HEAT TRANSFER IN A VERTICAL EVAPORATION CIRCUIT AT LOW PRESSURES AND IN VACUO UNDER CONDITIONS OF VIBRATIONAL INSTABILITY

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Data relating to the heat-transfer coefficients associated with the boiling of viscous solutions in tubes and annular channels (covering wide ranges of thermal fluxes and apparent levels) under conditions of natural circulation are presented and generalized.

Investigations into the thermohydrodynamical characteristics of evaporators and concentrators are usually carried out in single-tube vertical evaporation circuits [1-3]. The manner in which the local heat-transfer coefficients α_2 vary along the tube is extremely complicated [1-3]; it depends on a large number of parameters and cannot always be described by traditional relationships [4, 5], nor can it be explained by existing simplified models of heat transfer in steady-state two-phase flows. In tubes and annular channels there is a marked fall in α_2 toward the tube outlet [1-3] for comparatively low thermal fluxes (heat flows) q, even for apparently favorable thermohydrodynamical conditions (low gravimetric vapor contents x).

This effect, which takes place for low and moderate thermal fluxes, may be explained by the partial or complete loss of contact between the heat-emitting wall and the liquid [6].

A dispersed annular type of two-phase flow usually occurs in the outlet sections of a reasonably long steam-generating channel at low pressures or in vacuo. In this case the mass balance of the liquid in the film close to the wall is determined by three processes: the evaporation of the liquid from the film, the carrying away of liquid from the film (by the gas), and the arrival of drops from the core of the flow by virtue of diffusion.

In accordance with these three processes, research workers have proposed three models of the heat-transfer crisis [7] (there are actually more models than this, but we shall only discuss the most important cases): 1) the drying of the film; 2) the rupture of the film; 3) the diffusion of drops.

The model based on the rupture of the film as a result of the detachment of liquid particles has no clear experimental foundation. The fact is that, when the boundary film thins, the waves in it vanish, and liquid particles are no longer carried away by the gas. Even at supersonic velocities of the mixture there is a liquid microlayer at the tube wall. When heat arrives and there is little or no diffusion of liquid drops from the gas core, the microfilm may dry up.

Visual examination [6] shows that the film does not dry up at once. First of all individual dry spots appear, their boundaries changing continuously. Between the dry spots the liquid flows in the form of rivulets.

Experiments show the existence of a fairly wide range of working parameters in which drops arriving from the core are unable to maintain an adequate supply to the liquid film close to the wall [6]. This restricts the range of applicability of the diffusion model.

The computing relationships determining the conditions for the development of the heat-transfer crisis based on the diffusion model and the model of film drying relate to the medium and high pressures normally associated with the motion of steam-and-water flows.

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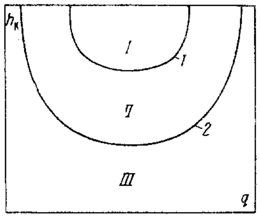

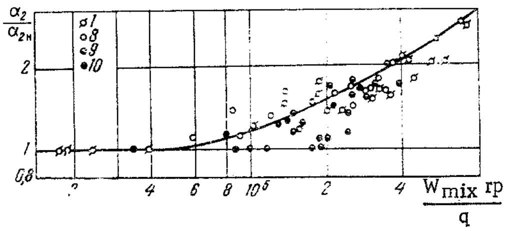

Fig. 1 Fig. 2

Fig. 1. Chart representing the operation of an evaporating circuit under conditions of natural circulation.

Fig. 2. The $\alpha_2/\alpha_{2H} = f(W_{mix} r \rho / q)$ relationship in the absence of well-defined low-frequency pulsations in the evaporating circuit. The characteristics of the experiments and the corre-responding notation are indicated in Table 1.

The relationship closest to our own conditions is

$$X_b^0 = 8.92 P^{0.15} (\rho W_0)^{-0.45}, \tag{1}$$

which is recommended for the conditions P = 6–50 kgf/cm^2 and ρW_0 = 500–2000 kg/(m^2 · sec) [8].

