HEAT TRANSFER IN LIQUID BOILING ON FINNED SURFACES

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Results of an experimental investigation of heat transfer in boiling of water and Freon-113 on cylindrical shells with longitudinal fins are presented.

Finned surfaces cooled by a boiling liquid are widely used in technology. A series of analytical [1, 2] and experimental [2-4] works have been devoted to the investigation of heat transfer in water and Freon-113 boiling on the surface of a single fin of constant cross section. In solving the heat-conductivity equations for the fin it is assumed that the temperature field in the fin is unidimensional, that there are no internal heat sources, that the thermal-conductivity coefficient of the fin material is constant, and that the local heat-transfer coefficients of the fin surface are equal to the heat-transfer coefficients of an isothermal surface for corresponding temperature heads. A numerical solution is presented in [1], while in [5] the isothermal boiling curve for water and Freon-113 is approximated by successive functions and the method of fin calculation is described. The calculated curves are in good agreement with experiment. In the critical region of the fin the divergence increases (more so in the case of water); the authors assume that this is connected with a transformation in the transition region of the boiling curve.

A significantly smaller number of works (mainly experimental) have been devoted to studies of heat transfer in liquid boiling on a system of fins. Analysis of multifin elements becomes complicated; it is necessary to consider fin interaction, which increases as the separation between fins decreases [3].

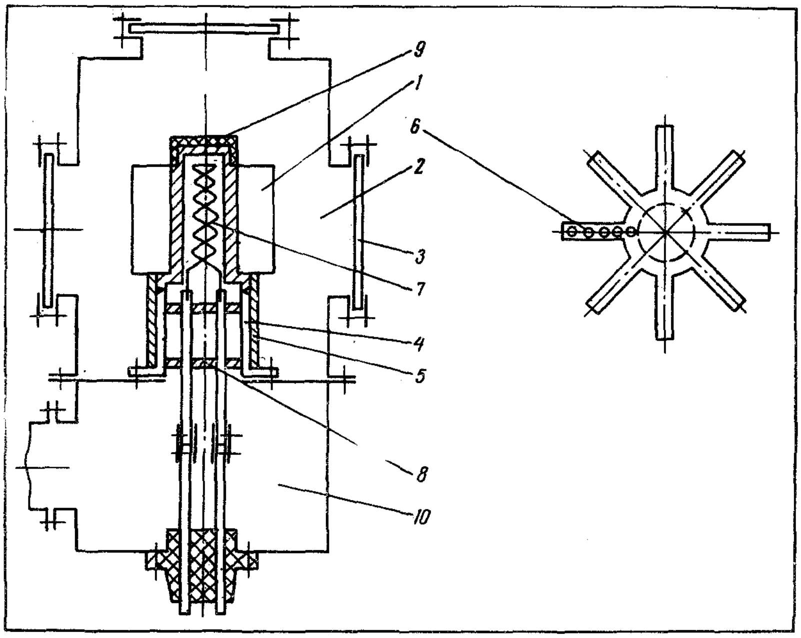

Fig. 1. Schematic diagram of experimental apparatus.

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This present study will examine heat transfer in water and Freon-113 boiling on cylindrical finned elements.* Cylindrical copper shells with outer diameter 30 mm, working lengths of 59 and 52 mm, and 8 or 16 longitudinal fins 20 mm high with thickness d_f 4 mm were used. The eight-fin elements had a minimum interfin separation $S \sim 8$ mm; the 16-fin elements had $S \cong 2$ mm; the supporting wall thickness was 5 mm.

The investigation of heat transfer in boiling on multifinned heat-discharging elements puts stringent requirements on the heat-supply system. In our study, electronic heating was used, permitting high thermal loads. The method is based on the conversion to heat of the kinetic energy of electrons excited by an electric field between the anode and the cathode when they collide with the anode surface. In our experiments the anode was the finned element, the cathode being located in the interior thereof. For normal cathode operation, a vacuum of 10^{-5}-10^{-6} mm Hg was maintained within the fin.

Figure 1 shows a schematic diagram of the experimental apparatus. The copper finned element 1 is located in a liquid filled chamber 2, provided with windows 3 for visual control and photography. To decrease heat loss to the element a stainless steel collar 4 was welded, with a layer of epoxy compound 5 on its surface. On the element wall and over the height of the fins Chromel–Alumel thermocouples 6 are mounted, 0.3 mm in diameter and located at three different cross sections. The tungsten cathode 7 was formed of 1 mm diameter wire, wound in the form of a bifilar spiral. The cathode was centered with disks 8, made of 22KhS ceramic. The cathode is located opposite the finned portion of the wall. The end of the element is covered by an insulating layer 9. The interior of the element is joined to a chamber 10, connected to the vacuum system. The anode was grounded and high voltage from a rectifier (silicon type VK-10), continuously variable from 0 to 4 kV, applied to the cathode, which was heated by a filament transformer. Anode current reached 7 A, filament current, 50 A. The thermal load required was obtained by changing filament current and anode voltage. The experiments were conducted at atmospheric pressure. Electrical power supplied to the element, supporting wall temperature, temperature over fin height, and liquid temperature were measured.

