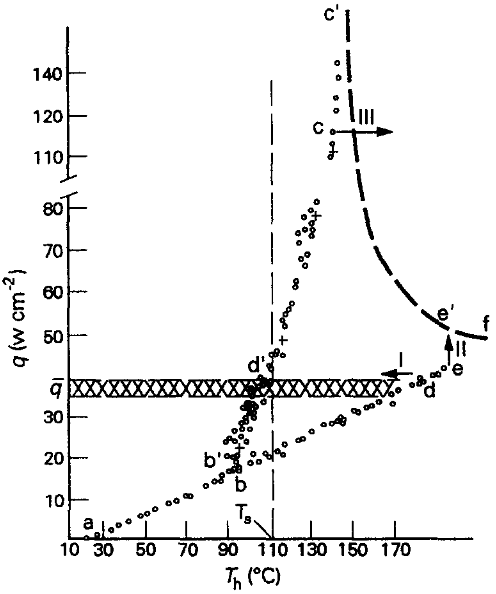

FIG. 1. The intensity of heat removal (q) vs the heating element surface temperature (T_h) (platinum wire of 100 μm diameter) in a toluene medium at a temperature of 20°C. abe, free-convective heat transfer regime; b′d′c′, bubble boiling regime; c′e′, branch of displaced boiling; (---) calculation by the equation $q = K_0 \exp(E/RT)$ as explained in the text.

(With regard to the problems tackled in the present work, the regime J = const. can be considered to be nearly equivalent to the regime q = const. as the transition between the branches is not accompanied by an appreciable change in the electric resistance of the element; for example, the transition along arrow 'I': $q'_d = 0.9q_d$. Close to this regime is also the regime of u = const.)

The conversion of the element to R = const. (stabilization of the mean integral temperature of the fuel element in time) is characterized by the rise of limiting loadings of the existence of the metastable heat transfer regime which is stable to temperature and hydrodynamic fluctuations in a liquid medium. This case is illustrated in Fig. 1, from which it is seen that the boundary of the free-convection regime expands up to the state corresponding to point 'c' ($q_c > q_d$), whereas the direction of the transition process spontaneously originating at this point of transition process is denoted by arrow 'II'. This experimental fact characterizing the effect of the means of heat load control on its limiting value indicated that under the conditions realized in the experiment, in the absence of artificial disturbance, the chance superheating sites on the element surface are dangerous for the single-phase free-convective mode of heat transfer, i.e. thermal perturbations rather than hydrodynamic perturbations exist in the system. If this is the case, only then is the system of controlling the regime R = const., which as compared with J = const. has a stronger thermal feedback between the parameters 'temperature–loading' and can ensure the expansion of the metastability region. (It will be recalled that a similar effect due to the same reasons was described earlier in ref. [6] dealing with investigations of the bubble boiling regime stability. Figure 1 illustrates this specific feature of bubble boiling: at R = const. the bubble boiling branch retains its stability against fluctuations up to the point 'c', whereas at J = const. a spontaneous transition into the film regime originates at the point 'c' (along arrow 'III').)

When studying the dynamics of metastable regime decomposition, the system controlling the J = const. regime has been selected as the main one. This choice is attributable to the fact that with this means of controlling the artificially initiated transition process, the development of the bubble boiling regime is always completed. The powering of the element from the source R = const. ensures the expansion of the boundaries of the region of stable metastability, but has a certain drawback from the viewpoint of the task of the present work: as is seen from Fig. 1, a considerable portion of branch 'be' has to be eliminated from consideration since the process of transition from the states lying on this portion terminates in the inhomogeneous regime of the mixed boiling branch 'c′e′f' (further details about the structure of mixed boiling can be obtained from ref. [6]). The methodological advantages of the use of a current regulator as a power source have already been discussed in Section 2.

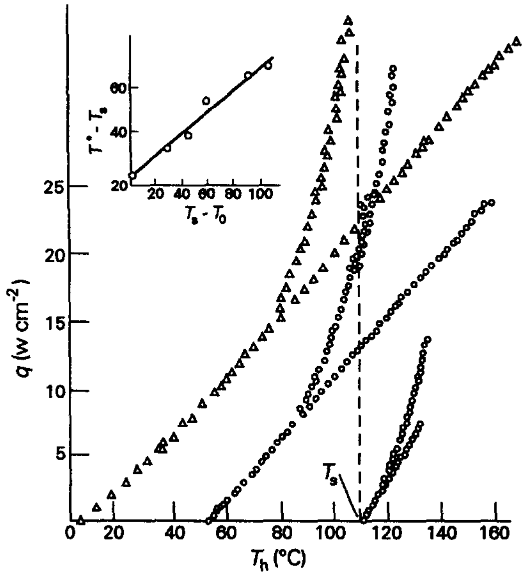

FIG. 2. The effect of the liquid medium temperature T_0 on the form and mutual location of the free-convective heat transfer and bubble boiling regions. The working fluid is toluene.

The width of the metastability region in which the single-phase heat conduction regime can be stable against random disturbances depends not only on the means of the element powering. An important factor which exerts a strong effect on this parameter of the loading characteristic is also the degree of subcooling of the working fluid. Figure 2 illustrates the evolution of loading characteristics of the element with variation of the temperature of toluene (T_0). It is seen that with a decrease in the degree of subcooling ($T_s - T_0$), the width of the metastable region ($T_* - T_b$) rapidly contracts and near $T_0 \approx T_s$ the region becomes so narrow that the study of the laws governing the dynamics of transition processes is fraught with great difficulties. In view of this, the attention in the present work is mostly paid to the conditions which are characterized by substantial subcooling. The methodological advantages of the use of cold fluid was noted earlier in this work.

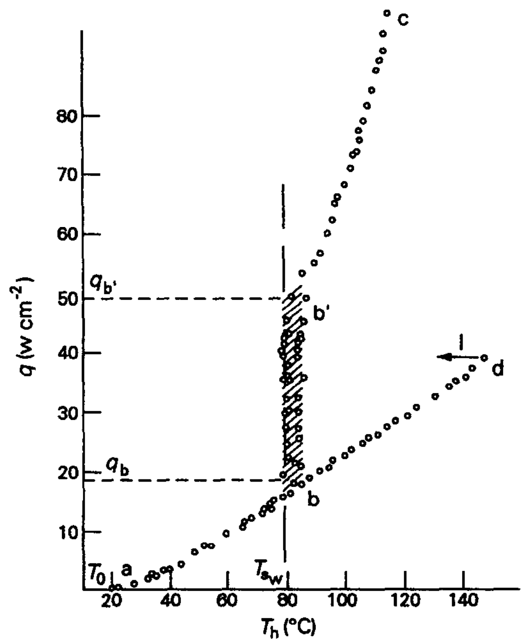

FIG. 3. Loading curves of ethanol with $T_0 = 20$°C. abc, free-convective heat transfer; bb′c, bubble boiling.

The boiling branches of the loading curves obtained for oxygen-containing hydrocarbon media (acetone, ethanol) differ qualitatively from the form represented in Fig. 1 characteristic for the group of saturated and aromatic hydrocarbon fluids. It is seen from Fig. 3, which illustrates the above-indicated specific features for the example of ethanol, that the function $q = q(T)$ ceases to be a curve which branches smoothly from the convective heat transfer branch and which is characterized by the derivative monotonically increasing with temperature: over the bubble boiling branch ('bbc') near $T \gtrsim T_s$ there appears a very steep segment 'bb' which may even have the state with the negative derivative. Loading characteristics of this type were considered by the present authors earlier [4] when dealing with the problem of the stability of bubble boiling under the conditions of self-oscillatory regimes within the range of loadings $q_b < q < q_{b'}$ (Fig. 3). From the point of view of the problems considered in the present work, the indicated specific feature of the boiling branch introduces an uncertainty into the dynamics of transition processes realizable within the range $q_b < q < q_{b'}$ with the result that the discussion of the laws typical of polar fluids is taken outside the scope of the present work. The specific, probably catalytic, participation of the surface of the element in the processes of boiling is hinted at by the very unexpected fact that the conformity separation of the boiling branch from that of convective single-phase heat transfer in non-polar fluids occurs at temperatures below T_s (see Fig. 1). Thorough checking and special refined calibration of the thermal resistance characteristic of the element have not revealed any methodological facts that would refute this result. Moreover, such abnormal behaviour has not been discovered in polar fluids, i.e. the whole boiling curve is always located to the right of the axis $T = T_s$ (Fig. 3). Nevertheless, the result is so paradoxical that the final inference about its validity cannot be made at the given stage.

