HEAT TRANSFER WITH VAPORIZATION IN A LIQUID FILM FLOWING DOWN A VERTICAL CORRUGATED SURFACE

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Data on heat transfer in a liquid film flowing down a longitudinally corrugated surface are correlated.

The use of corrugated tubes in film evaporators with vertical tubes in distilling installations leads to a significant gain in heat transfer [1, 2]. Only a few works are available [3-6] which present data concerning local and average heat-transfer coefficients for evaporation of a film of distilled and salt water, flowing down variously corrugated surfaces. It follows from these works that for certain values of Re, heat flux q, and characteristics of the corrugation, the average heat transfer is enhanced in comparison with a film flowing down a smooth surface.

The works mentioned above do not contain computational results for heat exchange with film evaporation on a corrugated surface or any recommendations as to the choice of optimal fluting characteristics. These questions are examined below.

Investigations of the hydrodynamics of films flowing along a longitudinally corrugated surface have shown [5] that due to the effect of surface forces, the thickness of the film is highly variable along the flow perimeter (Fig. 1). Evaporation is enhanced on such a surface over that of a smooth surface due to the appearance of a region l_1 with a thin (of the order of 0.02-0.05 mm) film and a thicker l_2 turbulent region. Maximum enhancement of heat transfer is attained for minimum flow rates wetting the surface or Re_{min}, while the degree to which the process is enhanced depends on the fluting parameters (Fig. 2a). As Re increases the average coefficient of heat transfer on a corrugated surface $\bar{\alpha}_p$ decreases, approaching the heat transfer for a smooth surface $\bar{\alpha}_{sm}$ (Fig. 2b).

As studies have shown [5], the local values of δ_x and α_x vary greatly along the flow perimeter, i.e., as a function of x (see Fig. 1). As a result, the temperature of the wall, in general, will also vary with x and will depend on the mutual thermal influence of the wall and the liquid film.

Since heat is transferred from the film surface by evaporation and $\bar{\alpha}_p$ does not depend on q (Fig. 2a) over a wide range of values of q, we will assume that the local values of α_x on the segments l_1 and l_2 are only functions of the film thickness δ_x. Then, the temperature of the wall T at the boundary with the film can be determined from a solution to the heat-conduction equation for the wall

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0. \tag{1}$$

The boundary conditions for (1) are as follows: a) x = 0, x = S/2, $\partial T/\partial x = 0$; b) y = 0, $T = T_0$; c) at the film-wall boundary

$$\frac{\partial T}{\partial y} = -\frac{\alpha_x}{\lambda_c}(T - T_s).$$

The heat transfer along the segment l_1 with the thin laminar film is determined by $\alpha_x = \lambda/\delta_x$, where the local thickness δ_x is defined by the equation [7]

$$\delta_x = \delta_0 + R_f - \sqrt{R_f^2 - x^2}. \tag{2}$$

R_f can be easily found geometrically for known surface corrugation [7]. As a result, the dependence for δ_x will have the form

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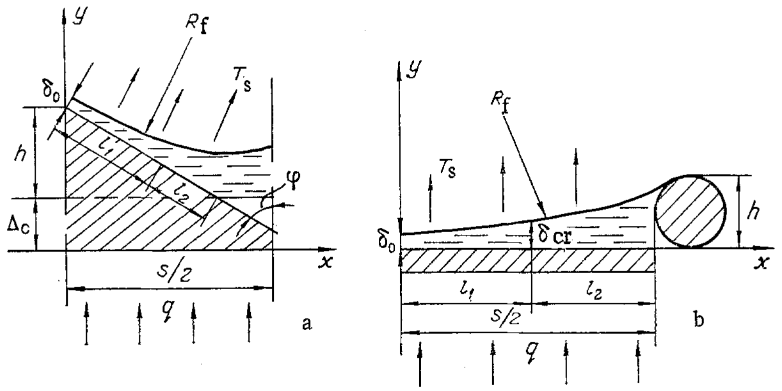

Fig. 1. Diagram showing the flow of a liquid film along a corrugated wall (a) and a surface deformed by a wire (b).

$$\frac{\delta_x}{S_0}=\frac{\delta_0}{S_0}+\frac{S_0}{8h}-\sqrt{\left(\frac{S_0}{8h}\right)^2-\left(\frac{x}{S_0}\right)^2}. \tag{3}$$

According to [7], δ_0 = 0.03-0.04 mm for minimum wetting flow rate or Re_{min}.

On the segment l_2, α_x varies little with x [5] and can be adequately computed from the known behavior for a smooth surface [8]. We arbitrarily assume l_1 = x at a point where δ_x corresponds to Re_{cr} = 400 [8]. Equation (1) is solved together with the boundary conditions by a relaxation method on a M-4030 computer. The computations are carried out for surfaces with the wall thickness at the base of a fin equal to Δ_w = 0.5-3 mm and thermal conductivity for the wall λ_w = 5-390 W/m•K, for the case when Re = Re_f, i.e., when the local coefficient of heat transfer and temperature differential along the fin are maximum.

