PRINCIPLES OF HEAT EXCHANGE IN EVAPORATION OF A LIQUID FILM ON A SMOOTH HORIZONTAL TUBE

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Experimental data are presented for the local heat liberation coefficient for flow of a liquid film on a smooth horizontal tube, permitting refinement of the concept of the heat exchange mechanism.

Heat exchangers with a liquid film flowing along horizontal tubes are used in evaporators of distillation and cooling apparatus and in heaters designed for various purposes. Rifert and Andrev [1] indicated the absence in the published literature of a sufficiently justified physical model of this process, as well as the divergence of calculated dependences of mean heat liberation coefficients. To obtain reliable information on the mechanism involved in this process, an experimental setup was created with an element which allowed determination of local heat liberation coefficients α_φ about the perimeter of the experimental tube. A detailed description of the apparatus and technique used for α_φ determination can be found in [2].

The experiments were performed at a constant thermal flux density q = 10 kW/m^2 and variable density Γ which was varied by changing the liquid flow rate from 0.08 to 0.4 kg/(m·sec). The liquid was supplied to the tube which was heated to the saturation temperature at atmospheric pressure. The distance between tubes was maintained constant at 10 mm. The outer diameter of the experimental tube d_o = 38 mm.

For q > 10 kW/m^2 development of bubbles, mainly in the rear portion of the tube, disrupted the hydrodynamics and character of heat exchange during liquid film flow, i.e., the boiling process affected heat exchange.

Figure 1 shows experimental data on local heat liberation coefficients α_φ over the tube perimeter. The maximum values of α_φ were obtained on the upper directrix of the tube, at the beginning of the hydrodynamic and thermal boundary layers. With further motion of the liquid film along the tube surface α_φ decreases for all values of Γ, due to increase in the thickness of the thermal boundary layer. It is quite evident that the less the irrigation density Γ the earlier stabilization of heat liberation α_φ sets in with respect to φ. Thus, at Γ = 0.08 already at $\varphi \geq 75°$ α_φ does not change up to φ = 120° and only in the rear section is there some increase in α_φ. At Γ = 0.4 the decrease in α_φ occurs up to φ = 120°. For $\varphi \geq 150°$ at all Γ there is some increase in α_φ, which can be explained by turbulization of the film by reverse waves which develop from collisions of liquid flows passing over the tube from both sides, or in analogy to flow over blunt tubes, by detachment phenomena in the boundary layer [1].

Figure 2 shows the effect on α_φ of irrigation density Γ for various φ. With increase in φ the effect of Γ on α_φ decreases. For Γ < 0.16 at φ > 120°, i.e.,, in the region of most stabilized film flow, α_φ decreases with increase in Γ, which is characteristic of a laminar stabilized film flow regime. For Γ > 0.16, which corresponds to Re_f > 530, α_φ increases with increase in Γ.

The dashed line of Fig. 2 for φ = 120° shows the result of local heat liberation calculations from equations for stabilized flow of a laminar and turbulent film on a vertical tube from [3]. The number Nu_φ is defined with consideration of the decrease in the gravity component, i.e., $Nu=\alpha_\varphi(\nu^2/g\sin\varphi)^{1/3}/\lambda$.

As is evident from Fig. 2, the experimental values of α_φ in the zone in which they are stabilized with respect to φ agree well with calculations. However, the stabilized portion of the liquid film flow along the horizontal tube, even for a 38-mm diameter, occupies a

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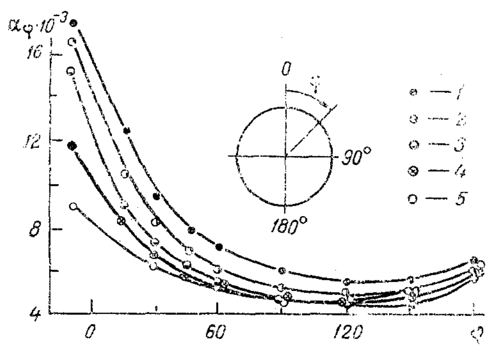

Fig. 1

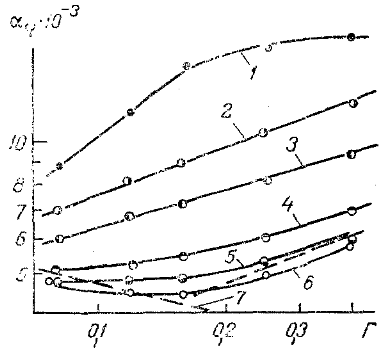

Fig. 2

Fig. 1. Local heat liberation α, W/(m²·K), for evaporation of liquid film on horizontal tube: 1) Γ = 0.4; 2) 0.25; 3) 0.16; 4) 0.12; 5) 0.08 kg/(m·sec). φ , deg.