4. ELECTROTHERMOGRAPHIC INVESTIGATION INTO THE DYNAMICS OF THE PROCESS OF TRANSITION FROM CONVECTION TO BOILING

The forthcoming experimental information on the decomposition dynamics of the metastable single-phase regime of heat transfer from the heating element refers to a model system, the static characteristic of which is presented in Fig. 1. Similar relationships were observed qualitatively in the media of hexane and benzene.

The process of transition from convection to bubble boiling was excited virtually throughout the entire metastable region $q_b < q < q_d$ in response to the local disturbance, irrespective of the means of its production (from a gas jet or an additional heater, see Section 2). Three intervals can be distinguished on the basis of the characteristic features of the oscillograms of the transition process in the metastable region.

Within the range of loadings up to $q = \bar{q} \approx 40$ W cm^{-2}, the times for the development of the transition process vary from 1 to 0.3 s (for an element 5 cm long and 0.01 cm in diameter). A typical oscillographic trace of this process of heat transfer regime rearrangement is given in Fig. 4(a). It is seen that the development of the stage of boiling regime formation ('b') on the element does not immediately follow the introduction of the disturbance, but occurs after a period lasting 0.1–0.3 s. Another feature of the transition process considered is the existence of oscillations of its velocity (the wavy character of 'bc').

At the loading $q > \bar{q}$ (see Fig. 4(b)) the rate of jumpwise decomposition of the single-phase metastable regime of heat transfer increases by about an order of magnitude (the characteristic times are 0.3–0.1 × 10^{-1} s). The induction stage is also preserved in this range of loadings.

In a narrow range of loadings adjacent to the value $q = \bar{q}$, the transition process may realize in both the regime of low and the regime of high velocities depending on the initial conditions. It has been established experimentally that in this range of non-uniqueness of the regimes of decomposition the high-velocity regime is more stable against the fluctuations accompanying the transition process, as illustrated by the oscillographic trace given in Fig. 4(c): this shows that the transition from convection to boiling started in the small velocity regime (stage 'bc') and then spontaneously goes over into the regime of rapid decomposition ('cc').

By adopting (for the time being as an assumption) that the local disturbances initiate the process of the autowave-type decomposition, the electrothermographic data for the dynamics can be easily presented as the velocity of the travelling wave of boiling which displaced the metastable regime sequentially from each layer vs the heat load (q) or the temperature of the element (T_h). The experimental results processed according to the technique described in Section 2 are presented in Fig. 5 and clearly illustrate the conclusion about the two regimes of the travelling wave of decomposition. The first regime is characterized by a velocity of the order of 10 cm s^{-1} and the second by a velocity of 10^2 cm s^{-1}. These values exceed by one to two orders of magnitude those characteristic for the thermal autowave processes studied earlier and realized in the case of spontaneous transitions between bubble and film boiling [5]. It is important to add that the temperature front accompanying the metastable regime decomposition wave not only fails to promote the acceleration of the transition processes considered, but must even retard their development, since the heat flux from the frontal zone lowers the superheating in the unperturbed (encompassed by the metastable regime) portion of the heating element.

Replacing the material of the element, its geometry and the liquid medium does not lead to qualitative changes in the results. Thus, the relationships derived in the experiments with nickel and platinum wires are nearly identical. The variation of the element diameter from 0.5 × 10^{-2} to 2 × 10^{-2} cm is not accompanied by essential quantitative changes in the dynamic characteristics of the transition process. Just as in toluene, there are two regimes of the metastable state decomposition in hexane, heptane and benzene; however, the absolute values of the velocities differ slightly. The maximum rates of autowave decomposition were recorded in the benzene medium: they attained values of 10–15 × 10^2 cm s^{-1}.

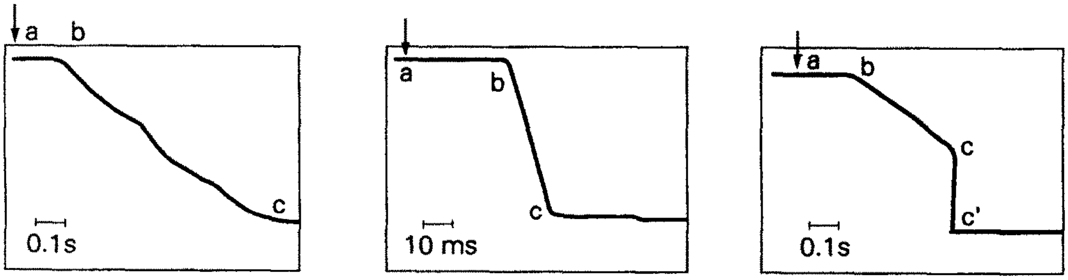

FIG. 4. Oscillographic traces of the rearrangement of the heat transfer regimes (toluene; $T_0 = 20$°C; platinum heating element of 100 μm diameter). Heat fluxes: (a) 32 W cm^{-2}; (b) 43 W cm^{-2}; (c) 37 W cm^{-2}.

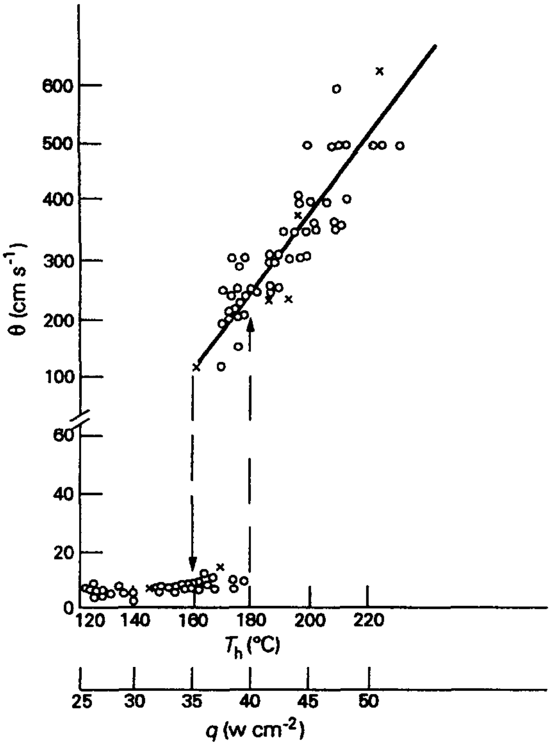

FIG. 5. The metastability decomposition wave velocity vs the heat flux q. The heating element temperature in toluene, $T_0 = 20°C$; (O - O) platinum element with diameter of 100 μm; (- - -) platinum element with diameter of 200 μm; (· · ·) nickel heating element 100 μm in diameter.