The thermal flux is composed of electron energy and cathode radiation energy. The former is the product of anode current multiplied by anode voltage, while the latter is the electrical power supplied to the filament. The anode current is determined by the voltage drop across a standard coil, as measured by a R375 (class 0.2) high-resistance potentiometer. Anode voltage was measured from the voltage drop across a standard coil connected in series with a MSV divider–high resistance box. Filament current was measured with a current transformer. Filament voltage was calculated from measurement of voltage on the filament transformer primary, with consideration of the transformer turns ratio.

Allowance was made for heat loss by radiation from the cathode and electron scattering through the lower end of the element, and the thermal conductivity of the stainless steel collar and cathode current leads. These losses did not exceed 5% in total.

The results obtained were processed in the form of dependences of thermal flux through the outer cylinder surface (diameter 30 mm) q as functions of the difference θ_0 between temperature at the base of the fin and liquid saturation temperature. Temperature at the fin base was determined by interpolation from temperature values on the wall and over the height of the fin.

In Fig. 2a the function $q = f(\theta_0)$ is presented, for water boiling on the surface of a 16-finned (points 1) and eight-finned (points 2) element. Analogous data for Freon-113 are presented in Fig. 2b.

A strict analytical computation of the heat transfer of finned shells conducting heat into a boiling liquid is quite difficult, since the temperature field in the fin and supporting wall is two-dimensional, and the heat-transfer coefficient is a nonlinear function of the local temperature head. In [7] it was shown that the total thermal flux dissipated into the boiling liquid by high conductivity (for example, copper) fins can be calculated with sufficient accuracy with a one-dimensional model. The results of [5] show that calculation with a one-dimensional model agrees satisfactorily with experimental data.

The experimental data of our study were compared with results of computation with the simplified one-dimensional model. It was assumed that the fin temperature changes only with fin height, and that the supporting wall temperature is constant (the surface is isothermal).

The thermal flux density through the support surface is then determined by the equation of thermal balance for the element of surface beneath the fin:

*Engineer L. A. Titova participated in the conduct of the work.

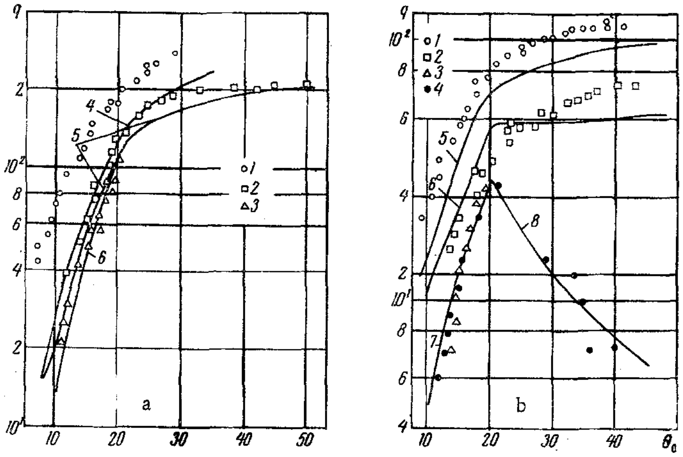

Fig. 2. Thermal flux density versus temperature head at fin base for water(a) (experimental data: 1, n = 16; 2, n = 8; 3, n = 0; calculated: 4, from Eq. (1), n = 16; 5, from Eq. (1), n = 8; 6, from 3) and for Freon-113 (b) (experimental data: 1, n = 16; 2, n = 8; 3, n = 0; 4, from [4], n = 0; calculated: 5, from Eq. (1), n = 16; 6, from Eq. (1), n = 8; 7, from 3, 4; 8, from 4). q, W/cm^2, θ_0, °C.

$$q = \frac{q_f \delta_f + q_0 s}{\delta_f + s}, \tag{1}$$

where q_f and q_0 are the thermal flux densities for a given θ_0 through the fin base and the nonfinned surface of the support surface. The value of q_f is calculated with the use of curves for boiling on an isothermal surface, by the method described in [5]. The thermal flux density q_0 is taken at the temperature head at the fin base θ_0.