Figure 3 shows the relative temperature differential along the wetted perimeter from the point with minimum film thickness δ_0 to the point with maximum film thickness. The figure also shows (curve 6) the computed local heat-transfer coefficients $\alpha_x = \lambda/\delta_x$ and experimental values of α_x, measured on electrically heated surfaces [5]. Analysis of the data (Fig. 3) shows that the variation in temperature with the fin height is significant for λ_w < 110 W/m•K.

The effect of the thermal conductivity of the wall on the heat-transfer intensity with evaporation of a film flowing down along a corrugated surface can be taken into account by the following function:

$$\frac{\bar{q}}{\bar{q}_{iso}}=0.35\left(\frac{\lambda}{\lambda_w}\right)^{-0.22}, \tag{4}$$

where $\bar{q}_{iso}$ corresponds to heat flow for an isothermal wall.

The experimental values for the heat-transfer coefficients for an isothermal surface $\bar{\alpha}_p$ were obtained (see Fig. 2b) for the flow of a water film heated to the saturation temperature inside a copper tube with length 1.5 m and internal diameter 20 mm.

For values of Re, for which enhancement of heat exchange is observed over that of a smooth tube, the heat transfer behaves in a manner characteristic of a laminar flow of a liquid film, when, as is well known [8], Nu = f(Re). For a corrugated surface, the simplex δ_x/S_0 or, according to (3), h/S_0 should be introduced into the computational dimensionless function describing the heat transfer.

Figure 4 shows $\overline{Nu}_0$ as a function of the fluting parameters, i.e., as a function of S_0/h, for all surfaces investigated in the present work and in [6] for Re = Re_{min}. According to the behavior shown maximum enhancement of heat exchange occurs with evaporation of a film on a corrugated surface for S_0/h = 6-8.

The characteristics of all the surfaces with fluted walls are presented in Table 1.

The experimental points for $\overline{Nu}_0$ for surfaces with different types of corrugation and for different saturation temperatures are located near one line described by the equation

$$\overline{Nu}_0=0.116\left(\frac{S_0}{h}\right)^{1.2}\exp\left(-0.2\frac{S_0}{h}\right). \tag{5}$$

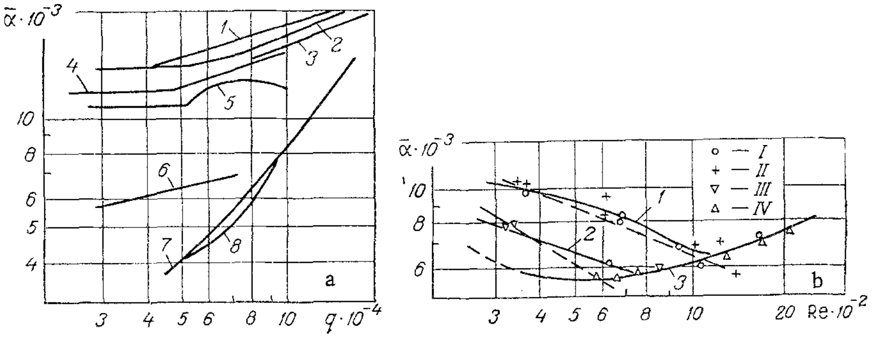

Fig. 2. Heat transfer with evaporation in a liquid film flowing down a longitudinally corrugated vertical surface with T_s = 373°K: a) effect of q for Re = Re_{min}; b) effect of Re: 1, 2) corrugated tube h = 0.8 mm, S = 2 mm (I); h = 0.7, S = 1.4 (II); h = 0.48, S = 1 (III); 3) smooth tube (IV); dashed lines correspond to calculation $\bar{\alpha}_p = \frac{1}{l}\int_0^l \alpha_x dx$, , where $\alpha_x = \lambda/\delta_x \cdot \bar{\alpha} \cdot 10^{-3}$, $W/m^2 \cdot K$; $q \cdot 10^{-4}$, W/m^2.

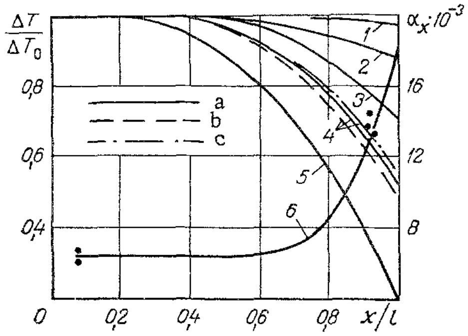

Fig. 3

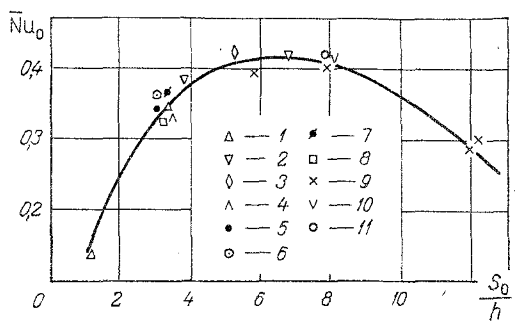

Fig. 4

Fig. 3. Temperature differential along the height of a fin (see Fig. 1a) with a wall thickness of Δ_w = 2 mm at the base of a fin (a), 3 mm (b), and 1 mm (c): 1) λ_w = 400 W/m·K; 2) 110; 3) 40; 4) 16; 5) 5; 6) $\alpha_x = \lambda/\delta_x$; experimental points are for T_s = 373°K.

