Journal of Engineering Physics and Thermophysics, Vol. 74, No. 3, 2001

BURNOUT HEAT TRANSFER IN BOILING UNDER CONDITIONS OF STEPWISE HEAT GENERATION

S. G. Obukhov

UDC 621.039.517

The results of experimental investigations on the time of the onset of boiling crisis in nonstationary heat generation are presented. A standard working formula is suggested for determining the time of the onset of burnout heat transfer in a wide range of heat loads, subcoolings, and pressures.

Boiling provides one of the types of high-intensity heat exchange. The majority of experimental investigations of nonstationary boiling have been carried out with helium and water (the elements of superconducting systems and nuclear reactors). Reliable operation of thermal engineering equipment is possible only in the precrisis mode of heat transfer, which necessitates the determination of conditions favoring the occurrence of burnout. Visual observations and oscillographic investigations of temperature dependences revealed the following modes of heat exchange in shock heating of the surface immersed in a liquid: nonstationary heat conduction, natural convection, bubble boiling, transient mode, and film boiling [1]. In a number of cases (depending on the ratio p/p_{cr} and relative heat flux q_w/q_{cr1}), some of the modes may be developed insufficiently or may be completely absent. In what follows, the results of generalization of the experimental data of [1, 2] are given. They were obtained in investigation of heat exchange on a liquid-wall interface upon increase in the supplied heat flux from zero to a certain fixed value determined by the degree of ac heating of the sample. The time of increase in the electric power was 5 msec. High-power welding transformers were used as energy sources. Water, TS-1 kerosene, Ai-93 gasoline, and diesel oil were used as heat-transfer agents. The test elements were stainless steel pipes (pipes used for the fuel elements of nuclear reactors) and plates of different materials located horizontally in a pool of liquid at rest. The majority of experiments were carried out on surfaces not "run-in" by preliminary boiling. This led to a decrease in the critical heat flux density q_{cr1} [3].

The carried-out evaluations of the time of occurrence of boiling crisis τ_{cr} from the well-known relations [4, 5] that were good for cryogenic liquids are inapplicable for kerosene and water (τ_{cr} determined from these formulas differs by an order of magnitude or more from the values obtained experimentally). These relations provide adequate results for the liquids for which the nonstationary crisis of boiling sets in during the period of the growth of vapor bubbles up to their detachment (organic liquids and cryogenic liquids characterized by an abnormally low value of the temperature difference for boiling-up and also by the closeness of the boiling-up temperature to the temperature of the limiting superheating of the liquid). For kerosene and water, this physical model of the crisis can work in the investigated range of pressures only when $q_w > 10q_{cr1}$.

The results of speed filming and of visual observation and evaluations from the relations describing the time of convection development showed that with $q_{cr} > 0.5q_{cr1}$, for both water and kerosene the influence of free convection on the process of crisis development upon power increase can be neglected, since $\tau_{cr} << \tau_{conv}$. Thus, the boiling crisis is preceded by the stages of nonstationary heat conduction and metastable bubble boiling (Fig. 1).

Kamsk Polytechnic Institute, Naberezhnye Chelny, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 74, No. 3, pp. 10–12, May–June, 2001. Original article submitted April 18, 2000.

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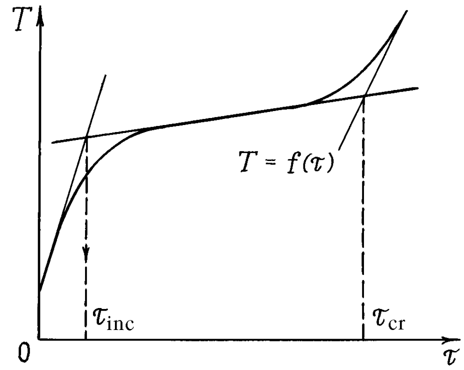


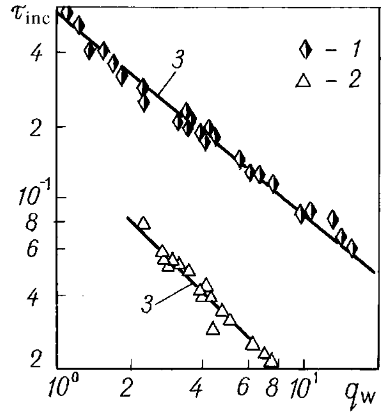


Fig. 1. Determination of the time of boiling inception and occurrence of heat-transfer crisis in a nonstationary process.

