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INVESTIGATIONS OF THE INTENSIFICATION OF WATER BOILING IN A VERTICAL TUBE

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Results of experimental investigations of the intensification of heat exchange in boiling of water due to the injection of a live steam have been given. The influence of different parameters on the degree of intensifying effect has been determined. The equation for calculation of the heat-transfer coefficient in boiling of a liquid in a vertical tube with the injection of a live steam on its initial portion has been obtained.

The power intensity of many industrial processes can be reduced by recuperation and utilization of the heat of technological flows and media. Utilization of secondary power resources (SPRs) of high potential requires no substantial additional material expenses and is widely used in designing new plants and reconstructing obsolete ones. With low-potential SPRs (for example, the heat of a low-pressure vapor), their direct use is difficult because of the low value of the heat-exchange driving force. Therefore, expensive apparatuses with large heat-transfer surfaces are required for such designs. To make the technologies of recuperation and utilization of low-potential SPRs less expensive, primarily by reducing the capital costs of their realization, and to extend the range of their application one must intensify heat exchange.

If, in the process of utilization of low-potential SPRs, the receiving heat-transfer agent is boiling liquid and the giving-up agent is condensable vapor (processes of evaporation, distillation, and rectification, those of heat exchange in refrigeration engineering, processes of processing of food-stuffs, etc.), in the case of small temperature differences between them the total intensity of the process is limited, as a rule, by the intensity of heat transfer in the boiling liquid. To reduce the total thermal resistance one must intensify boiling; therefore, it is of great scientific and practical interest to develop and investigate new methods of intensification of boiling heat exchange.

Different structural and technological methods of intensification of boiling, including intensification due to the dispersion of a gas into a boiling liquid, have been reviewed in [1]. Boiling can also be intensified in dispersion of a live steam into a boiling liquid [2, 3], but the results of investigations of this method have not been presented in the above publications.

We have carried out experimental investigations of the intensification of boiling of a liquid in a vertical tube with the injection of a live steam on the economizer portion. Selection of the vertical tube as the object of investigation is substantiated by the fact that it is the element of the most widespread type of tubular evaporators. The results of the research [4, 5] demonstrate an increase of up to 50% in the heat-transfer coefficient upon the injection of a live steam into the boiling liquid. It has been established that the degree of intensification is affected by the temperature difference, the level of the liquid, and the flow rate of the live steam.

We have created an experimental setup and have developed an experimental procedure [6] with the aim of particularizing the influence of different parameters on the intensity of boiling and obtaining the local characteristics of the process. The cell under study was a vertical single-tube evaporator with a natural-circulation circuit. The process of boiling was carried out in a copper tube with an inside diameter of 20 mm and a wall thickness of 4 mm. The height of the heated portion was 1 m. Thermocouples were flared out into the tube wall at different levels. Distilled water was used as the model liquid. The excess pressure of the steam above the boiling liquid was no higher than 1 kPa at a barometric pressure of 97 to 100 kPa. A saturated steam of pressure 110–200 kPa was used as the live steam.

The investigations were carried out for the following relative levels of a clear liquid in the tube: 0.35, 0.50, 0.63, and 0.75. In the experiments, the relative flow rate of the live steam β varied from 0.15 to 0.5. It is determined

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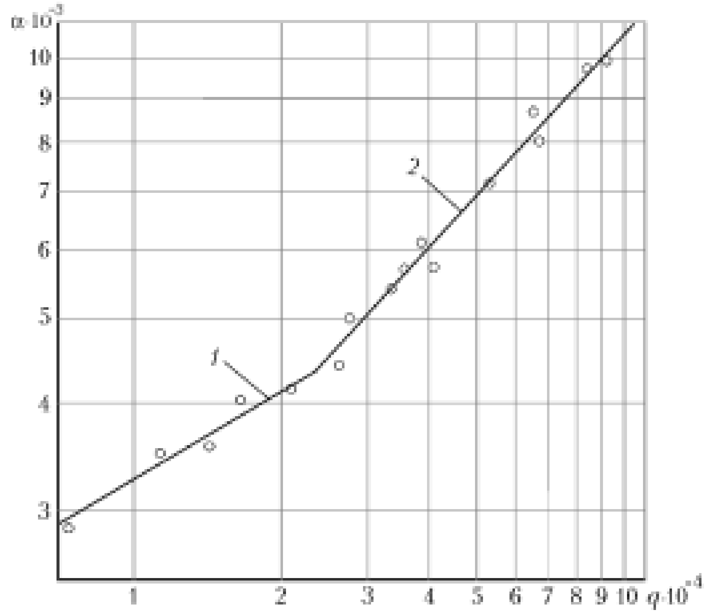

