HEAT TRANSFER DURING LIQUID BOILING ON FINS WITH AN INSULATING COATING

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The results of an analytic and experimental investigation of heat transfer during boiling of water and Freon-113 on a rod with an insulating coating are presented.

The use of lugs or fins of various profiles is one of the methods of increasing heat abstraction during evaporative cooling of thermally stressed devices [1]. With an increase of the heat flux conducted to the base of the lug, coexisting boiling regimes, viz., film, transitional, and nucleate, appear on its surface. Heat fluxes whose density is 4-6 times greater than the critical can be transmitted through the base of the fin (lug). In this case the temperature in the base of the lug exceeds the boiling point of the liquid by 200-300°C, which precludes the possibility of using thermolabile liquids.

To eliminate the zone of film boiling and reduce the surface temperature, it is expedient to create on the fin an insulating layer of variable thickness. In this case the temperature can be the same over the entire surface of the fin, and the boiling regime on any portion of the fin can be nucleate.

The results of investigating the thermal regimes of fins with an insulating coating (Fig. 1) are presented below. To determine the thickness of the insulation and the temperature distribution over the fin, we write the equation of heat balance for an element of the fin

$$\lambda f \frac{d^2\theta}{dy^2} - \alpha p \theta_s = 0. \quad (1)$$

For boundary conditions

$$\theta = \theta_s = \text{const and } \frac{d\theta}{dy} = \frac{\alpha\theta_s}{\lambda} \quad \text{for} \quad y = 0$$

the expression

$$\theta = \theta_s + \frac{\alpha p \theta_s}{\lambda f}\left(\frac{y^2}{2} + \frac{f}{p} y\right) \quad (2)$$

is the solution of Eq. (1). For a cylindrical rod Eq. (2) acquires the form

$$\theta = \theta_s\left[1 + \frac{\alpha}{\lambda}\left(\frac{2y^2}{d} + y\right)\right]. \quad (3)$$

The temperature in the base of the rod

$$\theta_b = \theta_s\left[1 + \frac{\alpha h}{\lambda}\left(1 + 2\frac{h}{d}\right)\right]. \quad (4)$$

The density of the heat flux through the base of the rod

$$q_b = \alpha\theta_s\left(1 + \frac{4h}{d}\right). \quad (5)$$

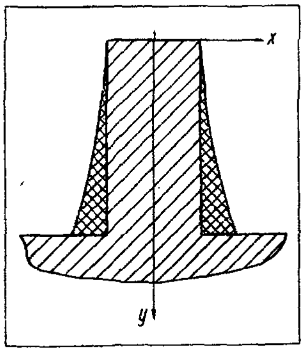

Fig. 1. Diagram of fin.

The thickness of the insulation is calculated from the relation for a one-dimensional heat flux through a plane wall

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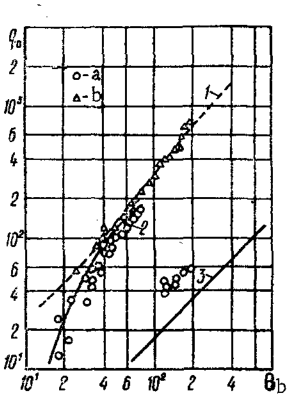

Fig. 2

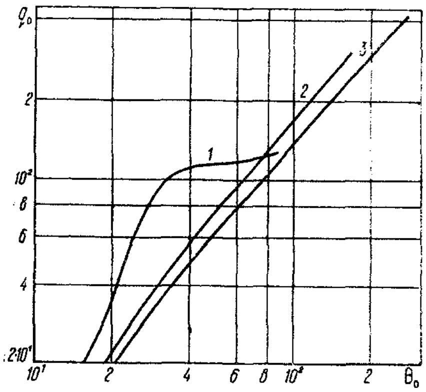

Fig. 3

Fig. 2. Boiling curves of Freon-113 at atmospheric pressure for rod d = 10 mm; h = 20 mm (q_b, W/cm^2, θ_b, °C): a) experimental data for Freon-113; b) experimental data for water; 1) according to Eqs. (4) and (5), nucleate boiling of water; 2 and 3) according to Eqs. (4) and (5), respectively nucleate and film boiling of Freon-113.

Fig. 3. Boiling curves of Freon-113 at atmospheric pressure for rods d = 6.35 mm: 1) experimental data [3], h = 30.6 mm, without insulation; 2 and 3) according to Eqs. (4) and (5), h = 30.6 mm and h = 40 mm respectively, with insulation.

$$\delta = \frac{(\theta - \theta_s)\lambda_{in}}{\alpha\theta_s}. \quad (6)$$

Substituting Eq. (3) into (6), we obtain the following expression for the thickness of the insulation:

$$\delta = \frac{\lambda_{in}}{\lambda}\left(\frac{2y^2}{d} + y\right). \quad (7)$$

For given λ_{in}, λ, and d the thickness of the insulation $\delta = f(y)$, i.e., does not depend on the magnitude of the dissipated heat flux. If the applied insulating layer increases considerably the heat-transfer surface, δ must be calculated with the use of the appropriate relations for a cylindrical wall and a correction must be introduced into Eq. (5).

