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TRANSIENT PROCESSES AND THERMOACOUSTIC EFFECTS IN SURFACE BOILING OF A LIQUID

E. V. Lykov and A. G. Sinetskaya

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The results of experimental investigation of the phenomenon of hysteresis and the prehistory of boiling on a cylindrical heater have been given. The transient processes associated with thermoacoustic effects in burnout of a liquid under natural convection have been considered.

Bubble, transient, and film regimes of boiling successively occur with continuous controlled growth in the temperature on the heating surface. Apparently, the intermediate, as it were, regime between stable bubble and film boilings is called transient here. Studying the replacement of convection by boiling, we also find many features of a transient process. It has been noted by I. I. Novikov [1] that such processes occur multiply. It appears that such transient processes may be explained in investigation of the so-called thermoacoustic effects in boiling of binary liquids [2]. Joint study of thermal and acoustic quantities in boiling reveals the distinctive features of the process studied on a setup whose block diagram is given in [2].

Pool boiling of water was carried out using a cylindrical copper heater of diameter 65 μm and a Nichrome heater of diameter 100 μm. Before the beginning of the experiments, the heater was subjected to conditioning in air: to calcination to red heat and cooling. To investigate boiling we placed the electric heater in a large volume of water, whose temperature was equal to 20–30^{o}C at normal atmospheric pressure and which was heated by a constant electric current. The temperature of the liquid core remained constant over the period of the experiment. Copper wire was used simultaneously as the heater and the resistance thermometer. To obtain the next realization of the hysteresis curve we first increased the thermal load to 2/3 rds of its critical value and then decreased it until the boiling stopped.

Figure 1 gives one realization of the curve enabling one to consider the mechanism of boiling of the liquid in detail with increase and subsequent decrease in the heating of a thermally stressed surface. The hysteresis curve has been obtained in the form of right-hand and left-hand branches. The course of the experiment on both branches is shown by the arrows. The experimental order of certain singular points on the hysteresis curve is marked by the figures. It is seen that a hysteresis and a characteristic bistable course of the process reveal themselves with a monotonic growth in the thermal load up to 2/3 rds of its critical value and a monotonic decrease down to a value for which the boiling stopped. No boiling has been found in the region of free convection with monotonic increase in the heating-surface temperature to the boiling point and with its monotonic reduction. If we go beyond the boiling point and return back, the hysteresis manifests itself.

If the thermal load is monotonically reduced, the process of boiling is delayed, i.e., it occurs in the region of low superheatings of liquids and small heat fluxes, substantially smaller than those on the right-hand branch of the curve. In Fig 1, we have the region of free convection from point 1 of the beginning of the experiment to point 3. The experiments show that water begins to boil for q = 0.4 MW/m^2 (Fig. 1, point 3). Beginning from this point and to point 8, we have boiling in the form of single vapor bubbles for q = 2 MW/m^2. Thereafter jet boiling is activated for q = 2.8 MW/m^2 (point 9). We decrease the thermal load from point 9 and find the delay of jet boiling to q = 1.8 MW/m^2 with monotonic decrease in the heater temperature. The observations show that, as the thermal load decreases, a reverse transition from jet boiling to bubble boiling occurs between points 9 and 10. As the thermal load drops further, the process of boiling continues to q = 0.3 MW/m^2 (point 15). The most important distinctive features of hysteresis manifest themselves in successive realization of the hysteresis curve on the same heater under stable conditions. Figure 2a shows the initial realization, whereas Fig. 2b shows the repeat realization.

Rostov-on-Don Academy of Agricultural Mechanical Engineering, 2 Strana Sovetov Sq., Rostov-on-Don, 344029, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 78, No. 4, pp. 22–26, July–August, 2005. Original article submitted December 3, 2004.

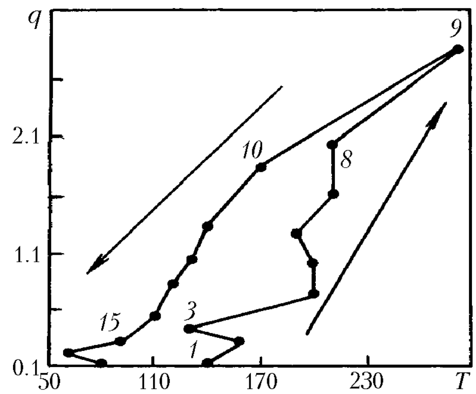

Fig. 1. Hysteresis curve in unsaturated boiling of a liquid.

