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HEAT TRANSFER AND CRITICAL HEAT FLUXES IN THE BOILING OF AQUEOUS SOLUTIONS OF POLYETHYLENE OXIDE AT REDUCED PRESSURES UNDER NATURAL-CONVECTION CONDITIONS

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UDC 536.248.2.001.5

Experimental data are presented on heat transfer and critical heat fluxes in the boiling of aqueous solutions of polyethylene oxide of different concentrations under conditions of natural convection at atmospheric and reduced temperatures.

Study of the effect of polymeric additives on the heat-transfer rate during boiling is of both scientific and practical interest. Thus, it was shown in [1, 2] that the addition of a small quantity of a polymer to a heat carrier may lead to an increase in the heat-transfer coefficient during boiling. However, there has as yet been relatively little research in this area [1-6]. The investigation [3] studied the separation diameters and frequency of separation of bubbles at a single artificial vaporation center under conditions of natural convection and in a flow. Experiments were conducted in [4] on the boiling of aqueous solutions of polymers with forced flow. The experimental data reported in [1-4] on the boiling of polymer solutions was obtained only at atmospheric pressure and in a narrow range of heat fluxes. The exception is the work [6], which studied the effect of surfactants on heat transfer during the boiling of water at atmospheric and increased pressures in the region of subcritical heat fluxes. There is no data on critical heat fluxes in polymer solutions, and no study has been made of boiling in the region of reduced pressures and the effect of subheating of the liquid mass to the saturation temperature.

This article presents results of a complex of studies on heat exchange in aqueous solutions of polyethylene oxide (PEO) (molecular weight $(3\text{-}5)\cdot 10^6$), including experiments on heat transfer during saturated nucleate boiling and heat-transfer crises in saturated and subheated liquid under conditions of natural convection at atmospheric and reduced pressures. The study was performed with solutions with the following mass concentrations at 20°C: 0.002; 0.005; 0.01; 0.02; 0.04; 0.08; 0.16; 0.32; 0.64; 1.28%. The working section was a 2.5-mm-diameter stainless steel tube with a surface corresponding to a class six finish. The section was placed horizontally in the working volume and heated directly by an alternating current. A Chromel–Alumel thermocouple was placed inside the tube. In determining the temperature of the heating surface, we introduced a correction for the temperature drop in the wall. Before measurements were made, the heat-liberating surface of the section was used for 2-3 h at near-critical heat fluxes. Polyethylene oxide belongs to a class of polymers having the property of reverse solubility, which amounts to a deterioration in solubility with an increase in temperature. The heating of solutions with a concentration above 0.01% to 90-100°C was accompanied by turbidity and the precipitation of fine flocs.

Institute of Thermophysics, Academy of Sciences of the USSR, Novosibirsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 47, No. 1, pp. 24-28, July, 1984. Original article submitted August 19, 1983.

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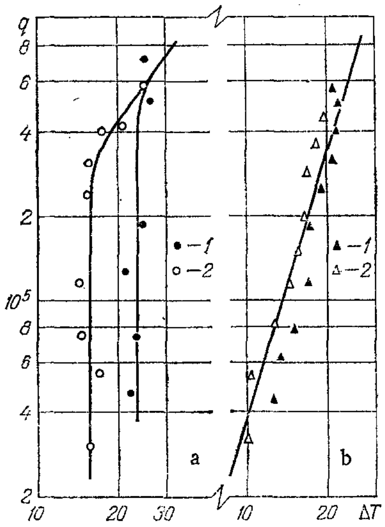

Fig. 1. Experimental data on the boiling of water (a) and a solution of polyethylene oxide of 0.04% concentration (b) under saturation conditions at a pressure $9.8 \cdot 10^3$ Pa: 1) increase in load; 2) decrease. q, W/m^2; ΔT, °K.

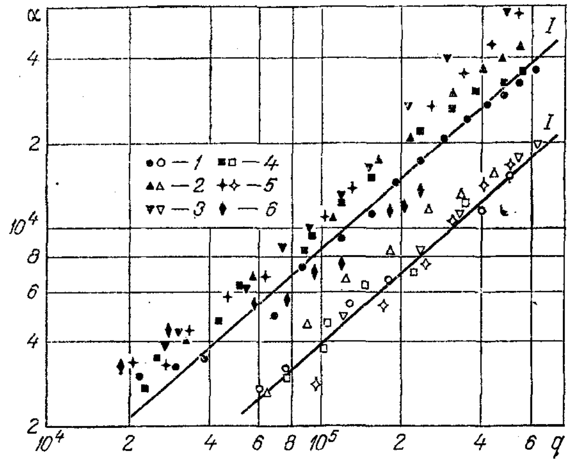

Fig. 2. Experimental data on heat transfer during the boiling of solutions of polyethylene oxide under saturation conditions at pressures of $98 \cdot 10^3$ (dark points) and $4.9 \cdot 10^3$ Pa (clear points): 1) PEO solution of 0.01% concentration; 2) 0.02; 3) 0.04; 4) 0.08; 5) 0.16; 6) 1.28%; I) averaging lines for water, α, W/(m^2·K); q, W/m^2.