5. MOTION PICTURE RECORDS OF THE AUTOWAVE PROCESS OF DECOMPOSITION OF THE METASTABLE REGIME OF HEAT EXCHANGE BETWEEN THE ELEMENT AND THE LIQUID MEDIUM

The conclusion made in the previous section regarding the autowave character of the decomposition of the metastable regime of operation of the heat generating element was based on indirect facts, the basis of which was the artificial excitation of the transition process in response to the disturbance introduced locally into the system. To obtain the complete answer to the question regarding the autowave regime of the rearrangement process propagation over the surface element, direct proof of the existence of such a regime was needed. This was obtained with the help of high-speed cine-photography. Moreover, no other regime except the autowave one has been detected in the course of the cinegraphic investigation of the transition process. The transition to boiling did not occur synchronously and uniformly at each point of the element even under the conditions of spontaneous decomposition of metastability when at the initial instant the cold fuel element was suddenly exposed to a load exceeding the limiting value q_d : the process was invariably initiated locally and developed following the laws of the travelling wave.

The analysis of the motion pictures illustrating the decomposition of the metastable regime of fuel element operation revealed that the load $q \approx \bar{q}$ separated the regions differing not only by dynamic characteristics of the transition process (as discussed above in connection with Fig. 5), but qualitatively substantial differences were discovered in the structure of the travelling wave.

Typical motion picture records of the process of rearrangement in the regime of a slow wave ($q < \bar{q}$) are presented in Fig. 6. In this region of heat loads the wave front is characterized by the presence of a vapour bubble which separates the vanishing metastable zone (to the right of the bubble) from the boiling zone

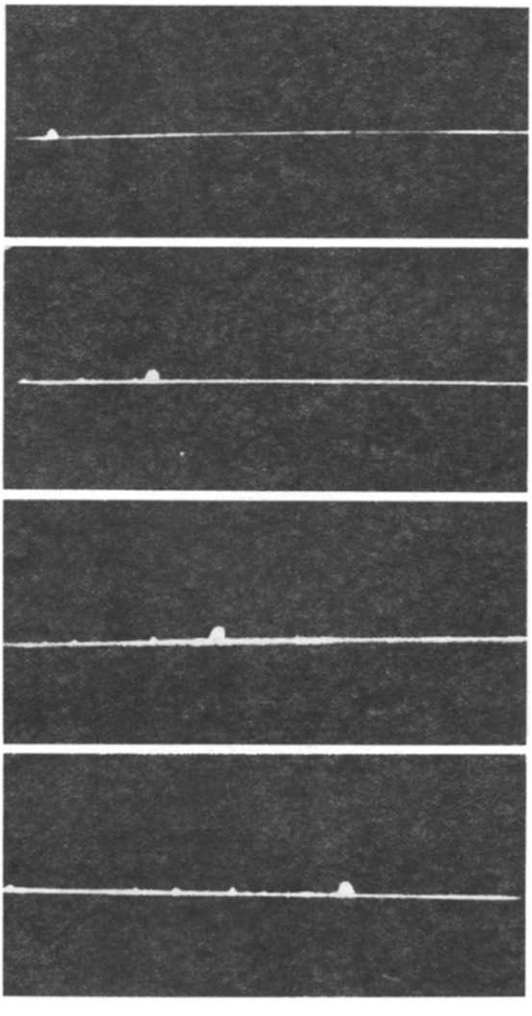

FIG. 6. Motion pictures of the propagation of a slow metastability decomposition wave. The speed of shooting is 1000 m s^{-1}. The platinum heating element is 100 μm in diameter. The medium is toluene at $T_0 = 20°C$, $q = 32$ W cm^{-2}. The first frame corresponds to the instant 0.1 s after the termination of the initiating disturbance.

displacing it (to the left). The bubble boundary always appears in that part of the element which is subjected to the disturbance (Fig. 6, frame 1; the disturbance is introduced from the left). For its formation the induction stage mentioned earlier is required. Then, the bubble boundary begins its translational motion on the average with a mean velocity coinciding with the data of electrothermographic measurements presented in Fig. 5. While moving, the frontal part of the bubble destroyed the surface film of the liquid, while at its rear part a picture is formed typical of steady-state bubble boiling with a chain of vapour bubbles initiating, growing and separating from the surface. The bubble boundary itself, while moving along the upper side of the element, hardly varies its size and does not detach from the surface until it ends the transition process over the entire element (frames 2–4).

A steep rise (by more than an order of magnitude) in the decomposition wave velocity at $q > \bar{q}$ strongly varies the structure of its front (see motion pictures in Fig. 7). The velocities are so high that the microdispersed vapour emulsion formed in the superheated liquid film at the initial stage of the metastable state decomposition does not have time to coalesce into a macrobubble for the period of wave passage through the given section of the element. As a result, the front acquires the form of a vapour-emulsive cloud elongated along the element, moving over the layer adjacent to the surface and having rather distinct frontal and rear boundaries. It is natural that the rear boundary is blurred to a greater extent, since it is here that all the stages of the process of metastable state decomposition exist simultaneously: from the stage of formation of the vapour nuclei emulsion to the completion of the microdisperse phase coalescence into a macrobubble. This observation seems to be very important, since it suggests that the conclusions about the efficient use of the data on the dynamic and structural features of the autowave transition process are fundamental ones in the study of the kinetics and mechanism of the phase transitions considered. Even now it is possible to estimate the lifetime of the microdispersed transition state ($t = h/v$) by measuring the length of the cloud (h) and knowing its velocity (v). It turns out to be equal to $1\text{–}3 \times 10^{-3}$ s and is almost independent of the loading, i.e. of the initial superheating of the element surface. In other words, the increase in the decomposition wave velocity is accompanied by a corresponding increase in the size of the nucleation zone in the travelling wave front.

Just as in the case of slow decomposition waves, the cinegraphic (Fig. 7) and electrothermographic (Fig. 5) measurements of the velocity in the region of high-velocity rearrangement give virtually coinciding results. It should be noted that on certain motion pictures of high-velocity rearrangement indications of the fluctuating character of front motion were discovered. The question whether these facts testify to the instability of the steady-state autowave process or whether they result from the non-uniform field of external parameters requires special analysis. The

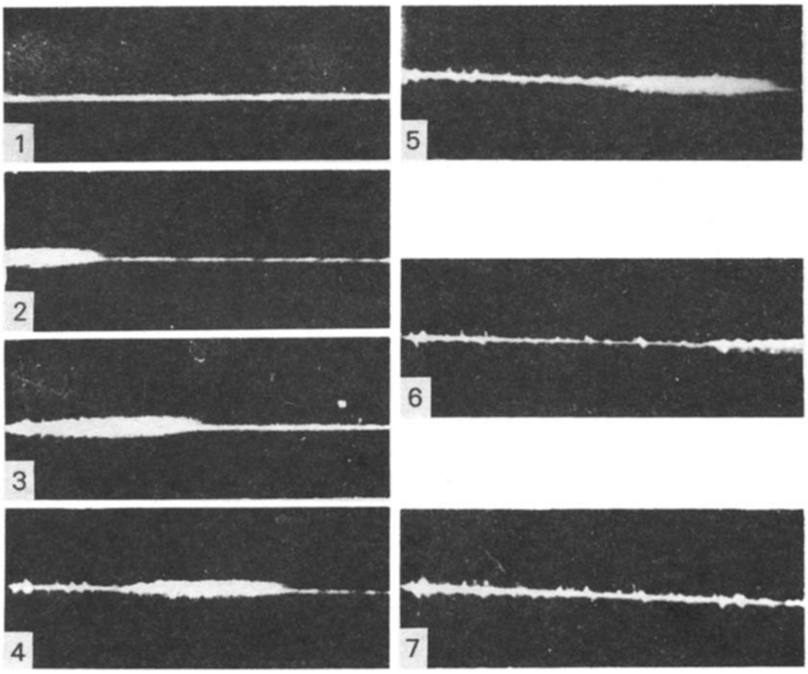

FIG. 7. Motion pictures of the propagation of a fast metastability decomposition wave. The speed of shooting is 1000 frames per second. The platinum heating element is 100 μm in diameter, the medium is toluene at $T_0 = 20°C$; $q = 43$ W cm^{-2}.

same also applies to the phenomenon of velocity oscillations observed at $q < \bar{q}$ (Section 4). Moreover, the motion pictures taken at loadings close to $\bar{q}$ made it possible to detect the spontaneous replacement of the slow regime of motion by the rapid one—the phenomenon first discovered in the case of the electrothermographic study of the process of rearrangement (see Fig. 4(c)). An example of a motion picture showing the transition of the slow wave into the rapid one is given in Fig. 8.

