HEAT EXCHANGE IN BOILING OF WATER, ETHANOL, AND THEIR MIXTURES ON A HEATING SURFACE WITH A POROUS COATING

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Results are offered from an experimental study of boiling of water, ethanol, and their mixtures on surfaces obtained by gas-thermal deposition of aluminum oxide and alloy ÉP-616 on a vertical tube element.

Recently there has been great interest in the effect of heating surface coatings on heat exchange in the boiling process, since coatings offer solutions to a number of problems, in particular, intensification of heat exchange during boiling.

Although attempts have been made to use various types of coatings (for example, polymers [1, 2]), the main effort has been directed toward capillary-porous coatings. Both deposited [1, 3-9] and sintered [10, 11] structures have been used. Deposited coatings are used more often, since they have a number of advantages, in particular, simplicity of production and high mechanical strength. Studies have been made of the boiling of water [1, 3, 4], cooling agents [1, 5, 6, 10], and cryogenic liquids [2, 7-9, 11]. Results obtained in a number of studies show that for cooling agents and cryogenic liquids use of a porous coating significantly intensifies heat liberation in boiling at low and moderate heat flux levels (by a factor of 3-8). For water the intensification is not so significant [3, 4] and is significantly dependent on the coating structure.

Thus, the results obtained by a number of authors testify convincingly that a porous coating on the heating surface has an intensifying effect on heat exchange in the boiling of pure liquids.

However, the literature offers no data on boiling of mixtures on such surfaces. At the same time, such studies are of undoubtable interest, since it is known that the intensity of vapor formation in mixtures is significantly lower than in boiling of pure components. The possibility of intensifying heat exchange during boiling of mixtures by coating the heating surface with a porous structure would be of great significance.

The present study will offer results of an investigation of boiling of double-distilled water, rectified ethanol, and their mixtures at atmospheric pressure on a surface obtained by gas-thermal deposition. The working element used was a vertical tube of Kh18N9T stainless steel, 60 mm long, with an outer diameter of 5 mm and a wall thickness of 0.25 mm. The materials deposited were alloy ÉP-616 (particle size 0.05-0.063 mm) and aluminum oxide Al_2O_3 (particle size 0.028 mm). The following specimens were studied: No. 1 (ÉP-616 coating 0.12 mm thick), No. 2 (substrate of ÉP-616, covered by aluminum oxide, coating thickness 0.08 mm), No. 3 (substrate of ÉP-616, covered by aluminum oxide, coating thickness 0.12 mm).

Experiments were performed with the apparatus depicted in Fig. 1. The operating section was heated by direct passage of dc electrical current. Measurements of the operating element's electrical resistance before and after depositing the coating showed that there was practically no change, i.e., heat liberation in the porous coating may be neglected.

The liquid saturation state was maintained by auxiliary heaters and variation of the condenser operating level.

To determine the intensity of heat liberation within the tubular element the hot junctions of two differential thermocouples were located 30 mm apart, symmetrically about the

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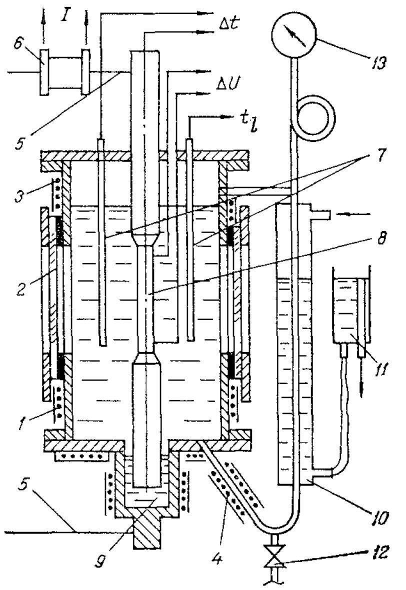

Fig. 1

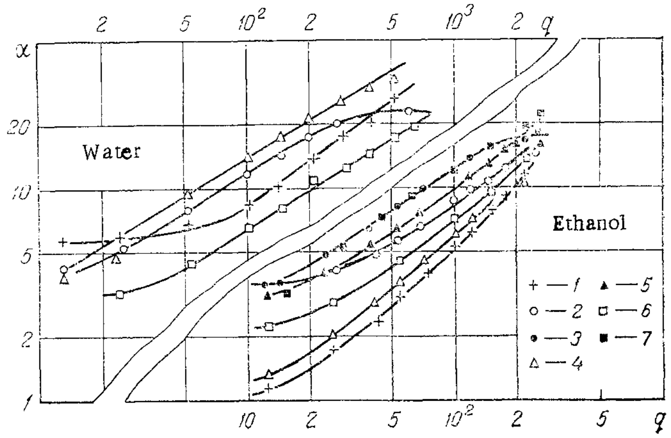

Fig. 2

Fig. 1. Diagram of experimental apparatus: 1) chamber; 2) window; 3, 4) heaters; 5) current leads; 6) shunt; 7) thermocouple sleeves; 8) operating element; 9) Wood's alloy; 10) condenser; 11) level regulator; 12) overflow valve; 13) manometer.