Fig. 2. Time of attainment of the thermal head of boiling-up vs. the increased heat flux density: 1) TS-1 kerosene, plates (δ = 0.5 mm); 2) water, pipes (δ = 0.2 mm; 1, 2) 12Kh18N9T, T_f = 20°C, p = 0.1 MPa); 3) calculation from (1). τ_{inc}, sec; q_w, MW/m^2

The time of attainment of the temperature difference for boiling-up (the time of the incipience of boiling τ_{inc}) was calculated from the formula suggested in [6] for nonstationary heat conduction in stepwise heat generation, with thermal inertia of the heater taken into account:

$$2\tau_{inc}^{1/2} - \tau_d^{1/2}\,[1 - \exp(-2\,(\tau_{inc}/\tau_d))] = (T_{inc} - T_s)\,(\pi\lambda'\rho'c_p')^{1/2}/q\,, \tag{1}$$

where τ_d is the complex which has the dimensionality of time and which is composed of the physical constants of the liquid and of the material of the heating surface wall: $\tau_d = (c_w\rho_w\delta_{eq})^2/(\pi\lambda'c_p'\rho')$; $\delta_{eq} = V_w/F_{ext}$ is the equivalent thickness of the wall.

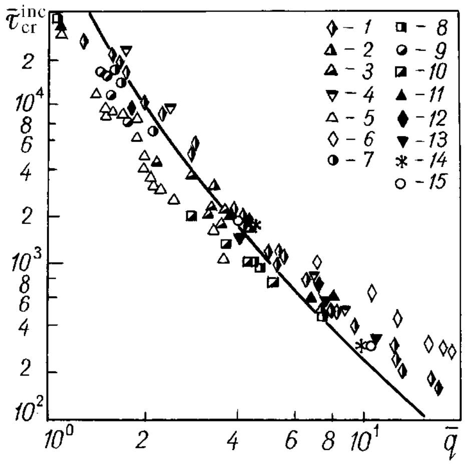
The temperature of the inception of boiling T_{inc} in formula (1) was determined from relation (1) of [1]. As is seen from Fig. 2, there is a good agreement of experimental data on the time of boiling inception with the calculation by relation (1).

It is suggested to calculate the time of the onset of burnout heat transfer τ_{cr} as the sum of the following times:

$$\tau_{cr} = \tau_{inc} + \tau_{cr}^{inc}\,. \tag{2}$$

Here, it is admitted that (1) before the inception of boiling (the time period τ_{inc}) the liquid in the wall layer is heated up; evaporation, if present, is insignificant and does not influence the mode of nonstationary heat conduction; (2) the temperature of the wall in the mode of metastable boiling (the period from the inception of boiling to burnout heat transfer) is approximately constant and is determined from empirical relation (1) of [1]; (3) the time of boiling inception τ_{inc} is determined from the well-known formula (1) on attainment of the temperature difference for boiling-up determined from relation (1) of [1] depending on the magnitude of the heating load.

Before determining τ_{cr}^{inc}, it should be recalled that earlier in [7] it turned out to be possible under "stationary" conditions to exceed the values of q_{cr1}, almost twice preserving high values of theheat-transfer coefficient α. It was presumed in that work that the liquid contacted the heating surface through thin films existing between the vapor clusters being formed. The slightest nonuniformity in heat supply led to rapid local evaporation of the films and caused hydrodynamic instability of the two-phase flow in the wall layer.



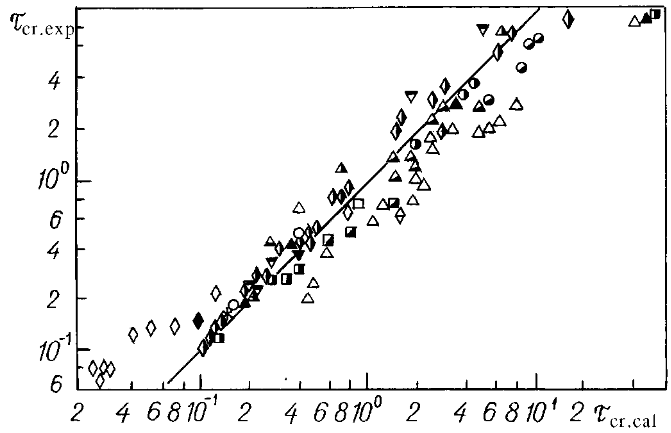


Fig. 3. Comparison of the experimental data with the results of calculation from (5) at $C = 2{\cdot}10^4$: 1–4, 13) kerosene; 5–12) water; 14) Ai-93; 15) diesel oil; 11–13) run-in surface; 1–4, 7–10, 13) plates, δ = 0.5 mm; 5, 6, 11, 12, 14, 15) pipes, δ = 0.2 mm; 1, 7, 9, 14, 15) 12Kh18N9T; 2–4, 8, 10, 13) D16AT; 1–3, 5, 7–13, 13–15) T_f = 20°C; 6, 12) T_f = 100°C; 4) T_f = –10°C; 1, 2, 4–8, 11–15) p = 0.1 MPa; 3, 9, 10) p = 0.6.