6. THE MECHANISM UNDERLYING THE AUTOWAVE PROCESS OF THE METASTABLE REGIME DECOMPOSITION

At the given stage of investigations the hypothesis about the cavitational mechanism of the autowave process of the metastable regime decomposition is being developed [4, 5]. The qualitative description of the operation of this mechanism is based on the following assumptions.

(1) The metastable regime is stable toward all disturbances that do not cause the loss of continuity (discontinuity) of the superheated film adjacent to the element surface or do not lead to the superheating of this film above the temperature of spontaneous decomposition (i.e. in terms of the theory of homogeneous nucleation, to falling outside the spinodal curve).

In the majority of experiments carried out the stage of initiation was accomplished with the help of the second condition, i.e. by introducing thermal disturbances. To elucidate the validity of the first condition, a number of experiments were undertaken with the autowave process excited by artificially introduced cavitation. It was found that ultrasound of certain intensity (16–35 kHz) can really excite the transient autowave process of decomposition, as with thermal excitation.

(2) The decomposition of the single-phase superheated liquid film occurring in the zone of initiation is accompanied by the release of the vapour phase, with the rate of its formation being so high that, having no time to recede into the bulk of the fluid (see Fig. 7), it exerts a strong mechanical effect on the neighbouring, still unperturbed portions of the metastable film. In other words, under consideration here is the generation in the course of local decomposition of the shock wave which may cause the rupture of liquid in the neighbouring layers or its separation from the surface element if the stresses induced by the shock exceed the tensile and shear strength of the liquid medium. The loss of liquid film continuity will induce phase transition and vapour release in the adjacent portion of the element which in turn will become the reason for the origination of the next shock. It is the opinion of the authors that it is just this mechanism with the feedback between the process of the metastable stage decomposition and the mechanical fragile disintegration of the superheated film which underlies the self-sustained autowave transition process.

(3) The picture of the self-sustained shock (cavi-

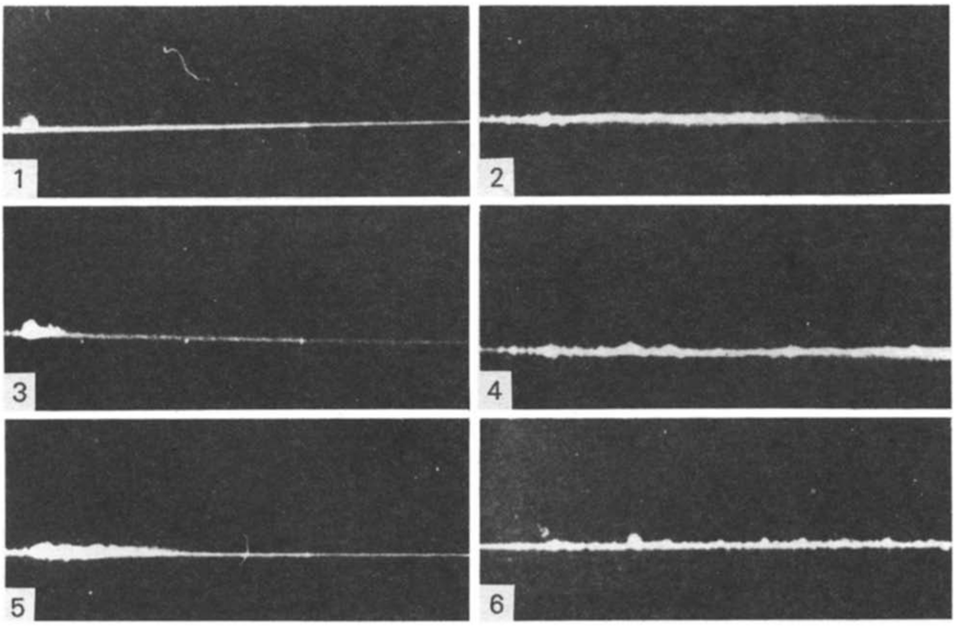

FIG. 8. Motion picture recording the process of the rearrangement of a slow wave into a fast one. The speed of shooting is 1000 frames per second. The platinum heater is 100 μm in diameter, the medium is toluene at $T_0 = 20°C$; $q = 37$ W cm^{-2}.

tational) wave described in Section 2 is very close in essence to the detonation wave, which is well known in the physics of combustion [8]. The difference is that in the process of detonation the energy is supplied to the shock wave from chemical reaction; in the processes of phase transitions considered here, the cavitational wave is fed by the mechanical energy released during the layer-by-layer decomposition of the metastable superheated liquid film in the form of shock vapour generation. An attempt will now be made to analyse the experimental data obtained within the framework of the concepts formulated above.

First, attention should be paid to the fact that the decomposition wave is always accompanied by a specific, hardly audible click. This acoustic signal can be quite justifiably considered as a certain indication of the autocavitational process having run along the element.

When referring to the cavitational mechanism of the process of autowave decomposition, it is necessary to note that the elementary event of cavitation, on which the developed concept is based, differs substantially from that generally accepted in the theory of cavitation. According to this theory [9], the shock effect originates not at the instant of liquid breakdown and cavity formation, but at the instant of the collapse of its boundaries, whereas in the picture of autowave decomposition considered above, the basic feature is the fact that the shock originates at the stage of the superheated liquid film continuity loss due to rapid (supersonic) escape of vapour from the walls of the cavity into the space formed.

Thus, the problem of fundamental importance for the whole ideology developed here is the problem of the search for direct indications of the origination of shock effects precisely in the narrow layer of superheated liquid adjacent to the surface of the element. To answer the problem raised, a special procedure was needed with the help of which it could be possible to obtain a useful signal directly from the decomposing metastable layer. This was done using the simplest technique based on the principles of thermoanemometry. It consists of the following. If there exist waves of hydrodynamic shocks which accompany the decomposition, then their energy must scatter not only in the direction of the element axis, but also in the volume of the liquid medium. If this is the case, the local hydraulic explosions originating in the surface layer will lead to the 'bouncing' of liquid jets off the surface into the volume, and these can be easily recorded by a thermoanemometer at a certain distance from the element not exceeding the length of decay of the submerged jets.

In Fig. 9 the oscillographic traces shown are obtained from two thermoanemometric platinum probes of diameter 0.5×10^{-2} cm installed above the element at a distance of about 10^{-1} cm, orientated normally to its axis and separated from each other by 3 cm. As was expected, the passage of the wave through the given section of the element really provokes the origination of the shock jet (spikes on oscillograms) recorded by the thermoanemometers. It is evident that the given procedure may also serve as an additional tool for measuring the velocities of the travelling wave of decomposition from the time the wave passes the zone located between the two probes.

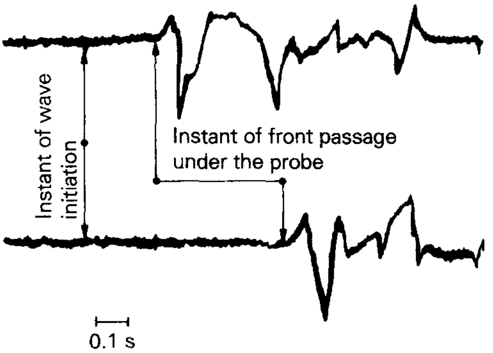

FIG. 9. Oscillographic record of the decomposition wave front with the help of thermoanemometric probes.