We first performed measurements on water in order to compare the effect of the additions of polyethylene oxide on boiling. In the region of subatmospheric pressures, the boiling curves for water are characterized by anomalous behavior [7, 8], consisting of independence of the overheating of the wall on the heat flux. A vertical section appears in the coordinates (q, ΔT) (Fig. 1) at reduced pressures. Also, a "hysteresis" effect is seen during the boiling of water in the low-pressure region. Here, heat transfer during nucleate boiling is different with an increase or decrease in the thermal load (Fig. 1a). The anomalous character of the boiling curve and the "hysteresis" are practically absent at pressures close to

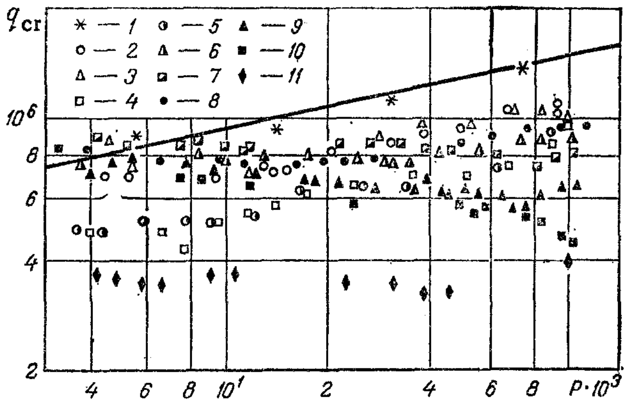

Fig. 3. Experimental data on the critical heat fluxes in the boiling of water and solutions of polyethylene oxide under saturation conditions: 1) water; 2) PEO solution of 0.002% concentration; 3) 0.005; 4) 0.01; 5) 0.02; 6) 0.04; 7) 0.08; 8) 0.16; 9) 0.32; 10) 0.64; 11) 1.28%. q_{cr}, W/m^2; P, Pa.

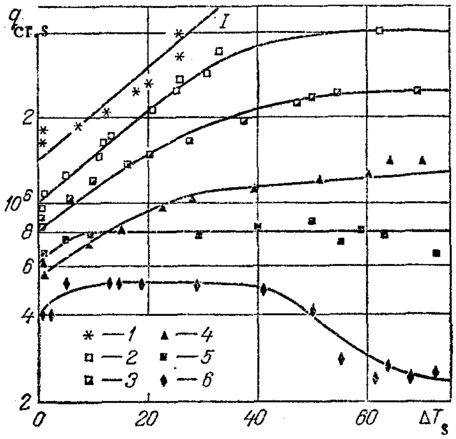

Fig. 4. Effect of subheating on the critical heat fluxes in the boiling of water and solutions of polyethylene oxide ($P = 98 \cdot 10^3$ Pa): 1) water; 2) PEO solution of 0.01% concentration; 3) 0.08; 4) 0.32; 5) 0.64; 6) 1.28%; I) calculation from Eq. (1). $q_{cr.s}$, W/m^2; ΔT_s, °K.

atmospheric. Studies conducted with aqueous solutions of PEO of different concentrations has shown that the curves of nucleate boiling in solutions of polyethylene oxide have almost no vertical sections and the "hysteresis" is considerably less pronounced (Fig. 1b). All of the data presented below on the nucleate boiling of water and polymer solutions was obtained with a reduced thermal load, which corresponds to the left branch of the hysteresis (Fig. 1a). This was done because the measurements are most reproducible in this case.

Experiments on heat transfer during the boiling of water showed that at atmospheric and reduced pressure the heat-transfer coefficient is proportional to the heat flux to the power of about 0.8 (Fig. 2). The addition of even a small amount of the polymer to the water leads to an increase in heat-transfer rate. For example, with a pressure of $98 \cdot 10^3$ Pa and a heat flux of $5 \cdot 10^5$ W/m^2, the heat-transfer coefficient in a PEO solution with 0.04% concentration exceeds the corresponding value of for water by a factor of two. In the region of lower heat fluxes, the increase in heat-transfer rate is less substantial. The lowest rate at $98 \cdot 10^3$ Pa was seen in a solution with the lowest of the investigated concentrations, 1.28%. The greatest turbidity is seen and the most precipitation of flocs occurs at this concentration. At a pressure of $4.9 \cdot 10^3$ Pa, the increase in the heat-transfer rate in the polymer solutions is less substantial.

Figure 3 shows the results of tests on critical heat flux in the saturated boiling of solutions of polyethylene oxide. Also shown here is a straight line averaging the data for water. The critical heat fluxes in the PEO solutions are lower than the corresponding values for water. An increase in the concentration of the solution leads to weakening of the dependence of the critical heat fluxes on pressure. When the concentrations of the solution are high, the character of the dependence of q_{cr} on pressure reverses and there is a decrease in the critical heat flux with an increase in pressure.