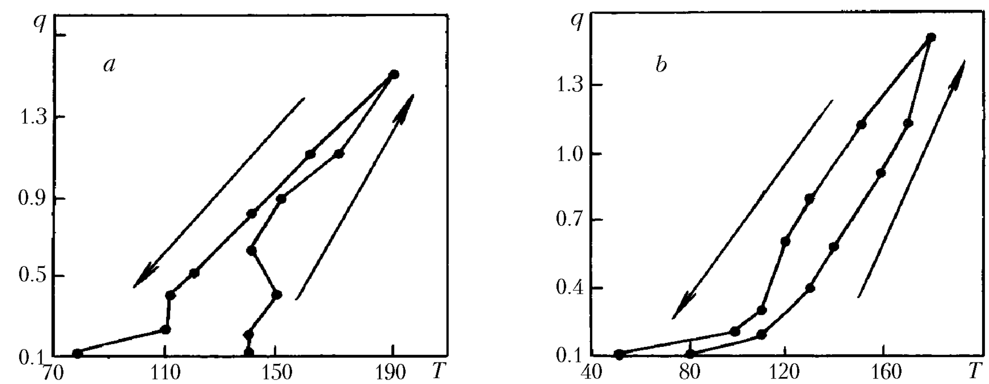

Fig. 2. Two successive curves of hysteresis of boiling.

The heater temperature was monotonically increased to a certain maximum and thereafter was reduced until the boiling stopped. A maximum value of the thermal load of q_{max} = 1.5 MW/m^2 in both realizations (Fig. 2) is attained at different temperatures: for Fig. 2a it is higher than that for Fig. 2b. It is seen that, in the replicate of the experiment on the same heater under the same conditions, the maximum value of the thermal load is attained at a lower temperature. The delay of boiling is nearly halved.

Let us investigate the relation of the transient processes to the distinctive features of thermoacoustic effects which have been described in [2] and are studied below. It is of interest to compare the acoustic curves of boiling of water on the heating surface to the hysteresis curves given in this work.

The process of heating is accompanied by thermoacoustic effects which are characterized by the acoustic pressure P and frequency characteristics (spectra). These effects are related to instantaneous and running acoustic spectra and reflect all substantial changes in the heat flux in transient processes of a boiling liquid. According to [3], a comparison of the integral and spectral acoustic characteristics to the thermophysical pattern of boiling provides valuable information for analysis of the mechanism of the process of boiling.

Figure 3 plots the acoustic pressure P as a function of the thermal load q in a boiling water. It is seen that the acoustic pressure increases to a certain maximum with thermal load and then decreases. Very significant levels of acoustic pressure are found. Point 1 in Fig. 3 is the point of the beginning of the experiment. A level of 5 mV corresponds to a pressure of 100 N/m^2, which is 80 dB higher than the initial audibility level. At point 5, the transition from the regime of motion of single vapor bubbles to that of jets and vapor columns occurs with growth in the thermal load. At this point, we have the acoustic burnout (boiling crisis) [4], after which the level of acoustic pressure decreases. Point 8 corresponds to the end of the process because of the damage to the heating surface. In Fig. 3, it is seen that the acoustic pressure is virtually constant from point 7 to point 8 before the melting of the heater. The vapor flow decreases. Point 7 corresponds to the burnout.

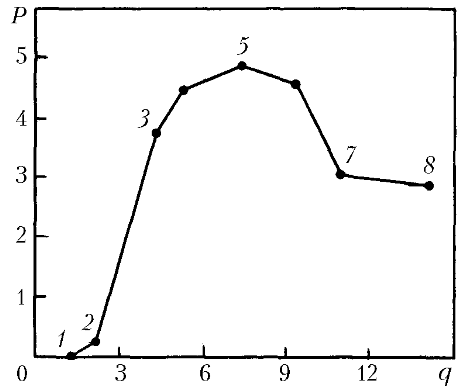

Fig. 3. Acoustic pressure P vs. thermal load q.