Figure 9 presents only the first qualitative results of the solution of the problem stated. There are potential possibilities in the procedure suggested. By having preserved the methodological scheme and complemented it with manometric and dynamometric measuring elements, it will probably be possible to carry out a quantitative investigation of the energy characteristics of the decomposition wave and to obtain wave extensive information about its structure.

The experiment described below is aimed at the elucidation of new aspects of the cavitational mechanism underlying the autowave decay. It states the question regarding the character of the interaction of the travelling wave with barriers installed on the element. The motion pictures in Figs. 10 and 11 illustrate the specific features of the passage of waves through apertures. A plane aperture was made of 5×10^{-2} cm thick copper foil. It was placed in a cuvette in the plane normal to the element. The wire element itself was passed coaxially through an aperture orifice of about 2×10^{-2} cm diameter, making sure that there was no contact between the element and the barrier.

It has been found in experiments (Fig. 10) that the aperture with the indicated characteristics is a 'transparent' object for a fast wave. It not only fails to stop the wave, but does not influence its speed perceptibly. It is precisely this result which was expected from the viewpoint of the shock wave concept. However, quite a different picture is observed when experiments are conducted in the mode of a slow wave (Fig. 11). The running bubble boundary stops at the barrier, the wave is blocked, and a state develops on the element in which two zones exist simultaneously: the zone of single-phase metastability

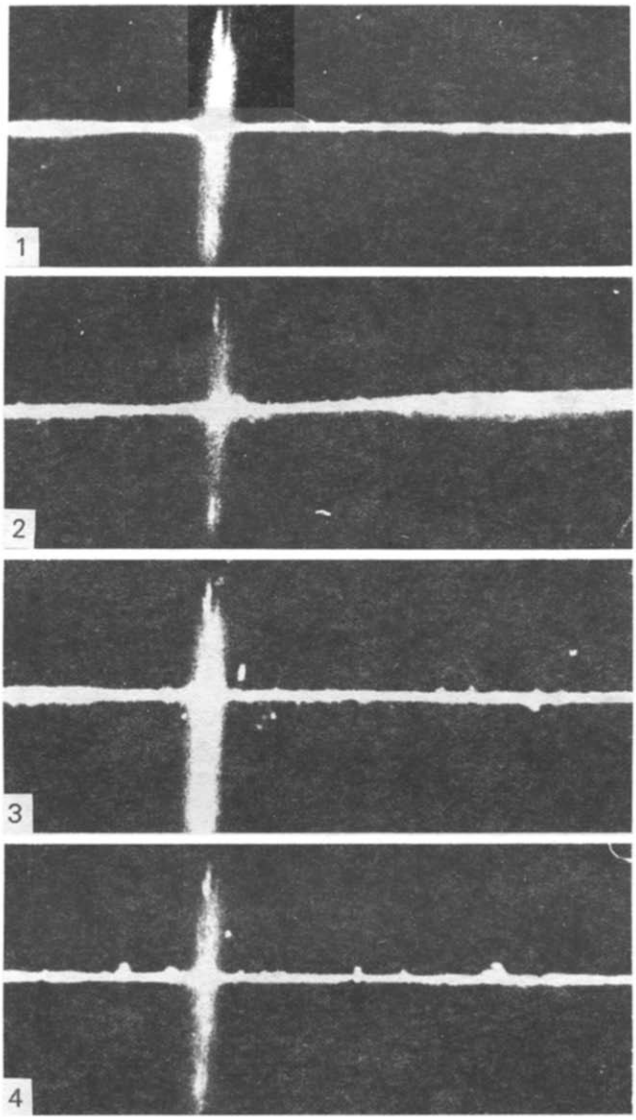

FIG. 10. Motion picture of the interaction of a fast decomposition wave with barriers.

to the right of the aperture and the zone of steady-state boiling to the left. The question as to what this specific feature of the regime of slow decomposition is due to requires special study. It may well be that the energy evolved during the decomposition of the metastable film in this regime is so limited that its slight scattering on the barrier is sufficient for the wave to be stopped. The possibility is not at all excluded that the mechanism of the autowave process at $q < \bar{q}$ might be quite different from that at $q > \bar{q}$ and the cavitation effects might cease to be predominant in it. For example, one of the following alternative mechanisms is quite possible. At each fixed instant of its existence on the element, the bubble has different temperature conditions on both sides: the superheated liquid layer and hot surface of the heater on the one side, and the liquid that gave heat off for vapour formation and the portion of the element cooled due to this on the other side. Having recalled the variation of the surface tension coefficient with temperature at the liquid–solid body interface, one can easily imagine that the temperature gradients may cause the motion of liquid orientated along the element and concentrated in the thin layer near this surface. Thus, the experimentally observed motion of the bubble boundary in the zone of metastability in the case of slow autowave decomposition can be associated with the action of the above-considered hydrodynamic factor which is simultaneously the consequence and the reason for the existence of the non-uniform temperature field on the 'liquid–heater' interface surface. Besides, it can be added that the absolute values of the velocities for the case of a slow wave (Fig. 5(a)) do not contradict the proposed

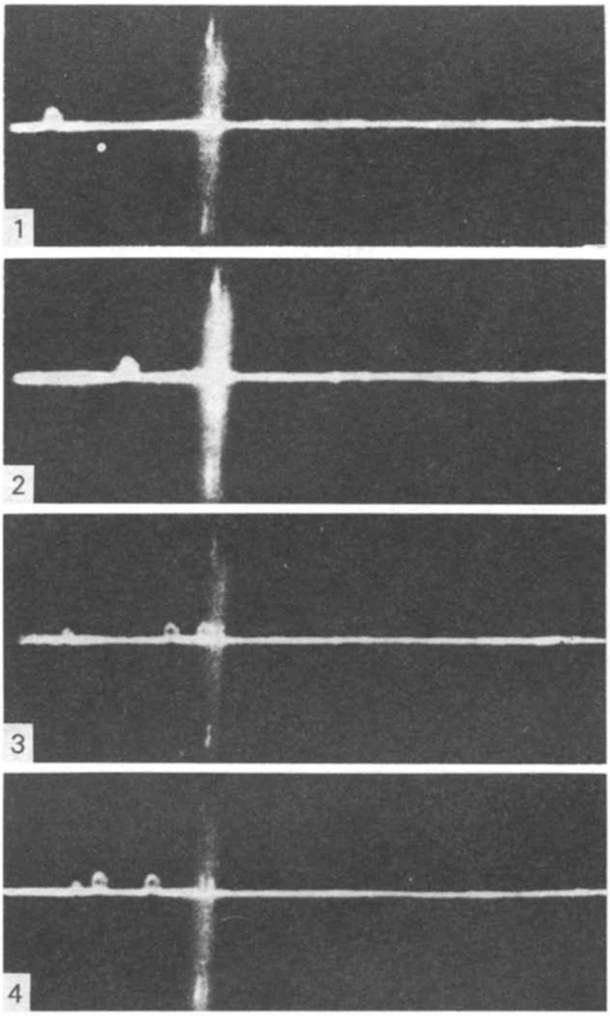

FIG. 11. Motion picture of the interaction of a slow decomposition wave with barriers.

hydrodynamic mechanism of the process of autowave rearrangements.