Fig. 2. Heat-liberation coefficient α (kW/(m^2·K)) for boiling of water and ethanol vs heat-flux density q (kW/m^2): 1) element without coating; 2) element No. 1, increased load; 3) element No. 1, decreased load; 4) element No. 2, increased load; 5) element No. 2, decreased load; 6) element No. 3, increased load; 7) element No. 3, decreased load.

vertical center point of the element. These were used to measure the mean temperature head between the inner surface of the element and the boiling liquid. The mean temperature head between the smooth outer element surface and the liquid was determined with consideration of the temperature drop within the element wall.

Experiments were performed over a heat-flux density range of 10^4–$6\cdot10^5$ W/m^2 (for water) and 10^4–$2.6\cdot10^5$ W/m^2 (for ethanol and water–ethanol mixtures).

The data obtained for water boiling (Fig. 2) agree qualitatively with the results of [3, 4]. However, in contrast to [3, 4] the function $\alpha = f(q)$ shows no abrupt changes. Apparently this is because a thicker coating was used in [3, 4], in which formation and stable existence of a pulsating vapor layer was possible. In the thin coating used in the present study formation of a stable vapor film is improbable.

Activation of a significant number of vapor-formation centers was observed even at low heat-flux densities (q = 20–50 kW/m^2). This is due to the fact that the porous surfaces used in the study provide better conditions for such activation than an uncoated surface. Since the porous layer hinders penetration of convective flows of cold liquid to the wall, i.e., to vapor-formation centers, the latter reach the saturation regime significantly earlier, as compared to a smooth surface. This means that the centers generate bubbles at a frequency determined essentially by the bubble growth time, which varies only slightly with change in wall temperature. And since the number of possible vapor-formation centers on a given surface is finite, earlier activation of a significant portion of the centers leads to a situation in which there is a significantly lower increase in intensity of heat liberation with increase in heat flux, determined by the density of active vapor-formation centers. This is reflected externally by a reduction in the exponent n in the dependence of α on q for a coated surface as compared to a smooth surface.

For the developed boiling range the results for water with a smooth element can be generalized with the equation

$$\alpha = 2.5\, q^{0.7}\,. \tag{1}$$

The dependence of α on q for specimens with a porous coating can be represented in the form

$$\alpha = Cq^{0,6}. \tag{2}$$

The value of the coefficient C depends on the character of the porous coating: for specimen No. 1 C = 12, for specimen No. 2 C = 13.2, and for specimen No. 3 C = 6.5.

In the heat-flux range of 50-300 kW/m², as compared to a smooth element specimens Nos. 1 and 2 show an intensification of heat liberation by an average of 1.5 times.

Specimen No. 3 had a greater thickness of deposited aluminum oxide with small pore size, which greatly increased the hydraulic resistance for vapor expulsion from the porous layer, as a result of which there was a reduction in the intensity of heat liberation for specimen No. 3, even compared to a smooth surface.

No hysteresis phenomena were observed in boiling of water on specimens with porous coatings.

The critical heat-flux level was determined visually by the development of local reddening of element surface. For specimens with a porous coating it proved to be an average of 25% lower than for a smooth element (for the smooth element $q_{cr} = 1.2 \cdot 10^6$ W/m²; for the porous coating, $q_{cr} = 0.9 \cdot 10^6$ W/m²).

Ethanol experiments were performed with the same elements — the smooth one and three with porous coatings. Results are presented in Fig. 2.

The character of the change in heat-liberation coefficient with heat-flux density was the same as in the case of water, namely, the slope of the curves $\alpha = f(q)$ for the coated elements was less than for the smooth element.

Due to the higher surface wettability of ethanol, it penetrates through the pores more easily, insuring conditions for normal vapor generation. In connection with this, element No. 3, which operated poorly with water, proved quite suitable for intensifying heat liberation in ethanol boiling.

A number of phenomena not found in water boiling were observed in ethanol boiling.

As the heat-flux density was increased, the temperature of the coated element wall increased smoothly (like the smooth element). But when a certain heat-flux level was reached (80-90% of the critical value) the wall temperature of the coated element began to decrease slowly, reaching a steady-state value after several minutes (at a constant heat-flux density). The amount of this decrease was 3-5°K.

It appears to us that this phenomenon is caused by activation of additional vapor-formation centers due to propagation of vapor nuclei of supercritical diameter in the porous layer when the latter contains a high vapor content (i.e., in the near-crisis range). The possibility of such a process is also indicated by the unusual character of the crisis observed in ethanol boiling in coated elements. When the critical heat-flux density is reached (300 kW/m² for the porous elements, which is also 25% less than for the smooth element), the element temperature first decreases over a certain period of time, and only then does the crisis set in, accompanied by an abrupt increase in wall temperature.

Such an unusual heat-liberation crisis is apparently due to activation of new vapor-formation centers in the precrisis regime (as was indicated above).