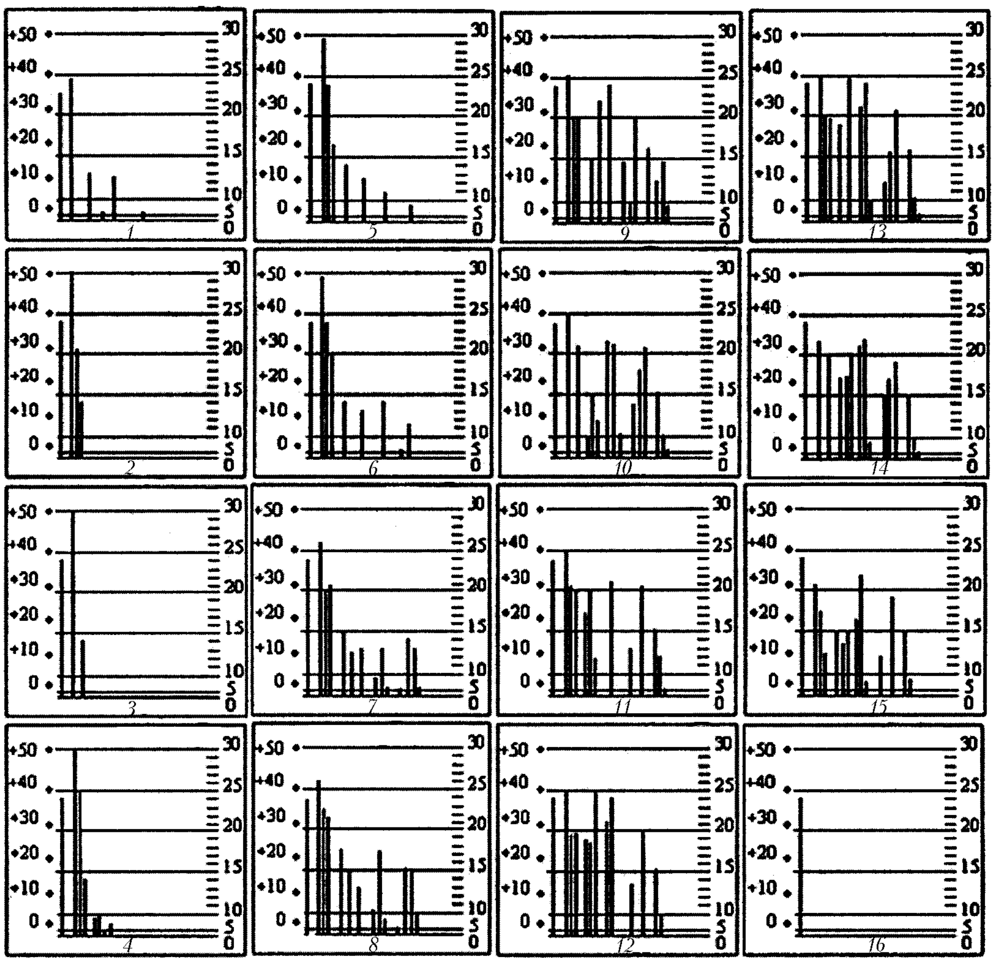

Fig. 4. Running acoustic spectrum of boiling of water along the entire curve.

The running acoustic spectrum (Fig. 4) taken with an ultrasonic-frequency spectrometer corresponds to the entire curve of boiling from the instant of boiling up to the final point at which the heater is burnt. The running spectrum reflects the course of development (time history) of the boiling growth in the thermal load and numerous distinctive features, including the so-called acoustic burnout [4, 5].

In Fig. 4, the verticals show the amplitude of acoustic vibrations in accordance with the frequency range on a certain filter. There are 16 third-octave bands in an ultrasonic-frequency spectrometer. The first vertical on each instantaneous spectrum on the left is a "plug," i.e., spectra in the entire range of the frequencies measured decrease in

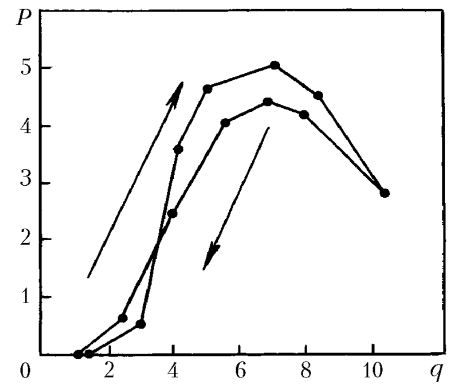

Fig. 5. Acoustic curve of hysteresis of boiling of a liquid.

amplitude by the value of the "plug," which is denoted by the numbers of the left-hand column from 0 to +50. The acoustic pressure in decibels (from 0 to 30) is given along the right-hand axis.

The initial instant in boiling up corresponds to the first instantaneous spectrum (frame 1, Fig. 4). With continuing growth in the thermal load, the running spectrum reveals a qualitative change in the spectral composition of sound; there is a characteristic frequency shift (frames 2–9). The shift of the maximum spectral frequency is very significant and is no less than 190 kHz (12.9 to 206 kHz). In developed boiling (beginning from frame 9), high-frequency components of the spectrum significantly grow with thermal load up to frame 15, which corresponds to the end of the process; therefore, boiling is absent from frame 16.

