LETTERS TO THE EDITOR

CALCULATION OF THE MAXIMUM CRITICAL HEAT FLUX DURING BUBBLE BOILING IN A LARGE VOLUME AT CYLINDRICAL AND SPHERICAL SURFACES

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The question of the effect of the geometry and size of the heater on the critical heat flux during bubble boiling has been raised repeatedly in the periodical literature [1-8] in the last decade.

A considerable increase in q_{max} (by two to five times) with a decrease in the radii R of horizontal cylinders or spheres in comparison with the maximum attainable critical heat loads during the boiling of the same liquids at surfaces of large size ($R \to \infty$) was discovered in original research of the I. I. Polzunov Central Scientific-Research Institute for Boilers and Turbines and of the Institute of Thermophysics, Siberian Branch, Academy of Sciences of the USSR [1-3] and in work performed later by foreign investigators [4-7].

This fact has practical importance for the solution of the problem of means of increasing the critical heat loads during the boiling of liquids.

In the authors' report [8], as well as in later reports [5-7], the theoretical explanation for this effect was based on aspects of the hydrodynamic theory of the boiling crisis developed in the works of Soviet [9-10] and foreign authors [11]. The difference in the explanation of the fact of an increase in q_{max} in these reports consists in the fact that in [8] it is connected with a change in the separation size of a vapor bubble, while in [5-7] it is connected with the ratio of the dimensions of the vapor jets which form on cylindrical and spherical surfaces during boiling.

Let us briefly examine the basic propositions of [8]. The following theoretical equations for the separation diameter D_0 of a single bubble were obtained from the equation of balance of the forces of surface tension and the Archimedes lifting forces acting on the vapor bubble at the moment of separation:

on a horizontal cylinder of radius R

$$D_0 = D_\infty \sqrt{\frac{2R}{2R + D_\infty}} \left[\frac{2R + D_\infty}{4R} + 0.273 \sqrt{\frac{2R + D_\infty}{2R}} + 0.227\right]^{1/3}, \quad (1)$$

and on a sphere of radius R

$$D_0 = D_\infty \sqrt{\frac{2R}{2R + D_\infty}}. \quad (2)$$

Here D_∞ is the separation size of a single vapor bubble at a surface of unlimited size ($R \to \infty$), which is determined by the Fritz equation:

$$D_\infty = 0.02\,\theta \sqrt{\frac{\sigma}{\gamma' - \gamma''}}. \quad (3)$$

Then an inverse linear relationship was assumed between the critical heat flux and the separation diameter of a vapor bubble. This position was rather well corroborated by the relatively limited experimental material presented in [1-3].

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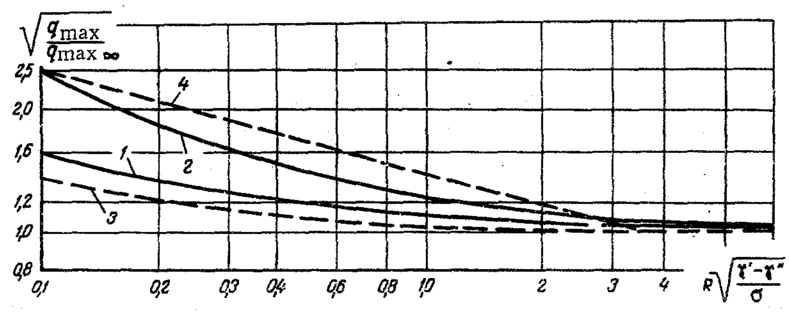

Fig. 1. Comparison of calculated (1, 2) and experimental data (3, 4) on maximum critical heat loads during boiling on horizontal cylinders (1, 3) and spheres (2, 4) in a large volume: 1) calculation from Eqs. (4) and (1); 2) calculation from Eqs. (4) and (2); 3) calculation from Eq. (5); 4) calculation from Eq. (6).

The experimental data published later in [4-7] permitted the refinement of the hypothesis advanced in [8] concerning the nature of the relationship between the critical heat flux q_{max} and the separation diameter D_0 of a vapor bubble. The refinement made the following dependence feasible:

$$\frac{q_{max}}{q_{max\,\infty}} = \left(\frac{D_\infty}{D_0}\right)^2. \tag{4}$$

With the choice of a contact angle $\theta = 50°$ (water, organic liquids, Freons at low pressures [12]) the separation size of a bubble as $R \to \infty$ becomes equal to the Laplace constant $D_\infty = \sqrt{\sigma/(\gamma' - \gamma'')}$, while the ratio $D_\infty/D_0 = \sqrt{q_{max}/q_{max,\infty}}$ is an equivalent function of the dimensionless radius $R\sqrt{(\gamma' - \gamma'')/\sigma}$ of the cylinder or sphere, determined by Eqs. (1) or (2), respectively.

The results of the calculation of the function

$$\sqrt{\frac{q_{max}}{q_{max}}} = f\left(R\sqrt{\frac{\gamma' - \gamma''}{\sigma}}\right)$$

for a cylinder and a sphere are presented in Fig. 1. Also presented there are empirical dependences which generalize the experimental data on q_{max} for horizontal cylinders [5] (900 experimental points)

$$\frac{q_{max}}{q_{max\infty}} = 1 + 2.55\exp\left(-3.44\sqrt{R\sqrt{\frac{\gamma' - \gamma''}{\sigma}}}\right) \tag{5}$$

and for spheres [6] (26 experimental points)

$$\left.\begin{aligned} q_{max}/q_{max,\infty} &= 1.88\left(R\sqrt{\frac{\gamma' - \gamma''}{\sigma}}\right)^{-0.5} \text{ for } 0.1 < R\sqrt{\frac{\gamma' - \gamma''}{\sigma}} \leqslant 3.55, \\ q_{max}/q_{max,\infty} &= 1.0 \text{ for } 3.55 \leqslant R\sqrt{\frac{\gamma' - \gamma''}{\sigma}} \leqslant 20. \end{aligned}\right\} \tag{6}$$

A comparison is made with the experimental data in the entire range of variation of the dimensionless radius of $0.1 \leq R\sqrt{(\gamma' - \gamma'')/\sigma} \leq 10$ for which there was experimental material on the heat-exchange crisis during the boiling of water, Freons, nitrogen, and other liquids on cylinders and spheres in a large volume. As seen from the graph, the deviation of the calculated values of $\sqrt{q_{max}/q_{max,\infty}}$ based on Eqs. (1), (2), and (4) at $\theta = 50°$ from the empirical curves does not exceed 10-15%, which corresponds to the accuracy of the generalization of the experimental data on $q_{max}/q_{max,\infty}$ by Eqs. (5) and (6) with which the comparison was made.

Thus, the proposed dependence (4) in conjunction with Eqs. (1) and (2) can be used successfully in practical calculations when estimating the maximum critical heat fluxes under conditions of the bubble boiling of liquids undergoing free convection around horizontal cylinders and spheres.

NOTATION

q_{max} is the maximum critical heat flux during boiling at a surface of finite size (of radius R);

$q_{max,\infty}$	is the maximum critical heat flux during boiling at the same surface with unlimited dimensions ($R \to \infty$);
γ', γ''	are the specific weights of liquid and vapor, respectively;
σ	is the surface-tension coefficient of liquid;
R	is the radius of horizontal cylinder or sphere;
D_0, D_∞	is the separation diameter of bubble at a surface of finite and of infinite radius, respectively.

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