Fig. 1. Processing of experimental data on boiling without a live steam in the coordinates $\alpha = f(g)$ for an optimum h: 1) $\alpha = 142.5q^{0.34}$; 2) $9.1q^{0.61}$. α, W/(m^2·K); q, W/m^2.

as the ratio of the flow rate of the live steam to that obtained due to the external heating without intensification for the same operating conditions (level of the clear liquid and temperature difference). The temperature difference in the boiling liquid (difference of the surface temperature of the tube wall and the saturation temperature of the liquid) ΔT was established within 2.5–11.5 K.

At the first stage of investigations, we carried out a series of experiments without intensifying heat exchange. We determined the influence of the level of a clear liquid in the steam-generating tube h and of the temperature difference ΔT on the heat-exchange intensity.

To eliminate the effect of running-in of the heating surface and to obtain stable results we operated the steam-generating tube for a long period (tens of hours) in boiling of the model liquid. The series of experiments were carried out only with the use of a direct run (with step-by-step increase in the heat-flux density) with the aim of eliminating the influence of the hysteresis of the heat flux for small temperature differences.

The experimental values of the coefficient of boiling heat transfer α were determined from the well-known Newton–Richmann equation as the ratio of the heat-flux density q to the difference of the surface temperature of the wall T_w and the boiling temperature T_0. The temperature of the surface of heating on the source side of the boiling liquid was taken as the arithmetic mean of the readings of the thermocouples caulked into the wall of the steam-generating tube.

The intensity of boiling heat exchange is dependent on numerous highly diverse factors whose influence frequently defies all attempts at accurate evaluation.

It has been established by multiple investigations that in pool boiling and in boiling in tubes, the influence of the heat-flux density on the heat exchange is governing and is characterized by the following empirical dependence:

$$\alpha = f(q) = Cq^n . \tag{1}$$

The plot (1) obtained from processing of the results of the experimental investigations of the authors for the optimum level of a clear liquid in the steam-generating tube is shown in Fig. 1. It has a characteristic bend at the boundary of the zones of convective heat transfer ($\alpha \sim q^{0.34}$) and developed nucleate boiling ($\alpha \sim q^{0.61}$).

The empirical equations obtained have a simple form but they fail to reflect the influence of different parameters on the heat-exchange intensity and hence have a narrow validity range. More valuable are equations in criterial form, which enable one to extend the experimental results obtained to such processes.

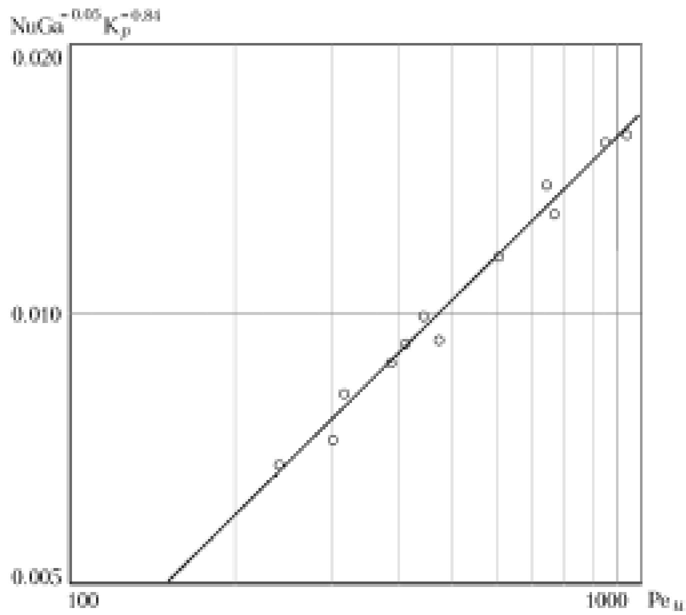

Fig. 2. Processing of experimental data on boiling without a live steam.