The experimental values of X_{yx} obtained in a circuit with natural circulation (l = 5 m, d = 28 mm) [8] were found to be 6.5–7.5 times lower than the limiting (boundary) vapor contents X_b^0 at which the heat-transfer crisis of the second kind occurred (i.e., at which the film dried up, no exchange of liquid taking place between the film and the gas core). The differences between the values of X_{yx} and X_b^0 are due firstly to the presence of low-frequency pulsations, and secondly to the large specific volumes of the vapor at atmospheric pressure. These latter are so great that the critical velocities of the vapor for which liquid is pulled strongly away from the boundary film are attained for very low mass contents of the vapor ($X < 0.1$).

Table 1 indicates the characteristic features of the experiments which were used for analysis and generalization.

On analyzing the results of these experiments, we come to the conclusion that the operation of a vertical evaporating circuit under conditions of natural circulation may be qualitatively expressed in the form of a map or chart (Fig. 1). The line 1 defines region I, involving slight pulsations in the flow of liquid. In region II, low-frequency pulsations with a period of the same order as the time required for the liquid to pass through the tube appear and extend very rapidly. Region II is also characterized by the fact that α_2 starts falling in the outlet sections of the tube. Region III may be called the region of well-defined critical phenomena: in the outlet sections α_2 falls sharply (on the left- and right-hand branches of curve 2), while the wall temperature increases (on the right-hand branch of curve 2). The pulsations in region III (on the right-hand branch of curve 2) are so well developed that liquid and vapor are ejected from the tube into the space beneath it. Region I is very limited; evaporators and concentrators often work in the region of vibrational instability II on the left-hand branch of curve 2.

In considering heat transfer over a fairly wide range of h_K and q it is essential to make proper allowance for effects associated with the hydrodynamic instability of the circuit.

Figure 2 employs the coordinates

$$\frac{\alpha_2}{\alpha_{2H}} = f\left(\frac{W_{mix} r \rho}{q}\right)$$

in order to express the results obtained in the absence of well-defined low-frequency pulsations. We see from the figure that local data regarding heat transfer to water and sugar solutions may be described by the well-known relationship [4]

$$\frac{\alpha_2}{\alpha_{2H}} = \left[1 + 1.5 \cdot 10^{-8} \left(\frac{W_{mix} r \rho}{q}\right)^{\frac{3}{2}}\right]^{\frac{1}{2}}. \tag{2}$$

TABLE 1. Characteristics of the Experiments Employed in the Generalization

Experiments	Experimental channel	l, m	d, m	Liquid	c_B, %	P_0, bar	h_K, %	$q \cdot 10^{-3}$, W/m^2	Notation
S.I. Tkachenko	Tube	5	0,028	Water	0	1	20—140	35,7—243	*1*
I.D. Stepchuka	The same	5	0,028	The same	0	0,6	20—100	177,5—220,5	*2*
A.N. Botina	"	5	0,028	"	0	0,5	30—60	65,3—166,0	*3*
V.Z. Globy	"	5	0,028	"	0	0,26	20—100	70,5—190	*4*
[1]	"	4,9	0,03	"	0	1	12—100	32—96,5	*5*
	"	4,9	0,03	Sugar solution	67	1	15—80	40—72,5	*6*
	"	1,8	0,03	Water	0	1	10—100	80—84,0	*7*
[2]	"	3,0	0,0337	The same	0	1	16—100	21,9—80,5	*8*
	"	3,0	0,0337	Sugar solution	30	1	27—100	18,7—73,8	*9*
	"	3,0	0,0337	The same	60	1	26—99	14,3—48,8	*10*
[3]	Annular channel	3,0	δ=1,85 mm	Water	0	1	25—100	12,0—58,0	*11*
	The same	3,0	δ=2,7 mm	The same	0	1	13—122	55—85,5	*12*
	"	3,0	δ=6,05 mm	"	0	1	33—94	8,6—64,0	*13*
	"	3,0	δ=6,05 mm	Sugar solution	30	1	44—57	15,8—41,0	*14*
	"	3,0	δ=6,05 mm	The same	57	0,527	46—63	8,0—55,0	*15*
	"	3,0	δ=2,7 mm	Water	0	1	17—97,5	11,3—56,8	*16*
	Bilateral heating Annular channel	3,0	δ=2,7 mm	Sugar solution	57	1,588	49—64	19,4—64,0	*17*