The critical heat-flux density is achieved at the maximum possible density of active vapor-formation centers [12]. This is true for both the smooth and coated elements. But in contrast to the smooth element, where activation of new centers occurs almost immediately upon increase in heat-flux density, with the porous element new centers are activated gradually as vapor nuclei propagate through the porous layer. Therefore, when the critical heat flux was reached in experiment due to a slight (10-15%) increase, the wall temperature first increased (since new centers were not activated), and then decreased as the new centers were activated. At the moment when the number of acting centers reached its limiting value, surface evaporation and crisis occurred.

It is also interesting that activated vapor-formation centers are suppressed significantly less well than on a smooth surface. This conclusion was reached, first, by visual observations of the boiling process, and second, by the presence of significant hysteresis in the curves $\alpha = f(q)$ for surfaces with a porous coating (Fig. 2).

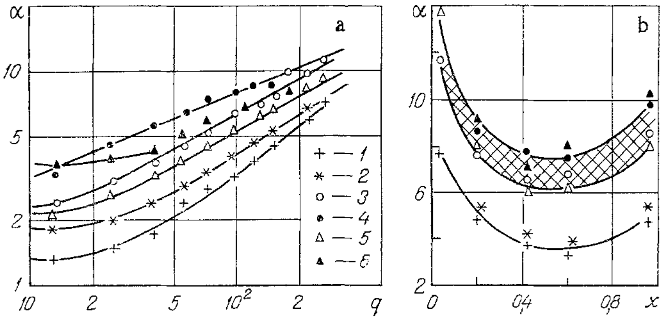

Fig. 3. Heat-liberation coefficient α (kW/m²·°K)) for boiling of water—ethanol mixture (ethanol concentration 0.41 by mass) vs heat-flux density q (kW/m²) (a) and vs mixture concentration at constant heat-flux q = 100 kW/m² (b): 1) uncoated element, increasing load; 2) uncoated element, decreasing load; 3) element No. 1, increasing load; 4) element No. 1, decreasing load; 5) element No. 2, increasing load; 6) element No. 2, decreasing load.

TABLE 1. Values of Constants C and n in Function $\alpha = Cq^n$ for Various Elements for Ethanol Boiling with Increase and Decrease in Thermal Loading

Element No.	Increased load		Decrease	
	C	n	C	n
1	8	0,6	12	0,6
2	0,33	0,85	10	0,6
3	2,4	0,7	12	0,6

For the smooth element the results obtained for ethanol boiling with both increase and decrease in load coincide. For the coated elements the heat-liberation coefficient depends on the direction in which the thermal load changes. The results obtained were processed in the form of a power function $\alpha = Cq^n$. Values obtained for the constants C and n are presented in Table 1.

At heat-flux densities of 50-200 kW/m² the hysteresis for ethanol boiling on coated elements can reach 40-50%. With consideration of this fact, the intensification of heat liberation on porous coated elements comprises 1.2-2.2 times as compared to smooth elements.

Experiments with mixtures were carried out with the smooth element and coated elements Nos. 1 and 2 at various mixture concentrations. Typical results for one concentration are shown in Fig. 3a.

The character of the dependence of the heat-liberation coefficient on heat-flux density for the mixtures is similar to that of the pure components: the slopes of the curves $\alpha = f(q)$ for the coated elements are less than for the smooth element. In contrast to the experiments with pure materials, hysteresis was observed with both smooth and coated elements. However, the hysteresis was greater for the latter. As the ethanol concentration in the mixture was reduced, the hysteresis decreases and practically disappears at a concentration of 0.2.

The intensifying effect of the coating in boiling of both pure liquids and mixtures is clearly evident from Fig. 3b, which shows the dependence of the heat-liberation coefficient on mixture concentration for a constant heat-flux density of q = 100 kW/m². With consideration of hysteresis and scattering of the results for the coated elements, heat liberation increases by a factor of 1.5-2 times.

For mixture boiling on a smooth element the reduction in the heat-liberation coefficient as compared to its additive value is explained by two reasons: a decrease in number of active vapor-formation centers and retardation of vapor bubble growth due to diffusion of components in the liquid in the vicinity of bubbles [12]. Since the character of the dependence $\alpha = f(q)$ for the smooth and porous elements is identical and the intensification for all concentration values is practically constant (1.5-2 times), we may conclude that for both pure liquids and mixtures the cause of the coating's intensifying action is a growth in the number of active vapor-formation centers. The role of diffusion here is always the same, i.e., despite the restricted conditions, diffusion processes in the coating studied differ little from those on a smooth surface.

Thus, the results of the studies performed indicate convincingly that use of deposited porous coatings permits an intensification of heat exchange in boiling of both pure substances (water, ethanol) and their mixtures. The amount of intensification achieved depends on the structure of the coating, the heat-flux density, and the prehistory of coating operation. For the specimens studied the intensity of heat liberation increases by a factor of 1.5-2 times.

NOTATION

α, heat-liberation coefficient, $W/(m^2\cdot{}^\circ K)$; q, heat-flux density, W/m^2; q_{cr}, critical heat flux density, W/m^2; x, mass concentration of ethanol in mixture; C, n, constants in expression $\alpha = C_q{}^n$.

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