Fig. 2. Effect of Γ for various φ: 1) φ = 0°; 2) 15; 3) 30; 4) 60; 5) 90; 6) 120°; 7) calculation with equation of [3].

smaller region, especially for large Γ, than does the initial segment. For a smaller tube diameter heat exchange will occur over the entire perimeter under boundary layer formation conditions. Theoretical solutions of the problem of heat exchange in the initial portion of a film flowing along a horizontal tube presented in [4, 5] give results for local heat liberation close to the solution for the case of flow of a smooth film over a planar surface [6, 7]. However, in the latter case the solutions were produced with simple calculation expressions. The expressions obtained in [6, 7] have a practically identical form:

$$\mathrm{Nu}_x = 0.83X^{0,65}\,(\mathrm{Re_f\;Pr})^{0,35}\,. \tag{1}$$

If we construct the function $\alpha_\varphi = f(\varphi)$, we find that heat liberation in the initial section (for φ = 15-90°) for all Γ from 0.12 to 0.4 depends on n ≈ 0.35-0.44, i.e., close to the prediction of Eq. (1).

We will assume that in the initial hydrodynamic and thermal portion for all Γ a laminar liquid film flow regime is maintained, and use Eq. (1) to calculate α_φ.

The liquid thermophysical properties and number Pr appearing in Eq. (1) are defined using the mean liquid film temperature.

The film thickness δ appearing in Eq. (1) was found from the Nusselt expression for a laminar stabilized film flow on an inclined surface, i.e., the variability of the force of gravity for different φ was considered.

As is evident from Fig. (3), Eq. (1) describes the experimental data on heat liberation during liquid film evaporation on a horizontal tube poorly in the initial boundary layer formation segment.

Since Fig. 3 shows data for various $\mathrm{Re_f}$, analysis of the character of function $\mathrm{Nu_x}/(\mathrm{Re_b Pr})^{0.35} = f(x)$ leads to the conclusion that the film path length has a greater effect on heat liberation than predicted by Eq. (1). Therefore, the experimental data were generalized with the following expression:

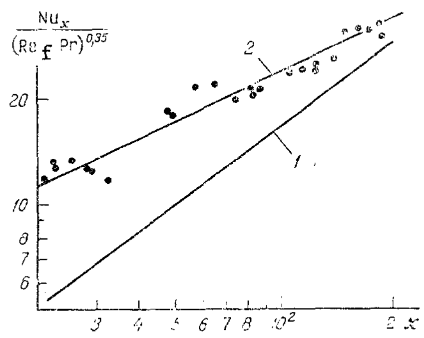

Fig. 3. Comparison of experimental data on heat exchange in initial thermal segment of tube with calculations: 1) with Eq. (1); 2) with Eq. (2).

$$\mathrm{Nu}_x = 2.31 X^{0.433} (\mathrm{Re}_f \ \mathrm{Pr})^{0.35}. \tag{2}$$

To determine the length of the stabilization segment $x_T = 0.5\ d_0 \varphi_t$ it is possible to begin from the principles of local heat liberation in the first approximation, proceeding in the following manner. According to Fig. 1, in the stabilized section α_φ for the region with laminar film flow can be calculated with an expression from [3]:

$$\mathrm{Nu}_f = 0.9 \mathrm{Re}_f^{-1/3}. \tag{3}$$

Substituting α_t from Eq. (3) in Eq. (2), defining δ with Nusselt's expression and replacing x in Eq. (2) by x_t, we find

$$\frac{x_T}{\delta} = 2.7 (\mathrm{Re}_f \ \mathrm{Pr})^{0.617}. \tag{4}$$

Calculation of φ_t with Eq. (4) for $\Gamma = 0.08$ yields $\varphi_t = 60°$, for $\Gamma = 0.16$, $\varphi_t = 90°$, which agrees with experiment.

With the aid of Eqs. (2) and (4) and expressions for the stabilized liquid film flow one can successfully calculate the mean heat liberation $\bar{\alpha}$ for liquid film evaporation on a horizontal tube. Calculations performed in this manner show that the calculated $\bar{\alpha}$ agree φ well with the data of Fig. 2 averaged over $\bar{\alpha}$, data on liquid film evaporation from other authors, a generalized analysis of which is presented in [8], and data on $\bar{\alpha}$ obtained in [9] for condensation of nonmoving vapor on horizontal tube packets for $\mathrm{Re}_f > 50$.

NOTATION

ν, λ, ρ, a, kinematic viscosity, thermal conductivity, density, and thermal diffusivity of liquid; δ, liquid film thickness; Γ, irrigation density; $x = 0.5\, d_0\, \varphi$; $\mathrm{Nu}_x = \frac{\alpha x}{\lambda}$; $X = \frac{x}{\delta}$; $\mathrm{Nu}_f = \frac{\alpha}{\lambda}\left(\frac{\nu^2}{g \sin\varphi}\right)^{\frac{1}{3}}$; $\mathrm{Re}_f = \frac{\Gamma}{\rho\nu}$; $\mathrm{Pr} = \frac{\nu}{a}$.

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