

INVESTIGATION OF BOILING HEAT TRANSFER AT A SURFACE WITH
A SYSTEM OF CYLINDRICAL CAVITIES UNDER CONDITIONS OF FREE MOTION

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UDC 536.423

Expressions are proposed for calculating the boiling curve for water, ethyl alcohol and R 113 on a surface with artificial nucleation sites in the form of cylindrical cavities.

The intensification of boiling heat transfer in evaporative cooling systems is a topical problem, since the temperature head in the boiling zone often constitutes a large part of the total temperature head between the cooled object and the ambient medium and needs to be reduced. The method [1] of reducing the temperature head in the heating zone by intensifying boiling as a result of the creation of artificial nucleation sites on the surface in the form of large cylindrical cavities with microrecesses in the walls enjoys a number of advantages over other methods: long-term heat-transfer stability, high reproducibility of the technical characteristics, possibility of regulating heat transfer by a suitable choice of cavity dimensions and spacing, simplicity of manufacture.

The dimensions of the cavities are an order greater than those of the microrecesses, the active boiling sites on ordinary surfaces (Fig. 1a). There are microrecesses only on the walls of the cavities. The rest of the surface is ground or polished to exclude the possible development of other boiling sites between the cavities and to ensure that vaporization is confined mainly to the cavities. In this case the heat-transfer properties of the surface will be improved.

For calculating the heat transfer in nucleate boiling on a heating surface the authors of [2-4] proposed a model, in accordance with which the heat flux density can be represented in the form of a sum of three components:

$$q = q_b + q_l + q_c \quad (1)$$

It is assumed that there is no overlap of the areas of influence around the nucleation sites and that the heat transfer from the surface is the sum of the heat transfer from the elementary cells, each of which has a nucleation site at its center.

The first component of Eq. (1) is the amount of heat going toward the formation in each cell of f vapor bubbles with separation diameter D_0 , per unit of time, multiplied by the cell density n :

$$q_b = \frac{\pi D_0^3}{6} f \rho'' n. \quad (2)$$

The second component takes into account the heat removed from the surface by replacement of part of the layer of superheated liquid upon separation of the vapor bubbles:

$$q_l = 0.5 \sqrt{\pi} \sqrt{\rho' \lambda' c_p} \sqrt{f} D_{if}^2 \Delta T n. \quad (3)$$

Each bubble leaving the heating surface carries away part of the superheated layer [2]. The breakaway zone is characterized by the diameter of the hydrodynamic influence area of the bubble D_{if} (Fig. 1b). It should be noted that there is no generally held opinion on the value of D_{if} . In [5] it is recommended that D_{if} be taken equal to $2D_0$. In [3] there is introduced the idea of an empirical parameter $K > 1$, the ratio of the breakaway area of the superheated layer to the projection of the bubble on the heating surface at the moment of separation. When $D_{if} = 2D_0$, K is equal to four. The authors of [3] propose that this value be treated as the upper bound of K and on the basis of an analysis of their own experimental data recommend taking $K = 1.8$. An investigation of the interaction of nucleation sites [4] sug-

Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 53, No. 1, pp. 5-11, July, 1987.
Original article submitted April 18, 1986.

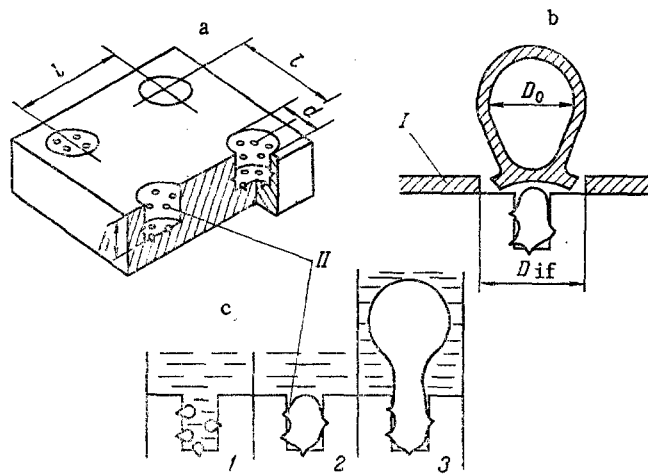


Fig. 1. Boiling surface with system of cavities: a) layout and dimensions; b) diagram showing part of superheated layer breaking away from rising bubble; c) bubble-forming mechanism; (I) superheated layer, (II) microrecesses.

gested that, depending on the boiling conditions, the value of the parameter K may vary from 1 to 8, but in that study high values of K were treated as atypical. According to the diagram for K presented in [4], values of $K < 1$ are also not to be excluded. In general, it may be assumed that D_{if} is not a constant but depends on a number of factors: the bubble separation diameter, the separation rate, the viscosity of the liquid, etc.