We now consider the question regarding the analogy between the transition processes and detonation waves. It is necessary to point out a substantial discrepancy with the traditional notions of the detonation theory associated with the absolute values of the rates of experimentally observed autowave metastability decay processes. The point of view taken is that the detonation wave of the normal regime is characterized by velocities exceeding the speed of sound. It follows from the data obtained that the velocities of the wave processes of phase transitions are substantially higher than those of the thermal processes, but at the same time they are one to two orders of magnitude smaller than the speed of sound in the vapour and liquid media. (It should be noted here that the sonic velocity in two-phase systems can be substantially smaller than in each of the media [10].) The reason for this seeming contradiction must most likely be traced back to the fact that the classical theory of detonation was constructed ignoring the dynamic aspects of the chemical reaction proper. In the present case the delay in the development of the branching stage of the formation of the sites for a new vapour phase (immediately following the stage of shock excitation) may strongly influence the dynamics of the wave motion and make the regime of its propagation degenerate, being characterized by small subsonic velocities. Indications of the real effect of this factor on the cavitation wave velocity can be deduced from the experimental existence of a long induction stage directly following decay initiation. A detailed theoretical consideration of this problem is outside the scope of the present paper.

Concluding this section it is impossible to fail to note the possible relationship between the above-given concepts and the phenomenon of steam explosion well known in the physics of boiling. To this end, it is necessary only to assume that the steam explosion is a detonation wave of shock vapour release originating during the decay of great volumes of a metastable liquid. In this regard, note should be made of ref. [11], in which the general idea regarding the possible action of the detonation mechanism in the processes of metastable state decomposition has been advanced theoretically for the first time (beyond the relation to a specific physical system).

7. STEADY-STATE BUBBLE BOILING IN A SUBCOOLED LIQUID—A POLYAUTOWAVE PROCESS

The development of the autowave concepts in application to the transition processes of the metastable regime decay has stimulated further investigations of the spatial and temporal features of the stationary regime of bubble boiling, i.e. of that final regime of heat conduction the attainment of which completes the above-indicated transition processes. It should be noted immediately that the whole analysis is based on the data obtained for boiling in a wire heat generating element in subcooled liquid. It is quite probable that the main conclusions can also be referred to more general cases.

The motion picture records of the steady-state boiling developing in space has led to the conclusion that the zones of formation and accumulation of vapour on the surface of a heat generating element always coexist with the zones of the single-phase metastable heat condition. In the case of a fixed load, the relationship between the zones remains invariable in time on the average (thus ensuring the integral quasi-stationarity of the process of boiling), though their location and boundaries are constantly in motion. In other words, over each fixed section of the element surface there takes place an essentially unsteady-state process, and the local regime of heat conduction undergoes a constant alternation of the stages of decay and subsequent recovery of the metastability.

The above-described picture is of general character over a wide range of heat loads, though it undergoes some transformations with increasing q, especially during the transition from the region of $q < \bar{q}$ to the region with $q > \bar{q}$, i.e. in transition through approximately the same value of the heat flux which separates the regions of the existence of the above-described two regimes of autowave rearrangements (see Sections 4 and 5).

At small heat fluxes the zones of vapour accumulation are solitary vapour bubbles oscillating over the surface element. The motion of each of them is always directed to the side of the metastable single-phase zone (for example, due to the action of the hydrodynamic mechanism considered in the previous section). Having destroyed the metastability of this zone and collected stream from it, the bubble turns in the reverse direction, since for this time near the heating surface there has formed a superheated liquid film ready to give off vapour. In character and velocity the motion of bubbles resembles the displacement of the bubble boundary in the processes of autowave transitions from convection to boiling at $q < \bar{q}$ (Section 5). The analysis of the picture observed has led to the conclusion that the stationary regime of bubble boiling represents the superposition of the whole set of simultaneous processes of autowave decay of the localized zones of metastability taking place over different sections of the element surface (but being in different time phases). Thus, the steady-state subcooled boiling regime can be determined as a polyautowave process.

With an increase in the heat flux, the above-described picture, while not changing qualitatively, experiences a certain quantitative evolution : the number of coexisting bubbles on the element surface increases (i.e. the number of zones of metastability increases and their average size decreases) ; their velocity rises (Fig. 5). The motion pictures recorded at $q > \bar{q}$ made it possible to reveal a new dynamic feature. It appears on the element in those zones which are located between adjacent bubbles, i.e. in the zones of metastability. If by any chance the bubbles move far apart from each other, a high degree of metastability accumulates in the intermediate single-phase zone (large superheating), and a spontaneous decay occurs in it by the laws of high-speed autowave rearrangement. The motion picture in Fig. 12 recorded such an event when the travelling bubble regime went over into the shock wave process. Thus, it has been established that in the indicated regime of steady-state bubble boiling there are elementary stages which are fully identical to both types of autowave rearrangements considered in this work. To increase clarity, pay attention to the closeness of the picture of the local decay of metastability recorded in Fig. 12 in the stationary regime of boiling to the above-described (Fig. 8) two-velocity regime of the autowave process.

The stage of shock decay of metastable zones developing in the process of bubble boiling is the reason for the appearance of specific features in the acoustic phone and for the dispersity of the vapour phase. The former is associated with the fact that in each cavitational event of the superheated liquid film decomposition in the surface zone of the single-phase state a high-frequency sonic energy is generated which is responsible for the appearance of the corresponding spectral band in a certain range of loadings at $q > \bar{q}$. The latter results from the fact that, as has already been noted in the previous section, the cavitation is accompanied by the repulsion of the superheated liquid film with a portion of the microdispersed vapour phase in it from the surface. For some reason, the microdispersity of the vapour phase is a factor which hinders its subsequent condensation in the cold volume of liquid which is saturated with microbubbles and acquires the form of a gas–liquid emulsion.

The bubble boiling regime described, which includes cavitational events occurring in close vicinity of the solid surface of the element, is associated with a sharp increase in the shock mechanical loadings on this surface. According to the observations made by

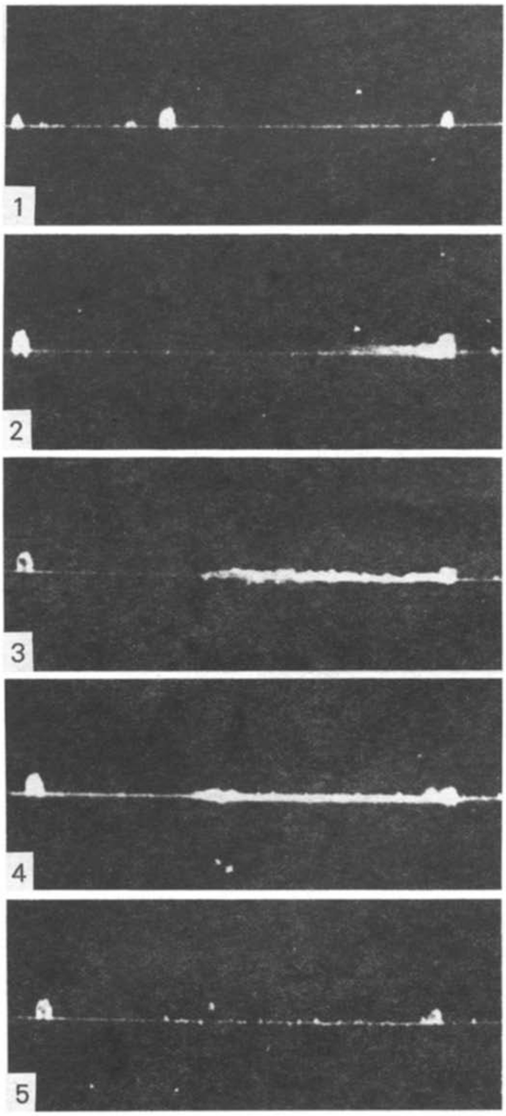

Fig. 12. Motion picture which records the event of the shockwave decomposition of the local metastability zone in a steady bubble boiling regime. Platinum wire 100 μm in diameter, the medium is toluene at $T_0 = 20$°C; $q = 60$ W cm^{-2}.

the present authors, such boiling leaves residual erosion tracks on the fuel element similar to those that appear on the surface of metallic ultrasonic wave guides that operated for a certain time in a liquid medium [9]. For the same reason, one can expect the existence of sonic–chemical effects in this regime of boiling [12]. In particular, these effects can be responsible for the vigorous formation of scale in the subcooled boiling zone which seems to be cooler than the zone of saturated boiling. For this purpose it is sufficient to assume that the precipitation of salt and its binding with the surface occurs in the events of brittle decomposition of liquid that lead to the chemical activation of the surface of its fragments, which as expected, is observed in the case of the cavitational decomposition of metastable surface layers. These corollaries following from the concepts developed in the present work are of great scientific and practical importance and require special study which lies beyond the scope of the present stage of investigation. The procedure suggested in ref. [13] for studying the rates of rearrangement of the catalyst surface which can be successfully used to obtain quantitative information on the dynamics of the fuel element surface decomposition in boiling should be referred to.