Fig. 4. Heat-exchange intensity with evaporation of a film on a corrugated surface with Re = Re_{min}: 1) rectangular fins; 2, 4) trapezoidal; 3-8) wavy fins; 9-11) cylindrical fins (see Fig. 1b); 1-6, 9) T_s = 373°K; 7, 10) T_s = 336°K; 8, 11) T_s = 322°K.

TABLE 1

No. of curves in Fig. 2a	Surface fluting	Data	Width of channel S, mm	Depth of channel h, mm	$\frac{S_0}{h}$	Material	Heat source
1	Trapezoidal	[4]	2,85	1,16	2,5	Cu—Ni	Constant current
2	Rippled	Author	2,06	0,6	3.4	Stainless steel	»
3	Trapezoidal	[4]	2,85	1,16	2,5	Cu—Ni	»
4	Rippled	Author	1,4	0,68	2,0	Copper	Steam
5	»	"	2,0	0,8	2,2	»	»
6	Smooth	"	—	—	—	»	»
7	Rectangular	[4]	2,85	2,54	1,12	Cu—Ni	Constant current
8	Trapezoidal	[4]	2,85	1,16	2,5	»	»

According to this function, with S_0/h = 1.5 and $S_0/h \geqslant 14$, $\overline{Nu}_0$ = 0.2, which corresponds to heat transfer for a smooth surface. Heat exchange is enhanced for $1.5 < S_0/h < 14$. It is interesting that the intensity of heat exchange for Re = Re_{min} does not depend on the numerical value of Re. Indeed, for the same value of S_0/h, but for different values of Re, $\bar{Nu}_0$ assumes the same value.

When Re exceeds Re_{min}, the segment with the thin film decreases and its contribution to the enhancement process decreases. For this reason, as the ratio Re/Re_{min} increases, the average heat transfer approaches the value for a smooth tube (see Fig. 2b).

When Re/Re_{min} varies from 1 to 3.5-4, all experimental data are described by the function

$$\frac{\bar{Nu}}{\bar{Nu}_0} = 0.96\left(\frac{Re}{Re_{min}}\right)^{-0.44}. \tag{6}$$

For $Re/Re_{min} \geqslant 4$, $\bar{\alpha}_p = \bar{\alpha}_{sm}$.

NOTATION

δ_x, local film thickness; δ_0, film thickness for x = 0; h, height of a fin; R_f, radius of curvature of the film; S, distance between fins; $S_0 = S/\sin\varphi$; Γ, flow density; λ, thermal conductivity of the liquid; λ_w, thermal conductivity of the wall; T_s, saturation temperature; $Re = \Gamma/\nu\rho$; $Nu = (\alpha/\lambda)(\nu^2/g)^{0.33}$.

LITERATURE CITED

1. D. G. Thomas and L. G. Alexander, "Improved high-performance fluted tube for thin-film evaporation and condensation," Desalination, 8, 13 (1970).
2. L. G. Alexander and H. W. Hoffman, "Performance characteristics of corrugated tubes for vertical tube evaporators," Paper ASME, NHT-30 (1970).
3. V. G. Rifert, A. I. Butuzov, and D. N. Belik, "Investigation of heat transfer with evaporation of water in a film flowing down the interior of a vertical tube with a finely corrugated surface," in: Heat Physics and Heat Engineering [in Russian], No. 23, Naukova Dumka, Kiev (1973), p. 128.
4. B. M. Johnson, G. Iansen, and P. C. Owzarski, "Enhanced evaporating film heat transfer from corrugated surfaces," Paper ASME, HT-33 (1971).
5. V. G. Rifert, P. A. Barabash, B. V. Andreev, et al., "Mechanism and intensity of heat exchange with evaporation in a liquid film flowing along a corrugated surface," in: Heat and Mass Transfer [in Russian], Minsk, Vol. 3, Pt. 1 (1976), p. 184.
6. V. G. Rifert and P. A. Barabash, "Heat exchange with evaporation in a film flowing down a vertical corrugated surface," Izv. Vyssh. Uchebn. Zaved., Mashinostr., No. 11, 70 (1978).
7. V. G. Rifert and P. A. Barabash, "Laws governing the hydrodynamics and heat exchange with evaporation in a film on a vertical surface with wire enhancers," Inzh.-Fiz. Zh., 28, 905 (1975).
8. E. G. Vorontsov and Yu. M. Tananaiko, Heat Exchange in Liquid Films [in Russian], Tekhnika, Kiev (1972).