Solving Eqs. (4) and (5) simultaneously, we obtain

$$\frac{\theta_b}{\theta_s} = \frac{2Q^2}{\pi^2\theta_s^2\lambda\alpha d^3} - 0.125\frac{\alpha d}{\lambda} + 1. \quad (8)$$

The second term of the right side of Eq. (8) is negligibly small and accordingly

$$d = 0.588\left[\frac{Q^2}{\theta_s\lambda\alpha(\theta_b - \theta_s)}\right]^{\frac{1}{3}}. \quad (9)$$

An experimental investigation of the possibility of maintaining developed nucleate boiling on the entire surface of insulation applied on a cylindrical lug was carried out on a device whose main element was a copper block with an electrical heater. The upper part of the block was a rod 10 mm in diameter and 38 mm long. On the rod was pressed a stainless steel, 20-mm-long bushing whose outside surface was the surface of a paraboloid of revolution. The thickness of the bushing was calculated by Eq. (7). The upper part of the rod on which the bushing was pressed was extended into a vertical cylindrical chamber filled with a boiling liquid. The remaining part of the copper rod was the measuring part; three Chromel–Alumel thermocouples were placed on it. Side windows were provided in the chamber for visual observation; a condenser was located in the upper part of the chamber.

As the temperature of the heated block increased, uniformly distributed centers of vaporization appeared on the surface of the bushing and end of the rod, which promoted the initiation of boiling on the isothermal surface. The coexistence of different boiling regimes on the surface, characteristic for a rod without insulation, was not observed even under loads critical for the given rod. With a further increase of the surface temperature nucleate boiling changed simultaneously to film boiling on the entire rod.

Articles [2, 3] are devoted to an investigation of nucleate boiling of Freon-113 on an isothermal surface, [3] to film boiling, and [4, 5] to nucleate boiling of water.

Figure 2 shows the function $q_b = f(\theta_b)$ for water and Freon-113 boiling at atmospheric pressure. The solid lines, the curves of nucleate and film boiling of Freon-113, were calculated on the basis of Eqs. (4) and (5) according to data in [3]. In the zone of nucleate boiling the experimental data are located slightly below the calculated curve, and in the zone of film boiling, higher. The increase of the fraction of heat dissipated at the place of embedment of the shaped bushing in the bottom of the chamber apparently has an effect in the second case.

The experimental values of the critical parameters ($q_b = 169$ W/cm^2, $\theta_b = 77.2$°C) differ little from the calculated ($q_b \doteq 172$ W/cm^2, $\theta_b = 73.5$°C).

The dashed line shows the boiling curve of distilled water calculated according to the data in [5]. The calculated critical values are $q_b = 1390$ W/cm^2, $\theta_b = 382$°C. The design of the device did not permit conducting heat fluxes exceeding 770 W/cm^2 ($\theta_b = 196$°C); it is natural that a film regime was not obtained. The maximum deviation of the experimental data from the calculated is 12%.

Figure 3 presents the boiling curves of Freon-113 up to the critical parameters for cylindrical rods with and without insulation (d = 6.35 mm). Curve 1 is plotted on the basis of experimental data [3] for a rod without insulation (h = 30.6 mm).

The critical density of the heat flux 130 W/cm^2 is reached at $\theta_b = 90$°C. Curves 2 and 3, calculated by Eqs. (4) and (5), correspond to insulation-covered rods 30.6 and 40 mm long.

In comparison with the rod without insulation, the critical loads for them increase respectively by a factor of 2.5 and 3, which is accompanied by an increase of the critical values of θ_b from 166 to 260°C. For small θ_b the densities of the heat flux through the base of the rod without insulation are considerably less than for the rod without it.

An analogous picture is observed during cooling with water whose use as a coolant permits abstracting from the developed surface (without insulation) only up to 600 W/cm^2 at $\theta_b = 150$-200°C [1].

In the case of cooling with thermostable liquids it is expedient to use fins on whose surface adjacent to the base the insulating layer is absent, which are effective also in the region of small θ_b.

An analysis of the results obtained show that an insulating layer appropriately applied on the rod surface permits maintaining nucleate boiling on the entire surface. In the region of large overheatings of the rod base the densities of the heat flux being abstracted exceed considerably the critical densities for an analogous rod without insulation.

The calculation based on the method presented agrees well with experiment.

NOTATION

q_0	is the density of the heat flux through the rod base;
Q	is the heat flux;
α	is the heat-transfer coefficient;
θ, θ_b, θ_s	are the excess temperature of, respectively, the fin, base of fin, and surface of the insulation over the saturation temperature of the liquid;
δ	is the thickness of the insulation;
d	is the rod diameter;
h	is the fin length;
f, p	are the area and perimeter of the cross section of the fin;
λ, λ_{in},	are the heat conductivity of the fin and insulation.

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