As heat loadings increase, the further decrease in the characteristic distance between the bubbles scurrying over the surface leads to the curtailment of the lifetime of the metastability zones and, consequently, of the degree of local superheating in them. Due to this factor, the frequency of cavitational effects becomes smaller and the shock-cavitational stage of bubble boiling gradually disappears. At loading near the limit of thermal stability ($q \sim q'_c$, Fig. 1) the space between the bubbles is such that they are almost in close vicinity of each other, whereas their oscillations degenerate into fluctuations near the equilibrium position. The above-considered evolution of the spatial organization of the process of boiling with a change in loadings is illustrated in Fig. 13 by two motion pictures (a and b), the first of which corresponds to loading only slightly exceeding q_b and the other obtained at $q \approx q'_c$.

8. CONCLUSIONS

(1) It has been established experimentally that the decomposition of the metastable regime of single-phase heat transfer from a solid surface to liquid has an autowave character and consists of the layer-by-

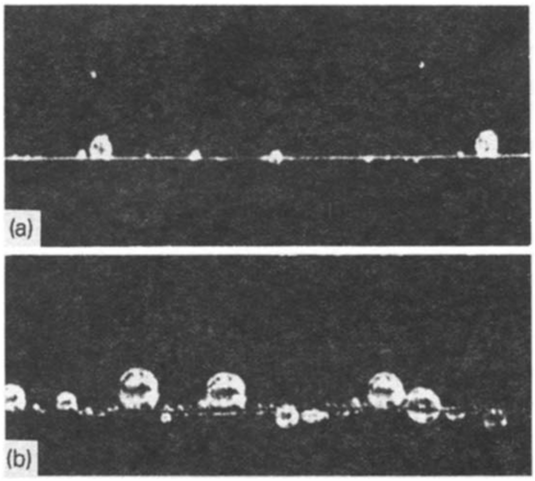

Fig. 13. The structural evolution of the regime of steady-state boiling with varying load. The platinum element is 100 μm in diameter, the medium is toluene at $T_0 = 20$°C; $q = 35$ W cm^{-2} (a); 140 W cm^{-2} (b).

layer formation of the boiling zone which displaces the metastable zone on the element.

(2) The existence of some critical value of heat flux has been found at which the decomposition travelling wave velocity varies jumpwise from a value of the order of 10 cm s^{-1} to 10^2–10^3 cm s^{-1}. It is shown that quantitative changes in the velocity characteristic are also accompanied by substantial qualitative changes in the structure of the transition process wave front.

(3) Based on the experimental evidence, the concept of the autocavitational mechanism of control of motion of the metastable decomposition front in the superheated liquid film at the heater surface has been developed. The closeness of this mechanism to the mechanism of detonation known from the physics of explosion is discussed. It is stated that the cavitational (shock) effect originates on the rupture of liquid and cavity collapse.

(4) Along with the cavitational (gas-dynamic) mechanism, the possibility is also considered for the existence of some other mechanism of hydrodynamic nature based on the involvement of the autowave process as a motive force for liquid motion near the fuel element surface.

(5) Based on the study of dynamic laws and structural aspects of steady-state subcooled bubble boiling, the conclusion is drawn that in this regime the local process is in a state of constant replacement of decomposition stages and subsequent recovery of metastability.

(6) It is established that even in the regime of steady-state boiling the decomposition of the zones of local metastability obeys the laws of travelling waves. In this case, high-speed events of wave decomposition may appear on the surface element along with slow waves. The above-developed scheme of the process of steady-state boiling made it possible to classify it as a polyautowave process, i.e. as the process representing the superposition of simultaneous (but occurring in different time phases) events of autowave rearrangements of the local regime.

9. INFERENCE

Concluding the discussion and clearly understanding that the concepts advanced are questionable, it is worthwhile highlighting the main elements in the physical mechanism of the threshold phenomena occurring in the transition from convective heat transfer to boiling, a deeper knowledge of which is required in principle in order to assert and develop the autowave approach to the description of dynamic trends in the transition processes considered.

First, recall that any model of the autowave alternations of homogeneous steady states of the system should always involve two requisite elements: a strongly non-linear kinetic mechanism and a specific physical mechanism of perturbation transfer in space.

The first mechanism leads to the appearance of a term of autocatalytic type in the mathematical model representing the process of progressive variation in the magnitude of the governing variable (for example, concentration of nuclei). This type of law has not been found in the literature on the physics of boiling, though, as has already been indicated in the Introduction the term 'chain process of boiling up' appears in refs. [2, 3] (see also refs. [14–16]). Really, the chain (more precisely, the branched-chain) mechanism is a classical example of the appearance of self-developing burst-like processes in different areas of physics and chemistry. However, as applied to their objects of study the authors of the above-cited works failed to suggest a particular scheme for the positive feedback that controls the dynamics of the multiplication of nuclei; whereas the equations suggested by them to describe the kinetics of the growth of a single (primary) vapour bubble do not relate to the branched-chain ideology. The non-linear mechanism in the qualitative models suggested in the present work should also be related to the branched-chain type. The specific features of this scheme of feedback consist of the multiplication of nuclei due to the autodispersion of the liquid film and incipience of nuclei on the surfaces of its 'fragments'. In other words, a hypothesis is suggested about the mutual excitation of the processes of boiling up and of the liquid film-destructing shock effect.

Thus, it must be borne in mind that the branched-chain process itself is not as yet an autowave process. The difference between this process, which develops uniformly throughout space, and the regime of self-sustained propagation of its front is the same as that between the thermal explosion and combustion, namely these are different (by physics and models) though closely interrelated phenomena [17]. For the transition to an autowave, the model should be augmented, as already mentioned above, with the second requisite element, i.e. with the term which represents the mechanism of transfer of the process-exciting disturbance throughout space. The authors of refs. [2, 3, 14–16] were probably the first to introduce the notion of the front into the physics of convective heat transfer metastable regime decomposition and estimated the values of the linear velocities of this process propagating from layer to layer (the value ~ 10 m s^{-1} given in ref. [14] correlates with the characteristics of a fast wave realizable in the region of great superheating—see Sections 4 and 5). However, in all likelihood these authors were unaware that the model, which describes the growth of a single vapour bubble and which disregards the process of disturbance transfer over the metastable liquid film, is devoid of the adequacy determining wave. The standpoint of the present authors regarding the physical mechanism of disturbance transfer is based entirely on hydrogas-dynamic factors, the specific nature of which varies in transition from the region of slow waves to that of fast waves (see Section 6). Of particular note is the fact that in developing the concept of the detonational (shock-cavitational) mechanism in the physics of the autowave decomposition of the metastable regime, the conclusion has been arrived at that it is necessary to reconsider the traditional concepts about the zone of action of the cavitational event and a hypothesis has been advanced about the origination of the shock effect not in the course of the vapour bubble collapse but during its birth, directly near the surface of the heating element. The above facts attest to the fundamental aspects of the cavitational concept formulated in the work. The authors of refs. [2, 3, 14–16] were probably the first who drew the attention of research workers to the possible controlling role of the cavitational mechanism in the processes of decomposition of metastable regimes, but it should be noted that in their model the scheme of the cavitational event in the processes of vapour generation is not physically specified.