Burnout and the critical thermal load may be explained based on the hydrodynamic approach [6]. If we assume that the critical vapor velocity characterizing burnout depends on the relation between the lifting forces, surface-tension forces, and inertial forces of the vapor flow, we obtain the following four quantities: $\rho'' U^2$, g, $(\rho' - \rho'')$, and σ for dimensional analysis. Hence, according to the dimensional theory and with allowance for the highest (critical) vapor velocity $U_{cr} = q_{cr}/\rho L$, we establish only one criterion K in the form of the following expression:

$$K = \frac{q_{cr}}{Lg\sqrt{\rho''}\sqrt[4]{\sigma g(\rho' - \rho'')}} .$$

In accordance with similarity theory, this means that all hydrodynamic characteristics of the pool boiling, such as, for example, the liquid and vapor velocities at individual points of the volume and the average vapor content in planes and directions in the volume, are determined by the numerical value of this criterion. This suggests that burnout is caused by the process of forcing out of the liquid from the heating surface.

The distinctive features of the transient processes are elucidated in studying the acoustic characteristics of the hysteresis of boiling. Figure 5 gives one realization of the acoustic curve of hysteresis of boiling on a cylindrical Nichrome heater of diameter 100 μm in water, where the liquid-core temperature was constant and equal to 28^{o}C. Just as in the previous figures, the course of development of the boiling is shown by the arrows. Here it is seen that the acoustic levels are higher in the case of direct course than those in reverse course and the acoustic pressure on the upper and lower branches is different for the same thermal loads.

It is assumed that the delay of boiling (see Figs. 1 and 2) is due to the small number of ready nucleation sites and to the difficulty of their formation on the cylindrical heater in early stages of boiling. Nucleation sites may exist and generate bubbles, disturbing the convective heat exchange of the heater only locally. The delay of boiling is, apparently, affected by nucleation sites. The larger the number of active sites acting in the beginning of boiling, the shorter will be the delay of boiling. In the opposite direction, i.e., with decrease in the thermal load in boiling, the duration of contact between the liquid and the heater increases, and boiling continues at lower temperatures. This is the reason why the process of boiling is delayed.

In all probability, the phenomenon of hysteresis in heat exchange is directly related to the transient processes in boiling of a liquid. We may draw, from the observations, a conclusion on the existence of the following transient processes referring to the mechanism of boiling in direct and reverse courses of the process: free convection in the motion of single bubbles, the motion of single vapor bubbles through coagulation of the bubbles into jets and columns and of jets and vapor columns to bubble boiling, and the motion of single bubbles to the free-convection zone.

Sound pulses in boiling result from the explosive growth in vapor bubbles [2]. The observations show that, as the thermal load monotonically increases, the separation diameter of vapor bubbles decreases but their separation frequency increases with acoustic pressure. After the acoustic burnout, we have developed boiling, i.e., the maximum vapor flow is formed.

The transient processes between the regime of motion of single vapor bubbles and the regime of vapor jets and columns is accompanied by the so-called acoustic burnout of the liquid. This enables one to prevent, in practice, the hazardous stage of heating of the thermally stressed surface and to determine the critical boiling point in further audition.

CONCLUSIONS

1. Transient processes that are related to the change in the mechanism of boiling of a liquid are partially explained by the behavior of the running acoustic spectrum of sound (noise) of boiling. This is confirmed by a comparison of the curves of hysteresis of boiling to the integral and spectral characteristics.

2. The transient process related to the change in the integral level of acoustic pressure enables one to prevent, in practice, the hazardous stage of heating of a thermally stressed surface both in the region of burnout and when the heater-overburning hazard exists.

NOTATION

g, free-fall acceleration, m/sec^2; L, heat of evaporation, J/kg; K, thermal criterion of phase transformation; P, acoustic pressure, mV; q, thermal load, MW/m^2; q_{cr}, critical thermal load, MW/m^2; q_{max}, maximum thermal load, MW/m^2; T, surface temperature of the heater, ^{o}C; U, average reduced velocity of the vapor, m/sec; U_{cr}, critical velocity of the vapor, m/sec; ρ', density of the liquid, kg/m^3; ρ'', density of the vapor, kg/m^3; σ, coefficient of surface tension of the liquid, N/m. Subscripts and superscripts: $'$, liquid; $''$, vapor; cr, critical; max, maximum.

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