Fig. 4. Comparison of the experimental data with the results calculated from (2) (notation is the same as in Fig. 3).

Similarly to the models of nonstationary crisis of boiling that were suggested in [5, 8], we assume that on increase in the heat load that exceeds the critical one, from the region of the two-phase layer into the liquid a fraction of heat is removed which corresponds to the stationary critical heat flux. The excess heat is spent to evaporate the liquid that circulates during the time τ_{cr}^{inc} near the heating surface reduced to a certain conventionally immobile wall layer of liquid of thickness δ. In [4, 5, 8], the scheme of calculation of the boiling crisis under nonstationary heat-generation conditions does not take into account the stages of single-phase heat exchange. This assumption is valid not in all of the cases, the more so with high subcoolings when the time of the mode of nonstationary heat conduction accounts for a substantial fraction in τ_{cr}.

We assume that at the instant of increase in heating load the temperature difference for boiling inception is attained on the surface of heating ΔT_{inc} (i.e., on the lapse of the time τ_{inc}). With this taken into account, the equation of heat balance on increase in heating load for the time interval $\tau_{inc} < \tau < \tau_{cr}$ in the surface–liquid system has the form

$$q_w \tau_{cr}^{inc} = r\rho'\delta + q_{cr1}\tau_{cr}^{inc} . \qquad (3)$$

With increase in the density of the increased heating load the thickness of the conventionally immobile wall layer δ decreases. The thickness of the liquid layer is governed by Re_{ev}, i.e., by the liquid viscosity and (for the condition of free motion) by the rate of vapor formation:

$$\delta = Cr\rho''v'/q_w \qquad (4)$$

(C is an experimental constant).

On rendering Eq. (3) dimensionless, with Eq. (4) taken into account, we have

$$\bar{q} = \frac{C}{\bar{q}\,\bar{\tau}_{cr}^{inc}} + 1 \quad \text{or} \quad \bar{\tau}_{cr}^{inc} = \frac{C}{\bar{q}\,(\bar{q} - 1)} , \qquad (5)$$

where

$$\bar{\tau}_{\rm cr}^{\rm inc} = \tau_{\rm cr}^{\rm inc} / [(r\rho'')^2 \rho' \nu' / (\rho'' q_{\rm cr1}^2)] \; ; \quad \bar{q} = q_{\rm w} / q_{\rm cr1} \; ;$$

$\bar{q}$ is the dimensionless increased heat flux density, $\bar{\tau}^{\rm inc}$ is the dimensionless time from the inception of boiling of the liquid to the occurrence of burnout heat transfer, and $q_{\rm w}$ is the increased heat flux density, and $q_{\rm cr1}$ is the first critical density of the heat flux.

A comparison of the experimentally obtained data with those calculated by Eq. (5) is presented in Fig. 3.

The calculated results agree satisfactorily with the experimental data. All the thermophysical properties of liquids were taken at a saturation temperature. The critical heat flux density $q_{\rm cr1}$ was taken for surfaces both unrun and run-in [3]. Figure 4 presents a comparison of the time of occurrence of the boiling crisis as calculated from Eq. (2) and experimental data.

Thus, experimental investigations have been carried out under conditions of an increase in heating load many times exceeding the critical one on surfaces of actual dimensions. On the basis of the proposed simplified model of the development of a boiling crisis, a dependence is suggested that allows one to determine the time of occurrence of the boiling crisis at a given level of heat generation.

NOTATION

q, heat-flux density; p, pressure; λ, thermal conductivity; ρ, density; c, specific heat ($c_{\rm w}$, of the wall, c_p, at a constant pressure); V, volume; F, area; δ, thickness; T, temperature; r, specific heat of vapor generation; Re, Reynolds number; ν, kinematic viscosity; α, heat-transfer coefficient; τ, time ($\tau_{\rm inc}$, time of boiling inception; $\tau_{\rm cr}$, time of occurrence of the boiling crisis; $\tau_{\rm con}$, time of convection development). Subscripts: w, wall; cr, heat-transfer crisis; cr1, first crisis of boiling; inc, boiling inception; d, dimensionality; s, saturated state; eq, equivalent; ext, external; ev, evaporation; f, surrounding fluid; ΔT, superheating. Superscripts: $'$, liquid; $''$, vapor; inc, interval between the boiling inception and occurrence of the heat-transfer crisis.

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