The third component of (1) is the heat removed by free convection from the area not affected by nucleate boiling:

$$q_c = 0.18\lambda' \left(\frac{g\beta c_p \rho'}{\nu' \lambda'} \right)^{1/3} \Delta T^{4/3} \left(l^2 - \frac{\pi D_{if}^2}{4} \right) n. \quad (4)$$

This approach to the heat-transfer calculations is physically justified for a surface with an ordered arrangement of identical artificial nucleation sites. However, the use of the model proposed in [2-4] is made difficult by the almost total lack of data on the bubble diameters, their rates of separation from large cylindrical cavities, and the corresponding influence area.

Below we present the results of investigating the internal boiling characteristics for a single cavity and propose a method of calculating the heat transfer from a surface with cavities.

The growth and separation of bubbles during the boiling of water, ethyl alcohol and R 113 on an individual cylindrical cavity was investigated by means of high-speed motion picture photography. The dimensions of the cavity were varied from 0.5 to 1.5 mm with respect to the diameter d and from 1 to 3 mm with respect to the depth h . In the various experiments the heat flux was varied from 30 to 90 kW/m², and the saturation pressure from 0.8 to 1.2 atm. The choice of liquids and the range of the factors investigated were determined by the practical problems of cooling radioelectronic equipment and the technical possibilities with regard to forming the cavities.

The research program and experimental conditions were established by a mathematical method of experiment design [6]. For each of the liquids investigated we constructed the orthogonal matrix of a complete three-factor plan of type 2^3 and carried out a regression analysis of the results.

The liquid was boiled on the end face of a copper bar 10 mm in diameter and 10 mm high. A cavity of the size required by the experimental conditions was drilled in the center of the copper face. The cavity size error did not exceed 0.1 mm. A thermocouple was embedded in the center of the specimen 1 mm from the bottom of the cavity. The heat flux density was determined from the readings of three thermocouples in a calibrated brass rod mounted between the specimen and the heater.

Before carrying out each experiment, we carefully polished the heat-transfer surface of the specimen with fine emery paper and degreased it with acetone. The chamber was filled with

liquid up to a constant level 100 mm above the heating surface. For several days the heating surface was degassed and broken in the boiling regime. After that we measured all the parameters and filmed the bubble formation and separation process. The boiling temperature head ΔT was determined as the difference between the temperature of the cavity base and the saturation temperature of the liquid. The error in determining the heat flux density was not more than 7%, the error in determining the superheating of the wall not more than 0.2°C at superheat values of from 4 to 12°C.

For filming we used a SKS-1M motion-picture camera. The filming speed was 300-700 frames per second, depending on the boiling rate. The bubble separation frequency was determined from time marks produced on the film by means of a neon lamp during filming. The equivalent separation diameter of the bubbles was measured with a MBS-1 microscope. A more detailed description of the apparatus and the method of processing the data is given in [7].

An analysis of the results obtained makes it possible to propose a single expression for calculating the separation diameter of the bubbles for all the liquids investigated:

$$D_0 = 1.82 \left[\frac{\sigma d}{g(\rho' - \rho'')} \right]^{1/3} \quad (5)$$

In [8] a similar expression, with a lower value of the constant coefficient ($C = 1.25$), was obtained for ethyl alcohol. The difference may be attributable to the fact that in [8] the values of the separation diameter were too low, since they were determined as the mean for bubbles growing on the same surface from cavities with diameters differing by a factor of 1.5-2.

For the separation frequency f we obtained interpolation formulas in the form of linear polynomials with dimensional coefficients for each liquid (d, h , mm):

for water

$$f = -22.61 + 11d + 7.35h + 5.29\Delta T - 4.4dh - 1.29h\Delta T, \quad (6)$$

for ethyl alcohol

$$f = -53.7 + 29.3d - 6.5h + 12.8\Delta T + 3.9dh - 7.4d\Delta T, \quad (7)$$

for R 113

$$f = -39.2 + 24.2d - 0.8h + 6.84\Delta T - 1.8d\Delta T. \quad (8)$$

On the basis of relations (5)-(8), the results of visual observation and an analysis of the motion picture frames it is possible to propose the following mechanism of operation of a cylindrical cavity in the vaporization regime (Fig. 1c). With increase in the wall temperature and the superheating of the liquid nucleation takes place in the microrecesses on the bottom and sides of the cavity (stage 1). As the bubbles grow, they merge into a single volume of vapor attached to the wall at the microrecesses (stage 2). This volume is separated from the cavity walls by an intermediate layer of liquid. Heat is transferred from the cavity walls by conduction through this film and evaporation from its surface. The vapor gradually fills the entire cavity, after which it starts to bubble through the cavity mouth (stage 3). In the initial stage of bubble growth in the liquid volume outside the cavity the external pressure at the phase interface increases, but at the moment of separation as a result of the cessation of bubble growth and the inertia of the liquid parting around the sphere it rapidly falls to a level below the pressure in the main volume. During this short period of reduced pressure associated with the separation of each bubble the cavity fills up with liquid. The inflowing liquid spreads over the cavity walls as a result of the action of capillary forces.