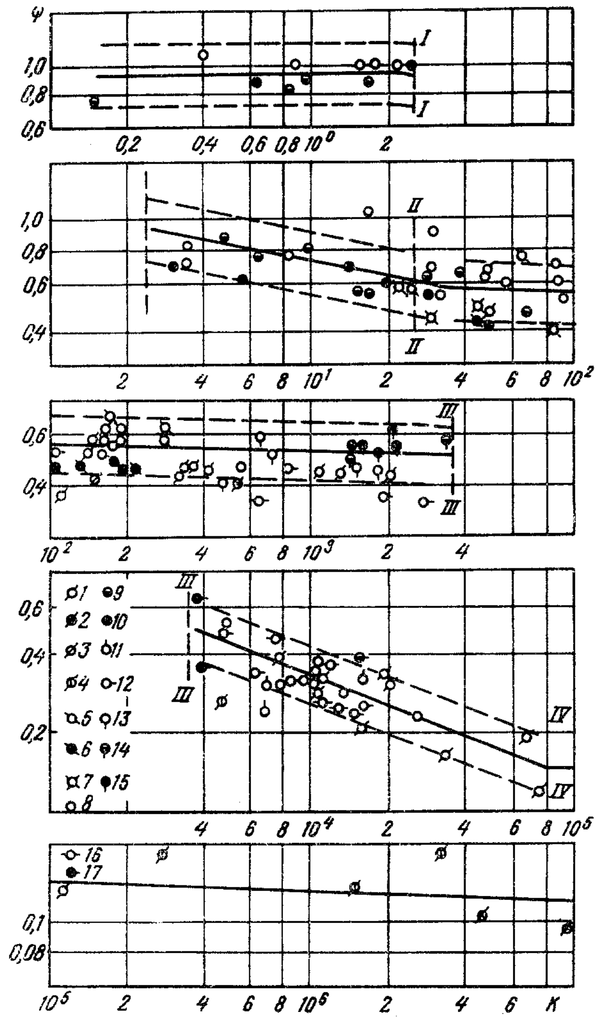

Fig. 3. The $\psi = f(K)$ relationship for the boiling of water and solutions in tubes and annular channels of an evaporation circuit with natural circulation. The characteristics and notation of the experiments are indicated in Table 1.

When low-frequency pulsations appear, the local α_2 start deviating from the calculated values.

A worsening of the heat transfer usually appears first of all in the outlet sections of the tube, i.e., critical phenomena develop primarily in these regions.

A model for the heat-transfer crisis in a steam-generating tube was proposed in [9] for the case of low pressures and pulsations inthe flow of liquid. In constructing this model, attention was paid to two facts: the flow perturbation took a certain time to pass down the tube, i.e., the pulsations of the medium at the tube inlet and outlet were shifted in phase; the pulsations in the flow of medium at the tube outlet were smoother than those at the inlet.

Under these conditions, waves corresponding both to an increase and to a decrease in the rate of flow of the medium travel along the steam-generating tube. At the outlet sections of the tube the film close to the wall may become extremely thin during the propagation of the diminishing-flow wave as a result of the imbalance between the inflow and outflow of liquid, and breaks may accordingly appear in the film. Thus, in addition to the known factors determining the onset of critical phenomena (the droplike decomposition of the film, the detachment of liquid from the film as a result of the pull of the gas, and the drying of the film) we now have another, namely, the "diminishing-flow wave," which, like the film-drying phenomenon, leads to the formation of dry spots; these dry spots (we believe) are less stable than those formed as a result of the drying of the film alone.

These spots will clearly vanish after the passage of the wave of increased flow along the channel, i.e., their time of existence is commensurable with the period of the pulsations. Perhaps we should draw attention to a slight arbitrariness involved in dividing the dry spots into two categories according to the principle of their formation. The fact is that the film breaks when it is so thin and the model of film-drying and the instability model are quite indistinguishable.