Study of the heat-transfer crises during boiling showed that two types of crises may occur in solutions of polyethylene oxide: the usual crisis associated with loss of hydrodynamic stability by the two-phase boundary layer and the subsequent formation of a vapor film on the heating surface; the so-called "slow" crisis, characterized by a slow, spontaneous increase in the temperature of the surface. There is a rapid increase in wall temperature during the hydrodynamic crisis. There is a spontaneous, smooth increase in wall temperature during the "slow" crisis at a certain thermal load, taken as the critical load. Here, no vapor film forms on the surface. The occurrence of the slow crisis is evidently due to an increase in the rate of adsorption of the polymer on the heating surface due to an increase in its concentration and the temperature in the superheated liquid boundary layer, as well as to the formation of a polymer film on the heating surface. This film offers additional thermal resistance to the removal of heat from the heating surface. The hydrodynamic crisis was observed in the tests in water and PEO solutions of low concentration. For solutions with a concentration of 0.32 and 0.64%, the hydrodynamic crisis takes place only at pressures below $49 \cdot 10^3$ Pa. At higher pressure, the slow crisis was seen for solutions of these concentrations. The slow crisis was seen throughout the investigated range of pressures for the solution with the highest concentration, 1.28%.

Figure 4 presents data on the effect of subheating of the liquid mass to the saturation temperature on the critical heat fluxes in water and the PEO solutions at atmospheric pressure. The effect of subheating for water is satisfactorily described by the Kutateladze formula [9]:

$$q_{\mathrm{cr,s}} / q_{\mathrm{cr}} \approx 1 + 0{,}08 \left(\rho' / \rho''\right)^{0,8} c_p \Delta T_s / r. \quad (1)$$

The character of the dependence of the critical heat fluxes on subheating remains the same for PEO solutions of low concentration in the region of small subheatings. As the concentration and degree of subheating are increased, the effect of ΔT_s on the critical heat flux decreases. In a solution with a 0.64% concentration, the critical loads are nearly independent of the amount of subheating. In a solution with the greatest of the investigated concentrations, 1.28%, a nearly twofold reduction in $q_{cr.s}$ is seen at subheatings in excess of 40°C. In a solution with a concentration of 0.08%, the "slow" crisis was seen with subheatings greater than 50°C. The slow crisis was seen throughout the investigated range of subheatings in solutions of greater concentration.

NOTATION

q, heat flux; q_{cr}, critical heat flux; $q_{cr.s}$, critical heat flux during boiling under subheating conditions; ΔT, overheating of heating surface relative to saturation temperature; ΔT_s, subheating of liquid core to the saturation temperature; α, heat-transfer coefficient; P, pressure; ρ', ρ'', densities of the liquid and vapor; c_p isobaric specific heat of water; r, heat of vaporization.

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STUDY OF FLOW ON THE SURFACE OF FINS ON CROSS-FINNED TUBES

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UDC 536.24:533.6.011

The visualization method was used to study the washing of a flow of air over the surface of fins on tubes with external fins in an annular arrangement.

There has been far too little study of the hydrodynamics of flow about cross-finned tubes, which determines the laws governing local and surface-mean heat exchange. This article attempts to study flow on the surface of fins in a staggered bundle of cross-washed tubes with external annular finning by visualizing it in a soot—kerosine suspension. The results of our observations, reported below, pertain mainly to the first row of the bundle. This permits the data to be compared with adequate accuracy to well-known data on the distribution of local heat-transfer coefficients on the surface of annular fins [1, 2]. Two types of completely turned steel tubes differing in the height of the fins were used to make up a bundle with the spacing characteristics $S_1 = 84$ mm and $S_2 = 200$ mm. The main dimensions of the finned tubes are shown in Table 1. The experiments were conducted in an open wind tunnel with a through part having a cross section of 71 × 334 mm. The tubes used for the visualization had a joint at the middle of their height. The ends mated to one another at the joint were polished and coated with white nitrocellulose enamel.

During the tests the surface of the fin below the joint was coated with a thin layer of the soot—kerosine suspension. Then both halves of the tube were joined together and the tube was placed in the working part of the stand. Here, it was held in an isothermal air flow. The flow, interacting with the suspension film, was compelled to move in streamlines and formed a flow pattern in the form of streaks and points. Over time the kerosine evaporated and the soot particles remained at the locations on the tube surface to which they had been moved while in the suspended state. The thus-obtained images of the surface had lighter sections corresponding to zones of the surface that had been washed by the flow with the most intensity. Zones with zero velocity or a slight circulating motion appeared as dark spots or bands.

Figures 1 and 2 show photographs illustrating results of the tests. Study of the photographs made it possible to establish several features of flow about the fins.

The forcing of the flow out of the interfin channel is evident. This is related to an increase in the thickness of the boundary layer on the fin, so that the streamlines are below the midsection (Fig. 1a and c, and Fig. 2a and c) and the contours of the vortical aft zone beyond the tube (Fig. 2b) diverge from the longitudinal axis of the picture and have a curvature inverse to that which is typical of transverse flow over a smooth cylinder.

The dark band at the front edge of the fin (Fig. 1a) is evidently the result of flow separation beyond the sharp inlet edge, the presence of this band having been noted in works

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Kiev Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 47, No. 1, pp. 28-34, July, 1984. Original article submitted March 18, 1983.

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