SPECIFIC FEATURES OF THE EFFECT OF PRESSURE ON THE HEAT-TRANSFER RATE IN THE BOILING OF WATER ON A POROUS SURFACE

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The data on the combined effect of pressure, structure thickness, and heat-flux density on heat transfer during the boiling of water on a porous surface are given, and a relation for the calculation of the heat-transfer coefficient is grouped.

The effect of pressure is one of the key problems in calculating the heat-transfer rate in boiling on surfaces with porous coatings and its solution remains urgent. Literature sources report contradictory information on the increase [1], decrease [2], or approximate equality [3] of the degree of the effect of pressure on heat transfer in boiling on a porous surface, as compared with a smooth surface. The difference in qualitative pictures of the pressure effect may be explained, as stated in [4], by the fact that the influence of a porous coating with the prescribed characteristics (mean size of pores, thickness, porosity, etc.) greatly depends on the range of working pressures. In other words, the level of the pressure effect depends substantially on the type and characteristics of a porous structure. The data of [5] allow one to suppose that the level of pressure effect on the heat-transfer rate in boiling on a surface with a porous coating depends on the heat-flux density. However, in virtually all of the familiar calculational relations on the heat-transfer coefficient the dependence of the degree of the pressure effect on the properties of the porous structure and heat-flux density is neglected.

The present paper is aimed at the study of the combined effect of the thickness of the porous structure, heat-flux density, and saturation pressure on the heat-transfer rate during the boiling of water. The test sample was a substrate in the form of a copper disk with a diameter of 30 mm, a thickness of 2 mm, and with a sintered copper metal-fiber capillary porous structure. The length and diameter of the fibers were $l_f = 3$ mm and $d_f = 50$ μm, respectively. The coating porosity was $\Pi = 84\%$, the thickness $\delta = 0.1, 0.4, 0.8, 1, 2, 4, 10$ mm, the effective diameter of pores $d_{ef} = 105$ μm. The experiments were conducted at saturation pressures ranging from $P = 0.1$ to $1 \cdot 10^5$ Pa.

The experimental setup (Fig. 1) was in the form of a cylindrical chamber with a condenser, an external heater and observation windows at the ends. The internal volume of the chamber at the location of the test sample was sealed by using a Teflon collet as a gasket. The test sample was soldered to a copper block. The main heater was pressed against the copper block from below. Four thermocouples were caulked to the lower portion of the substrate; their averaged readings were used to determine the temperature of the heated surface. The removed heat flux was determined by the readings of three thermocouples embedded in the copper block. Two thermocouples in the liquid volume served to determine the saturation temperature. All of the measurements were performed in the steady-state mode by a stepwise increase in the heat load. The level to which the chamber was filled with water provided for a self-similar character of the heat-transfer rate during boiling relative to the height of the liquid column over the heating surface.

To prove the reliability of the results obtained, the experiments for water boiling on a smooth industrial-grade surface were conducted over the entire range of working pressures and on a porous coating at atmospheric pressure. The experimental results, as can be seen from Fig. 2, are in satisfactory agreement with the data of [6] and [3].

Analysis of the test data showed that the effect of pressure on the heat-transfer rate decreases with increase in heat-flux density q. As Fig. 2 indicates, for heat-flux densities close to $3 \cdot 10^4$ W/m^2 the effect of pressure during boiling on a 1 mm-thick porous surface is about twice stronger than on a smooth surface. When $q \approx 2 \cdot 10^5$ W/m^2, the effect of pressure on the heat-transfer rates on smooth and porous surfaces is almost identical. At large q the effect of pressure on heat transfer during boiling on a porous surface becomes smaller than on a smooth surface.

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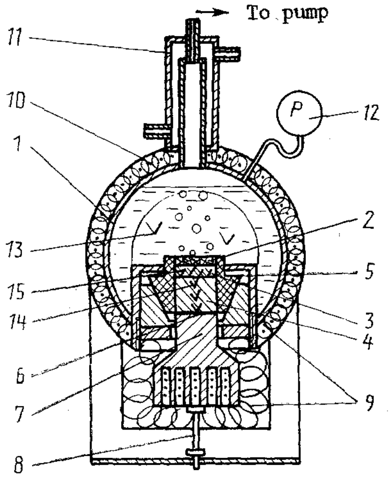

Fig. 1. Diagram of the experimental setup: 1) chamber; 2) capillary-porous structure; 3) substrate; 4) copper block; 5) collet; 6) lead gasket; 7) main heater; 8) support; 9) insulation; 10) outer heater; 11) condenser; 12) vacuum gauge; 13, 14, 15) thermocouples.