In order to clarify the dependence of D_{if} on the boiling conditions we processed the experimental data on D_0 and f obtained for a single cavity for various q and ΔT [7], starting from the assumed equality

$$q \frac{\pi D_{if}^2}{4} = \frac{\pi D_0^3}{6} f \rho'' r + 0.5 V \pi \sqrt{\rho'' \lambda' c_p} V \bar{f} D_{if}^2 \Delta T. \quad (9)$$

It was also assumed that D_{if} is proportional to the separation diameter D_0 and the separation frequency f of the vapor bubbles (these factors reflect the influence of the regime parameters of the boiling process), proportional to the diameter d of the mouth of the nucleation site, i.e., the geometric parameter directly influencing D_0 , and inversely proportional to the viscosity of the liquid ν' .

The results (see Fig. 2) demonstrate the possibility of using the following expression to approximate the dependence of the ratio D_{if}/D_0 on the dimensionless complex D_0df/ν' with a maximum deviation of not more than 25%:

$$\frac{D_{if}}{D_0} = 0.176 \left(\frac{D_0df}{\nu'} \right)^{0.4} \quad (10)$$

It should be noted that there are boiling regimes in which $D_{if} < D_0$. This can be explained as follows. As a rule, the experimental points for the region D_{if}/D_0 in Fig. 2 correspond to low bubble separation frequencies ($f \leq 10$). At a relatively low growth rate the vapor bubbles overcome a superheated layer with a diameter much less than D_0 . The subsequent growth of the bubbles takes place outside the superheated layer and they separate in a neck with a diameter close to that of the cavity. Immediately after separation at the neck the bottom of the bubble, which has the shape of an inverted cone, is observed to be pulled sharply upwards, and in this process part of the superheated layer breaks away and is entrained behind the bubble. The diameter of the breakaway area is always greater than the diameter of the cavity, but may be less or greater (depending on the separation frequency and the viscosity of the liquid) than the separation diameter of the bubble.

These data make it possible to recommend the following method of estimating the heat transfer from a surface with cavities: 1) for a given geometry of the cavity system and a given liquid from (5) we determine the separation diameter of the vapor bubbles D_0 ; 2) we assign the value of ΔT and determine the bubble separation frequency from (6)-(8); 3) from (10) we determine D_{if} ; 4) we find the heat flux density from (1)-(4).

By making calculations for several values of ΔT it is possible to construct the boiling curve for a given surface.

In order to check the calculation method we carried out experiments to investigate the intensification of boiling heat transfer at a surface with a system of cavities using water as the liquid. The water boiled at the surface of a horizontal copper disk 38 mm in diameter and 10 mm thick. The design of the apparatus and the experimental procedure were similar to those employed in the single-cavity experiments and are described in detail in [1].

We used an orthogonal central composite second-order design for 5 factors that comprised 27 experiments. The factors investigated were varied over the following intervals: $d = 0.5-1.5$ mm, $h = 0.9-4.1$ mm, $l = 2.7-4.3$ mm, $q = 15-185$ kW/m², $P = 0.68-1.32$ atm. As the target function Y determining the intensification of heat transfer as compared with a smooth surface we used the reciprocal superheat ratio: $Y = \Delta T_{sm}/\Delta T \geq 1$.

The dependence obtained has the form of a second-degree polynomial ($l, d, h, \text{ mm}$):

$$Y = 4.147 - 1.17l + 0.707h + 3.236d - 0.193q - 3.395P - 0.149h^2 - 1.856d^2 + 0.009q^2 + 0.971P + 0.323hd - 0.02hq \quad (11)$$

An increase in heat-transfer intensification is observed as $l, P,$ and q decrease. Varying d and h does not have a clearcut effect on Y . By differentiating (11) with respect to d and h and solving the equations obtained simultaneously with (11), it is possible to determine the optimum values of d and h for given $l, P,$ and q .

On the factor range investigated the use of this method of intensifying boiling makes it possible to reduce the superheating of the heating surface by a factor of approximately 5 as compared with a smooth technical surface. Thus, for example, when $l = 2.7$ mm, $h = 3.6$ mm, $d = 1.2$ mm, $P = 0.68$ atm, and $q = 1.5$ W/cm² the heat transfer from a surface with cavities is 3.4 times greater than that from a smooth surface.