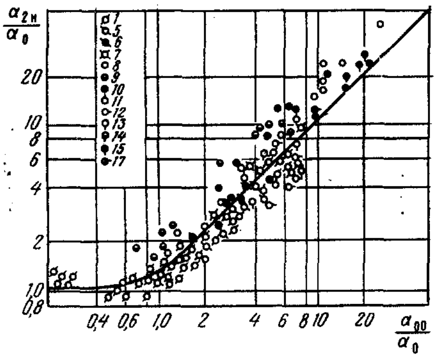

Fig. 4. The $\alpha_{2H}/\alpha_0 = f(\alpha_{00}/\alpha_0)$ relationship for the boiling of water and solutions in tubes and annular channels. The characteristics of the experiments and the notation are indicated in Table 1.

In setting up an analytical relationship describing heat transfer with unstable vapor – liquid flows, the decisive factor reducing heat transfer is that of the dry spots periodically appearing and vanishing under conditions of low-frequency pulsations.

Let the relative area of the dry spots at a certain instant of time be proportional to:

$$\frac{F_{d.s}}{F_{boil}} \sim \frac{l_{boil}}{\delta_{film}}, \tag{3}$$

while the relative period of existence of these spots is proportional to the relative period of the pulsations

$$\tau^* \sim \frac{T}{\tau}, \tag{4}$$

where

$$\tau = \delta_{film}\Big/\left(\frac{q}{r\rho}\right) = \delta_{film}/v. \tag{5}$$

Taking the period of low-frequency pulsations T as proportional to the time spent by the liquid in the tube ϑ we obtain

$$\tau^* = \vartheta v/\delta_{film} \tag{6}$$

The parameter determining the degree of use of the surface under conditions of low-frequency pulsations takes the form

$$K = \frac{F_{d.s.}}{F_{boil}}\tau^* = \frac{l_{boil}v\vartheta}{\delta^2_{film}} \tag{7}$$

or on putting $\delta_{film} \sim R(1-\varphi_{av})$ for a tube and $\delta_{film} \sim (R - r_{ex})(1-\varphi_{av})$ for an annular channel we have in general

$$K = \frac{l_{boil}v\vartheta}{(R - r_{ex})^2(1-\varphi_{av})^2}, \tag{8}$$

where

$$\vartheta = \frac{l_{ex}(1-\varphi_{ex}) + (l_{ex} - l_{boil})\varphi_{av}}{W_0}.$$

We determine φ_{av} for $W_{mix} < 50$ m / sec from the nomograms of [10], and for $W_{mix} > 50$ m / sec from the results of [11].

Under conditions of low-frequency pulsations the quantity α_2/α_{2H} depends on the parameters $W_{mix}r\rho/q$; $l_{boil}v\vartheta/[(R - r_{ex})^2(1-\varphi_{av})^2]$ and Eq. (2) takes the form

$$\frac{\alpha_2}{\alpha_{2H}} = \psi(K)\left[1 + 1.5\cdot 10^{-8}\left(\frac{W_{mix}r\rho}{q}\right)^{\frac{3}{2}}\right]^{\frac{1}{2}}. \tag{9}$$

Figure 3 gives the $\psi - K$ relationships in tubes and annular channels for the evaporation of water and sugar solutions (the characteristics and the notation of the experiments are indicated in Table 1). The horizontal part of the curve 0 – I corresponds to the first region in Fig. 1, parts I – II and II – III correspond to the second region, with different degrees of development of the pulsations, parts III – IV and IV – V to the third region, in which critical phenomena are clearly developed.

In order to make proper use of Eq. (9) we require data regarding α_{2H}. In order to calculate α_{2H} in the case of the boiling of water certain recommendations already exist [4]. In analyzing the experiments of Table 1 and Fig. 3 we made use of the experimental values of α_{2H}.