We have analyzed calculation relations for determination of the coefficient of heat transfer in pool boiling and in boiling in tubes, which were obtained from the dimensional analysis and the theory of thermodynamic similarity and on the basis of theoretical and semiempirical methods. The calculation dependences of G. N. Kruzhilin [7], S. S. Kutateladze [8], M. A. Kichigin and N. Yu. Tobilevich [9, 10], V. I. Tolubinskii [11], and a number of other researchers [12–15] were used.

It has been revealed that most of the data of different experimenters and the data of our investigations of the boiling in the region of developed nucleate boiling are generalized with the lowest error by two criterial systems proposed by M. A. Kichigin and N. Yu. Tobilevich and V. I. Tolubinskii respectively:

$$\mathrm{Nu} = C_1\, \mathrm{Pe}_u^m\, \mathrm{Ga}^{0.05}\, \mathrm{K}_p^{0.84}\,, \tag{2}$$

$$\mathrm{Nu} = C_1\, \mathrm{K}^m\, \mathrm{Pr}^{-0.2}\,. \tag{3}$$

In expanded form, the above criterial systems are represented by the formulas

$$\frac{\alpha l_0}{\lambda} = C_1 \left(\frac{q l_0}{r\rho'' a}\right)^m \left(\frac{g l_0^3}{\nu^2}\right)^{0.05} \left(\frac{p l_0}{\sigma}\right)^{0.84}, \tag{4}$$

$$\frac{\alpha l_0}{\lambda} = C_1 \left(\frac{q}{r\rho''\omega''}\right)^m \left(\frac{\nu}{a}\right)^{-0.2}, \tag{5}$$

where $l_0 = \sqrt{\sigma / g(\rho' - \rho'')}$ is the governing linear dimension proportional to the separation diameter of a steam bubble.

The results of processing of experimental data obtained by the authors with the use of the criterial system of Kichigin and Tobilevich are given in Fig. 2. It is seen in the figure that experimental points are satisfactorily grouped along the averaging straight line described by the equation $\mathrm{NuGa}^{-0.05}\mathrm{K}_p^{-0.84} = 2.4 \cdot 10^{-4}\, \mathrm{Pe}_u^{0.61}$. The analogous results with a deviation of the experimental data from the calculated data of no higher than 7% have been obtained with the use of the criterial system of V. I. Tolubinskii.

Generalization is represented by the refined dimensionless equations

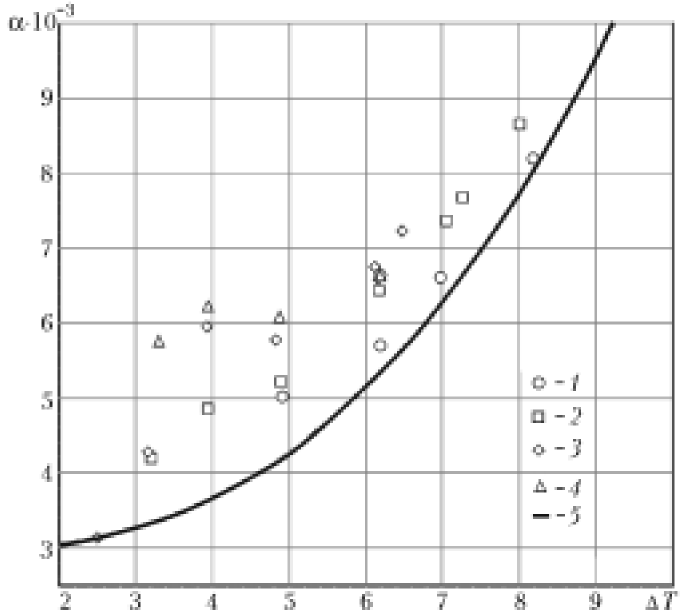

Fig. 3. Dependence of α on ΔT for h = 0.5: 1) β = 0.15, 2) 0.25, 3) 0.33, 4) 0.50; 5) 0. α, W/(m^2·K); ΔT, ^{o}C.

$$\mathrm{Nu} = 2.39 \cdot 10^{-4}\, \mathrm{Pe}_u^{0.61}\, \mathrm{Ga}^{0.05}\, \mathrm{K}_p^{0.84} , \tag{6}$$

$$\mathrm{Nu} = 68\, \mathrm{K}^{0.61}\, \mathrm{Pr}^{-0.2} . \tag{7}$$

At the second stage of investigations, we carried out experiments with the injection of a live steam into the boiling liquid. We studied the influence of the quantity of the injected light phase on the degree of intensification of heat exchange.