In Fig. 3 the boiling curves calculated from (1) are compared with the results of measurements [1, 9, 10] of the mean heat transfer from surfaces with systems of artificial sites. The agreement is best for the data of [1], less good for [9] and [10]. This may be because in [1] efforts were made to ensure that the geometric dimensions of all the sites were the

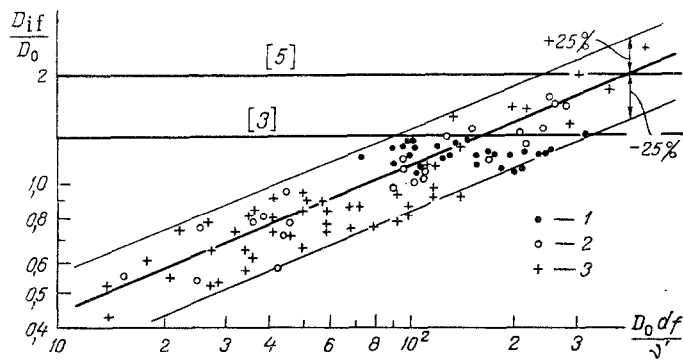


Fig. 2

Fig. 2. Results of processing data on D_0 and f in accordance with (9) to obtain the dependence of D_{if} on the boiling conditions: (1) for R 113; (2) for ethyl alcohol; (3) for water.

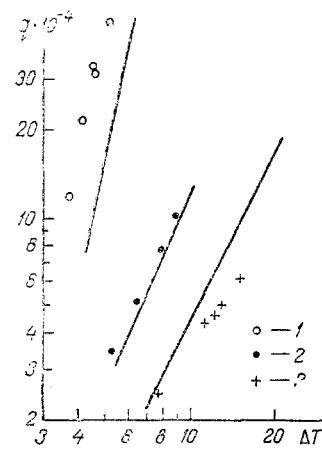


Fig. 3

Fig. 3. Heat transfer from a surface with a system of artificial nucleation sites calculated from (1) as compared with the experimental data: (1) for water boiling on a surface with $d = 0.2$ mm, $h = 0.62$ mm, $l = 0.6$ mm [9]; (2) the same with $d = 1$ mm, $h = 2.5$ mm, $l = 3.5$ mm [1]; (3) for ethyl alcohol boiling on a surface with $d = 0.2$ mm, $h = 1$ mm, $l = 2.5$ mm [10].

same, whereas in [10] and particularly in [9] because of the technologies employed the shape and size of the cavity mouths clearly could not be kept identical.

NOTATION

q , heat-flux density, W/m^2 ; ρ' and ρ'' , densities of the liquid and the vapor, kg/m^3 ; r , heat of vaporization, J/kg ; λ' , thermal conductivity, $W/(m \cdot K)$; c_p , specific heat, $J/(kg \cdot K)$; ν' , viscosity, m^2/sec ; β , volumetric expansion coefficient, K^{-1} ; g , acceleration of gravity, m/sec^2 ; D_0 , bubble separation diameter, m ; D_{if} , bubble influence zone diameter, m ; f , separation frequency, sec^{-1} ; $n = 1/l^2$, nucleation site density, m^{-2} ; l , distance between cavity centers, m ; ΔT , boiling temperature head, $^{\circ}K$; σ , surface tension, N/m ; d and h , diameter and depth of the cavity, m ; and P , saturation pressure, atm .

LITERATURE CITED

1. V. I. Reznikov and N. I. Kozlov, in: Problems of Radioelectronics, Ser. TRTO [in Russian], No. 3 (1985), pp. 94-105.
2. Maikik and Rohsenow, Trans. Am. Soc. Mech. Eng. Ser. C, J. Heat Transfer, 91, No. 2 (1969).
3. Fatkh and Dzhad, Trans. Am. Soc. Mech. Eng. Ser. C, J. Heat Transfer, 100, No. 1 (1978).
4. Dzhad and Lavdas, Trans. Am. Soc. Mech. Eng. Ser. C, J. Heat Transfer, 102, No. 3 (1980).
5. C. Y. Han and P. Griffith, Int. J. Heat Mass Transfer, 8, 887-915 (1965).
6. G. N. Danilova and V. I. Reznikov, in: Refrigerating Machines and Thermotransformers. Thermogasdynamics Processes in Refrigerating Machines. International Collection of Papers [in Russian], Leningrad (1984), pp. 94-103.
7. V. I. Reznikov and V. V. Kobyzhev, in: Problems of Radioelectronics, Ser. TRTO [in Russian], No. 2 (1985), pp. 102-118.
8. Nakayama, Daikoku, and Nakadzima, Trans. Am. Soc. Mech. Eng. Ser. C, J. Heat Transfer, 104, No. 2 (1982).
9. Nakayama, Daikoku, Kuvahara, and Nakadzima, Trans. Am. Soc. Mech. Eng. Ser. C, J. Heat Transfer, 102, No. 3 (1980).
10. Y. Heled, J. Ricklis, and A. Orell, Int. J. Heat Mass Transfer, 13, No. 3, 503-516 (1970).