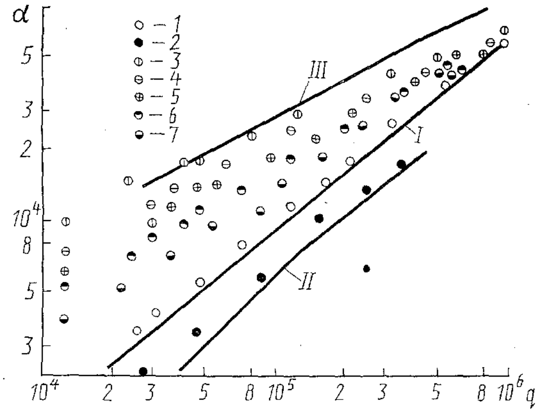

Fig. 2. Comparison of test data on heat transfer with boiling water at different pressures: boiling on a smooth surface: 1) P = $1\cdot10^5$ Pa; 2) $0.1\cdot10^5$ [data of [6]: I) P = $1\cdot10^5$ Pa, II) $0.11\cdot10^5$]; boiling on a surface with a porous coating (Π = 84 %, δ = 1 mm): 3) P = $1\cdot10^5$ Pa; 4) $0.5\cdot10^5$; 5) $0.3\cdot10^5$; 6) $0.2\cdot10^5$; 7) $0.1\cdot10^5$ Pa [III) data of [3], Π = 84 %, δ = 0.8 mm; P = $1\cdot10^5$ Pa]. α in W/($m^2\cdot$K); q in W/m^2.

This effect of pressure may, probably, be attributed to the fact that with increasing P the superheating, which is required for the liquid to boil-up and for the pores of a certain diameter to fill up, decreases. It is known that at atmospheric pressure water begins to boil on a porous surface at ΔT = 1-2 K. At reduced pressures this superheat is insufficient to initiate boiling. Since the number of potential evaporation centers on a porous surface is much higher than on a smooth one, the shift of the onset of boiling towards smaller ΔT leads to an increase in the effect of pressure on the heat-transfer rate during boiling on a porous surface as compared to the rate for a smooth surface within a small heat-flux regime. As q(ΔT) **grows, boiling begins in increasingly finer pores. At some ΔT pores whose diameters are close to the maximum of the curve of the differential size-distribution of pores [7] begin "to participate," i.e., for each pressure there exists a superheat ΔT_{max} which is the starting point at which the overwhelming majority of the potential evaporation centers on a porous surface be-**