Figure 4 uses the coordinates

$$\frac{\alpha_{2H}}{\alpha_0} = f\left(\frac{\alpha_{00}}{\alpha_0}\right)$$

to represent the experiments generalized in Fig. 3. The data relating to α_{2H} values in tubes are described by an interpolation equation proposed by S. S. Kutateladze:

$$\frac{\alpha_{2H}}{\alpha_0} = \sqrt{1+\left(\frac{\alpha_{00}}{\alpha_0}\right)^2}, \tag{10}$$

$$\alpha_{00} = 0.7\alpha_{l.v} \; [4].$$

Data relating to the boiling of sugar solutions (30 and 60% dry material or DM), extracted from [2] and presented in Fig. 4, lay 50% above the curve. Data relating to annular slots [3] were satisfactorily described by Eq. (10) on replacing α_{2H} by

$$\alpha^*_{2H} = \alpha_{2H}\left(\frac{\delta}{D_{aut}}\right)^{0.4}.$$

The coefficient $\alpha_{l.v.}$ was calculated [12] by means of the equation

$$\mathrm{Nu} = 1{,}04\cdot 10^{-4}\mathrm{Pe}_u^{0,7}\mathrm{Ga}^{0,125}K_p^{0,7}, \tag{11a}$$

where

$$\mathrm{Nu} = \frac{\alpha_{l.v}}{\lambda}; \quad \mathrm{Pe}_u = \frac{q}{r\gamma''}\cdot\frac{l}{a}; \quad \mathrm{Ga} = \frac{gl^3}{\nu^2}; \quad K_p = \frac{P}{\sqrt{\sigma(\gamma'-\gamma'')}}. \tag{11b}$$

Equation (9) enables us not only to calculate heat transfer in a channel of specified geometrical size and shape within a wide range of the flow parameters but also to find the optimum geometrical size and shape of the channel for a liquid of specified physical properties.

The hydrodynamic characteristics and the intensity of heat transfer are related to one another more closely in evaporators and concentrators than in steam generators. The generalizing equation (9) clearly reflects this relationship.

NOTATION

P	is the pressure;
q	is the thermal flux (heat flow);
h_K	is the apparent piezometric level in the evaporator;
α_2	is the heat-transfer coefficient between the liquid and the wall of the tube;
$\alpha_{l.v.}$	is the heat-transfer coefficient in a large volume;
α_0	is the heat-transfer coefficient in a single-phase flow;
α_{00}	is the heat-transfer coefficient for boiling in tubes within a region in which the rate of circulation has no influence on the intensity of heat transfer in the course of boiling;
α_{2H}	is the heat-transfer coefficient at the beginning of the boiling section, in which $\alpha_{2H} = f(q, W_0)$;
X	is the gravimetric vapor content;
r	is the latent heat of vaporization;
ρ	is the density of the liquid;
γ', γ''	are the specific gravity of water and steam;
ν	is the kinematic viscosity of the liquid;
a	is the thermal diffusivity;
σ	is the surface tension at the liquid – vapor interface;
λ	is the thermal conductivity;
g	is the acceleration of Earth's gravity;
DM	is the percentage of dry materials in the solution;
$l = \sqrt{\sigma/\gamma'}$	is the linear dimension;

W_0, W_{mix}	is the rate of circulation of the mixture in the apparatus;
d, l	are the diameter and length of boiling tube;
R	is the internal radius of heated tube;
r_{ex}	is the external radius of inner tube (insertion-piece in the annular channel); for a tube with no insertion-piece $r_{ex} = 0$;
δ	is the width of the annular channel;
D_{aut}	is the arbitrary or effective automodel diameter (according to [3] $D_{aut} = 20$ mm);
F_{ds}	is the area of dry spots in the tube at a certain instant of time;
l_{boil}, F_{boil}	are the length and area of the boiling section of the tube;
δ_{film}	is the thickness of the liquid film averaged along the boiling part of the tube if all the liquid were concentrated at the heating wall;
φ_{av}	is the true volumetric vapor content averaged along the boiling part of the tube;
τ	is the time for the evaporation of the liquid boundary (wall) film;
T	is the period of the low-frequency pulsations in the flow of liquid in the steam-generating tube;
ϑ	is the time spent by the liquid in the tube.

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