The next problem which requires special attention when studying the autowave dynamics of the metastable heat transfer decomposition is the problem about the role of the boiling regime which culminates the transition process. Based on the results obtained by the present authors, it is possible to assert that the mechanism which governs the dynamics of the process of transition is entirely involved in the stage of the superheated liquid layer decomposition near the heater surface, whereas the subsequent stages (either the formation of bubble boiling or immediate attainment of the film regime) do not exert a substantial effect on the boiling-up front velocity. In refs. [2, 3, 14–16], emphasis was made only on one form of metastability decomposition, namely on the direct transition from the single-phase to the film boiling regime (bypassing the bubble regime). The authors of the above works attach great importance to the formation of the film regime in the transition process, regarding this transition to be a self-sustained phenomenon and even calling it the 'third crisis of boiling'. In the present authors' opinion, the decomposition wave velocity depends in the main on the superheating of the liquid layer near the surface (i.e. on the metastability degree, potential energy residue in this layer), whereas the stages of the coalescence of the finely-dispersed phase and formation of steady-state boiling regimes are secondary; they fall far behind the forward front of the travelling decomposition wave and do not exert any effect on the laws governing its motion.

The final problem, which from the point of view of the present authors is of great importance for the study of the autowave transition process, is that concerning the means and conditions required to excite metastable regime decomposition. The investigation of travelling waves would be very limited without resorting in experiments to operation of artificial local initiation of the process. This operation can be aptly called 'ignition' by analogy with the theory of combustion. It may well be that a whole trend will develop in future dealing with the study of the laws of this stage: analysis of the threshold parameters of the wave-exciting disturbance, of the role of the physical nature of the disturbance, etc. In other words, the same thing that occurred in the science of combustion should take place and cause the development of a separate and very important section—the theory of ignition [17]. At the present stage of investigation no task has as yet been set to study the critical conditions for the initiation of the decomposition front. Effort has been concentrated on the development of various physical procedures (thermal, jet-like, ultrasonic) for the local excitation of the autowave process. The investigation of the transition from convection to boiling under the conditions of a spontaneously initiated process (as presently adopted in virtually all the studies of the metastable system decomposition [1–3, 14–16]) leads to a variety of uncertainties because of the increase of the role of fluctuations and chance factors, thus greatly contracting the parametric boundaries of the region of study of transition processes and generally bereaving the data of the necessary correctness.

This section was specifically presented in polemical form in order to stimulate the discussions that could speed up the determination of the ideology in the dynamic theory of the formation of the processes of boiling so important for the physics of boiling.

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ASPECTS DYNAMIQUES ET STRUCTURELS DES MECANISMES DU TRANSFERT THERMIQUE CONVECTIF MONOPHASIQUE PENDANT LA FORMATION DE L'EBULLITION ET LE REGIME METASTABLE

Résumé—On étudie le mécanisme accompagnant la formation des bulles en régime d'ébullition sur la surface de l'élément de chauffage. Les recherches sont faites avec des fils de platine chauffés électriquement placés au sein de différents hydrocarbures. Le mécanisme de transition entre la convection et l'ébullition est induit par des perturbations locales dans la région de métastabilité. On a trouvé que le mécanisme de transition en onde isolée est initié dans les conditions décrites. Dépendant de la profondeur de pénétration dans la région métastable, le mécanisme de transition peut prendre place selon deux modes—d'onde lente ou rapide—qui diffèrent par l'échelle de vitesse et la structure du front. Les relations entre la vitesse d'onde et la température de l'élément chauffant sont obtenues. La conclusion est que le mécanisme peut être identique à celui du phénomène de détonation. Les résultats obtenus sont étendus au cas de l'ébullition permanente d'un liquide sous-refroidi. On pense que dans les conditions considérées cette ébullition est un mécanisme de plusieurs ondes séparées, la superposition de mécanismes d'ondes isolées lentes et rapides qui prennent place simultanément sur le chauffoir. Les principales conclusions sont confirmées par les résultats de photographies ultra rapides.

UNTERSUCHUNG DER DYNAMIK UND STRUKTUR DES ÜBERGANGSPROZESSES VON EINPHASIGER KONVEKTION ZUM BLASENSIEDEN

Zusammenfassung—Die vorliegende Arbeit beschäftigt sich mit der Untersuchung des Mechanismus, welcher der Entstehung von Blasensieden an der Oberfläche eines Heizelementes zugrundeliegt. Die Untersuchungen werden mit elektrisch beheizten Platindrähten durchgeführt, die in verschiedenen Kohlenwasserstoffen eingetaucht sind. Der Übergang von freier Konvektion zum Blasensieden wird durch lokale Störungen im metastabilen Gebiet ausgelöst. Es zeigt sich, daß unter den beschreibenen Bedingungen ein sogenannter "self-wave-Typ" des Übergangs eintritt. Abhängig davon, wie weit der Vorgang im metastablien Gebiet verläuft, kann der Übergangsprozeß auf zwei Arten—schnelle und langsame Wellen—eintreten, die sich durch den Geschwindigkeitsbereich und die Struktur der Wellenfront unterscheiden. Der Zusammenhang zwischen der Wellengeschwindigkeit und der Temperatur des Heizelementes konnte herausgefunden werden. Mögliche Mechanismen des self-wave-Übergangs werden betrachtet. Es wird der Schluß gezogen, daß der Vorgang identisch mit Detonationsvorgängen ist. Die gewonnenen Ergebnisse werden auf den Fall des stationären Blasensiedens von unterkühlter Flüssigkeit ausgedehnt. Daraus kann geschlossen werden, daß unter den betrachteten Bedingungen Blasensieden einen mehrfachen self-wave-Prozeß darstellt, das heißt, daß schnelle und langsame self-wave-Vorgänge gleichzeitig auf der Heizplatte ablaufen. Die wichtigsten Schlußfolgerungen werden durch Hochgeschwindigkeitsaufnahmen bestätigt.

ДИНАМИЧЕСКИЕ И СТРУКТУРНЫЕ ОСОБЕННОСТИ ПРОЦЕССОВ РАСПАДА МЕТАСТАБИЛЬНОГО РЕЖИМА ОДНОФАЗНОЙ КОНВЕКТИВНОЙ ТЕПЛОПЕРЕДАЧИ И ФОРМИРОВАНИЯ ПУЗЫРЬКОВОГО КИПЕНИЯ

Аннотация—Работа посвящена изучению вопроса о механизме формирования на поверхности тепловыделяющего элемента режима пузырькового кипения. Исследования проведены на нагреваемых током платиновых проволочках, помещенных в среду различных углеводородов. Процесс перехода от конвекции к кипению возбуждался локальными возмущениями в области метастабильности. Обнаружено, что в описанных условиях инициируется переходной процесс автоволнового типа. В зависимости от глубины вторжения в область метастабильности переходный процесс может протекать в двух режимах – медленной и быстрой волны, отличающихся масштабом скорости и структурой фронта. Получены зависимости скорости волны от температуры нагревательного элемента. Рассмотрены возможные механизмы автоволнового переходного процесса. Сделан вывод о близости изученного процесса явлению детонации. Полученные результаты обобщены на случай стационарного пузырькового кипения недогретой жидкости. Сделан вывод о том, что в рассматриваемых условиях пузырьковое кипение представляет собой полиавтоволновой процесс, т.е. суперпозицию одновременно протекающих на нагревателе бысторых и медленных автоволновых процессов. Основные выводы подтверждены результатами скоростной киносъемки.