Curves of boiling on an isothermal surface obtained by various investigators differ widely due to both configuration and smoothness of the surface. Therefore in our study, experiments were also conducted with isothermal surfaces: a vertical cylindrical shell with no fins, 28 mm in diameter, 52 mm in length, prepared and heated in a manner analogous to the finned elements. The data obtained for the bubble region are presented in Fig. 2a, b. For water, they agree well with the results of [6], for Freon-113, with the results of [4]. Curve 6 of Fig. 2a is an approximation of experimental data for water $q_0 = 12.9 \cdot 10^{-3}\theta_0^3$, curve 7 of Fig. 2b is an approximation $q_0 = 2.89 \cdot 10^{-3}\theta_0^3$ for Freon-113. The transition boiling curve for water (from data of [3]) is expressed by the function $q_0 = 125$ W/cm^2; for Freon-113 (from data of [4]), by the function $q_0 = 9.2 \cdot 10^3\theta_0^{-2}$ (curve 8, Fig. 2b), These relationships were used in calculating q.

In order to evaluate the effect of the nonisothermal state of the support surface, a thermal calculation was performed for the finned shell with a one-dimensional model, in which temperature change in the fin was considered only with respect to height, and for the support surface, only over an axis directed along the surface.

Analysis showed that calculation of the elements studied by Eq. (1) leads to a reduction in q values (in comparison with the second method of calculation) no greater than 5% for Freon-113 and 8% for water. In Fig. 2 the experimental data are compared with results of calculation by Eq. (1). In Fig. 2a curves 4 and 5, in Fig. 2b curves 5 and 6 correspond to the experimental points 1 and 2.

The experimental data for the 8-finned element with minimum fin separation s ≅ 8 mm, cooled by both water and Freon-113, were found to be in good agreement with the results of calculation by Eq. (1). In the region of developed boiling the deviation of the data is no greater than 30%. In the region subcritical for an isothermal surface ($\theta_0 < 20$°C) the thermal flux density q through the support surface exceeds q_0 insignificantly. At a temperature head of $\theta_0 = 30$°C the water boiling curve approaches 200 W/cm^2. For further increase in temperature head the thermal load undergoes practically no change. The boiling crisis was observed at $\theta_0 \cong 50$°C. For Freon-113 the critical load of 54 W/cm^2 was attained at $\theta_0 = 45$°C.

For the 16-finned cylinder with minimum fin separation of 2 mm, the experimental data exceeded the calculated values, more so in the case of water. The Freon-113 boiling curve coincided with, and the water boiling curve exceeded the calculated curve $q_f = f(\theta_0)$ for a single fin.

A temperature head of $\theta_0 = 30°C$ corresponded to a load of 280 W/cm^2 for water; a crisis was not reached. The critical load for Freon-113 boiling was 90 W/cm^2 at $\theta_0 \cong 41°C$. The motion of the vapor – liquid mixture in the narrow trapezoidal separations between the fins is evidently the cause of heat-transfer intensification on the fin surface and support wall, and of the deviation observed in the data for this element. In the temperature head range studied, developed boiling of water (in contrast to Freon-113) was observed only on a small portion of the fin adjacent to the base, where the magnitude of the separation is minimum. Therefore, the effect of separation is expressed more clearly for water.

NOTATION

q, q_f, q_0	are the thermal flux density across shell surface, fin base, and unfinned surface of supporting wall;
θ_0	is the difference in temperature between base of fin and liquid saturation temperature;
δ_f	is the fin thickness;
s	is the minimum fin separation;
n	is the number of fins.

LITERATURE CITED

1. K. W. Haley, and J. W. Westwater, Proc. of Third Int. Heat Transfer Conf., Vol. 3, Chicago (1966).
2. L. I. Roizen, and I. N. Dul'kin, Izv. VUZ. Énergetika, No. 3 (1968).
3. Sh. A. Bertere, Heat and Mass Transfer [in Russian], Vol. 9, Minsk (1968).
4. S. A. Kovalev, V. M. Zhukov, and G. M. Kazakov, Teplofiz. Vys. Temp., 8, No. 1 (1970).
5. I. N. Dul'kin, N. I. Rakushina, L. I. Roizen, and V. G. Fastovskii, Inzh.-Fiz. Zh., 19, No. 4, (1970).
6. V. M. Borishanskii, Énergomashinostroenie, No. 7 (1958).
7. L. I. Roizen, V. N. Evteev, and I. N. Dul'kin, Élektronnaya Tekhnika, Ser. 1, Élektronika SVCh, No. 7 (1970).