The results of the experiment are given in Fig. 3 in the form of the dependences $\alpha = f(\Delta T, \beta)$ for h = 0.5. Injection of the live steam into the liquid contributes to the increase in the coefficient of boiling heat exchange; the degree of intensification increases with β. The influence of the heat-flux density on the heat-transfer coefficient is ambiguous. When a certain critical q whose value is lower than the heat-flux density corresponding to the transition from the free-convective zone to the zone of nucleate boiling is attained, the heat-transfer coefficient sharply increases. Further increase in q leads to a reduction in the intensifying effect; the heat-transfer coefficient remains 10 to 15% higher than that in the case of boiling without the injection of a live steam for the same operating conditions.

In the course of the investigations, it has also been established that the positive action of the injection of a live steam increases with the level of clear liquid in the steam-generating tube. However this increase is slight for liquid levels higher than the optimum level.

It is proposed that with injection of a live steam the coefficient of heat transfer in boiling of water and diluted aqueous solutions α_i be determined from the formula

$$\alpha_i = B\alpha . \tag{8}$$

Figure 4 gives the experimental dependences of the coefficient B on the temperature difference ΔT for different values of β and h = 0.5. It has been established that in the case of injection of a live steam into the boiling liquid the heat-transfer intensity increases most vigorously for β = 0.25–0.33. As β increases from 0.33 to 0.5, just as for $\beta < 0.25$, the relative change in the heat-transfer coefficient is slight.

In generalizing the results of experimental investigations of the intensification of heat exchange in boiling of a liquid in a vertical tube with the injection of a live steam, for the optimum regimes of the process we obtained the empirical relation

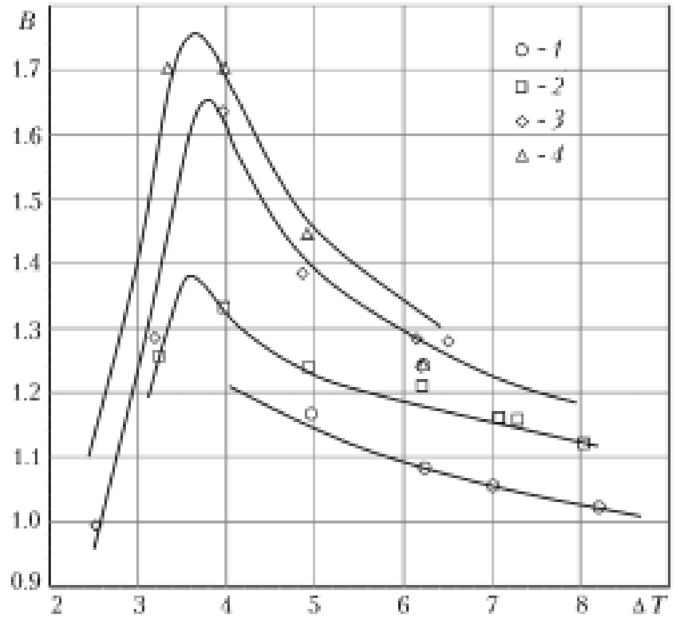

Fig. 4. Dependence of $B = \alpha_i/2$ on ΔT for h = 0.5: 1–4) notation is the same as in Fig. 3. ΔT, ^{o}C.