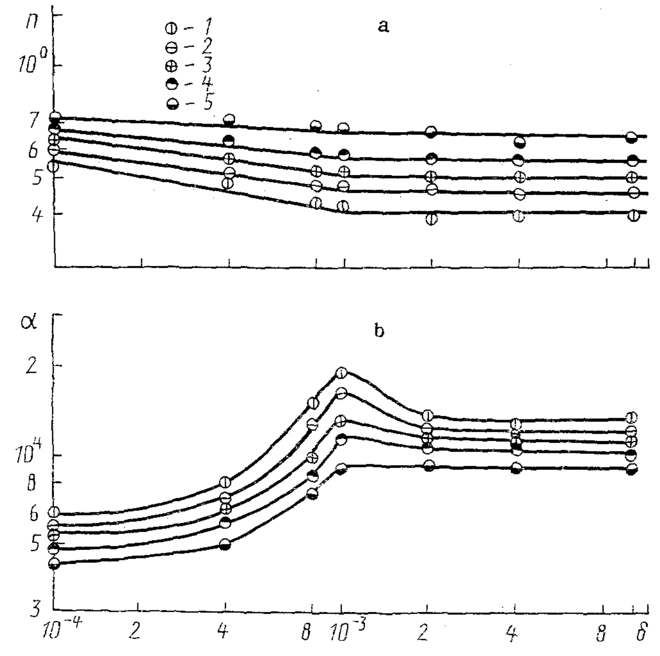

Fig. 3. Dependence of the power exponent n (a) and the heat-transfer rate ($q = 5 \cdot 10^4$ W/m^2) (b) on the porous structure thickness at different pressures: 1) $P = 1 \cdot 10^5$ Pa; 2) $0.5 \cdot 10^5$; 3) $0.3 \cdot 10^5$; 4) $0.2 \cdot 10^5$; 5) $0.1 \cdot 10^5$ Pa. δ in m.

come active. When $\Delta T > \Delta T_{max}$, boiling begins in very small size pores, the number of which is not high, as well as on the rough parts of the heating surface. Therefore, due to a comparatively small increase in the number of active evaporation centers, the growth of the heat-transfer rate for $\Delta T > \Delta T_{max}$ is insignificant. Since with the increase in pressure ΔT_{max} decreases, at low and moderate heat fluxes the effect of pressure on the heat-transfer rate, which is related to the attainment of ΔT_{max}, is significantly higher than at large q when, for all of the studied pressures, the condition $\Delta T \geq \Delta T_{max}$ and, consequently, an approximate equivalence of the number of active vapor generation centers are reached. The above analysis allows one to substantiate the dependence of the degree of the pressure effect on the heat-transfer rate during boiling on a porous surface on the heat-flux density. Consequently, the power index n in the relation $\alpha = Cq^n$ depends not only on the coating thickness, as is mentioned in [8], but also on pressure.

The results of the experiments show that n depends on δ at coating thicknesses ranging from 0.1 to 1 mm (Fig. 3a). This dependence of n on δ becomes weaker with decrease in pressure. Thus, at $P = 1 \cdot 10^5$ Pa, $n \sim \delta^{-0.17}$, and at $P = 0.1 \cdot 10^5$ Pa, $n \sim \delta^{-0.04}$. In the range of porous structure thicknesses from 1 to 10 mm, a self-similar character of n as a function of δ is observed over the entire region of pressures studied.

In the analysis of the test data, the effect of pressure on the form of the curve of the dependence of the heat-transfer rate on the porous structure thickness (Fig. 3b) was found. At $P = 1 \cdot 10^5$ Pa and $0.5 \cdot 10^5$ Pa the curve $\alpha = f(\delta)$ has a distinct maximum at $\delta = 1$ mm, then, as δ increases, the heat-transfer rate decreases and, starting from $\delta = 2$ mm, α virtually does not change. At lower pressures the self-similar character of the dependence of α on δ starts to manifest right after α reaches maximum at $\delta = 1$ mm. Correspondingly, at $\delta = 1$ mm the effect of pressure on the heat-transfer rate is maximal.

The results of the experimental study of heat transfer during water boiling under free-flow conditions on a copper metal-fiber-coated surface with an 84% porosity for structure thickness between 0.1-10 mm and for saturation pressures between $0.1 \cdot 10^5$-$1 \cdot 10^5$ Pa are well approximated by the relation

$$\alpha = Kq^n \delta^m P^l, \tag{1}$$

where $K = 1.17 \cdot 10^4$; $m = 6.8\, P^{-0.17}$; $l = 0.28$ for $0.1 \le \delta \le 1$ mm; $K = 1.58$; $m = 7.6\, P^{-0.26}$; $l = 0.7$ for $1 \le \delta \le 10$ mm; $n = 2.8\, \delta^{-0.12}\, P^{-0.25}$.

Equation (1) generalizes 95% of the present test data as well as the data of [3] with a less than ±35% error.

Thus, the presented results point to a complex and multi-valued effect of pressure on the heat-transfer rate during the boiling of water on a surface with porous coatings. From the data obtained, one may conclude about the combined effect of the saturation pressure, porous structure thickness, and heat flux density on heat transfer.

NOTATION

l, length; d, diameter; Π, coating porosity; δ, coating thickness; P, pressure; q, heat flux density; ΔT, temperature head; α, heat-transfer coefficient. Indices: f, fiber; ef, effective; max, maximum.

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