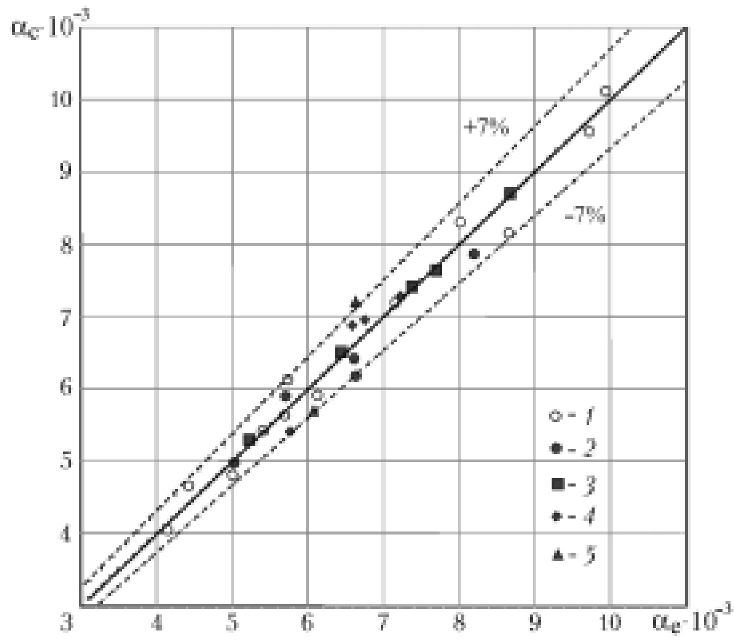

Fig. 5. Correlation of the values of α_i by Eq. (10): 1) β = 0; 2) 0.15; 3) 0.25; 4) 0.33; 5) 0.50. α_c and α_e, W/(m^2·K).

$$B = 12.1\beta^{0.152}\, q^{-0.196}\,. \tag{9}$$

The calculation dependence (8) with account for (6), (7), and (9) takes the form

$$\alpha_i = B\,\frac{\lambda}{l_0}\,2.39\cdot10^{-4}\,\mathrm{Pe}_u^{0.61}\,\mathrm{Ga}^{0.05}\,\mathrm{K}_p^{0.84}\,, \tag{10}$$

or

$$\alpha_i = B \frac{\lambda}{l_0} 68\ \mathrm{K}^{0.61}\ \mathrm{Pr}^{-0.2}\ . \tag{11}$$

When β = 0.1–0.5 and q = 20–80 kW/m^2 the coefficient of variation of α_i values calculated from (10) and (11) from the experimental values is no higher than 7%, which is confirmed by the correlation plot in Fig. 5.

The criterial equations obtained can be recommended for engineering calculations of intensified vertical evaporators with the injection of a live steam into the boiling liquid.

Conclusions. The above analysis of the state of the art in investigations of the intensification of heat exchange in combination with the results of the experimental investigations of the authors allows us to make the following statements:

(1) injection of a live steam into the boiling liquid is an efficient means of increasing the heat-exchange coefficients for small temperature differences;

(2) change in the character of heat exchange due to the "explosive" increase in the heat-transfer coefficients upon the injection of a live steam occurs for smaller temperature differences than the critical temperature differences of transition from the free-convective regime of boiling to a nucleate regime;

(3) the intensifying action on heat exchange increases with increase in the relative flow rate of the live steam and is maximum in boiling of water in the range of temperature difference 3–6 K;

(4) one can increase the heat-transfer coefficients 1.5–2 times by injection of a live steam into the boiling liquid.

NOTATION

a, thermal diffusivity, m^2/sec; g, free-fall acceleration, m/sec^2; h, relative height of the level of a clear liquid in the steam-generating tube; l_0, governing geometric dimension, m; m, n, C, and C_1, coefficients; p, absolute pressure of the secondary steam above the boiling liquid, N/m^2; q, heat-flux density, W/m^2; r, specific heat of evaporation, J/kg; B, coefficient of the degree of intensification of heat exchange; Ga, K, Nu, Pe, and Pr, Galilei, Jacob–Tolubinskii, Nusselt, Péclet, and Prandtl numbers, respectively; K_p, pressure criterion; Pe_u, Péclet number for the process of boiling; T_0, boiling temperature of the liquid, K; T_w, surface temperature of the tube wall, K; α and α_i, coefficient of heat transfer from the tube wall to the boiling liquid without intensification and with intensification by a live steam, W/(m^2·K); α_c and α_e, calculated and experimental values of the heat-transfer coefficients, W/(m^2·K); β, relative flow rate of the live steam; λ, thermal conductivity, W/(m·K); ν, coefficient of kinematic viscosity, m^2/sec; ρ', density of the liquid, kg/m^3; ρ'', density of the steam, kg/m^3; σ, coefficient of surface tension, N/m; ω'', rate of growth of a vapor bubble, m/sec; ΔT, temperature difference, K. Subscripts: i, intensified; c, calculated; w, wall; e, experimental; $'$, liquid; $''$, steam.

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