HEAT-TRANSFER CRISIS DURING PULSATORY INSTABILITY IN A VERTICAL EVAPORATOR SYSTEM UNDER ATMOSPHERIC PRESSURE

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Universal relations are derived for determining the limits of crisis-free operation in a vertical evaporator system where liquid solutions with various physical properties vaporize under atmospheric pressure.

It has been established experimentally [1, 2] that in a vertical free-circulation system under low pressure or vacuum it is possible, at a certain combination of an entirely moderate thermal flux q and some apparent liquid level h (in terms of weight), to find a reduced coefficient of heat transfer between the wall of the heater tube and the boiling liquid in the exit zone.

In a free-circulation system the functions $\alpha_{2m} = f(h)$ and $\alpha_{2m} = f(w_0)$ at q = const or Δt = const have a maximum [1]. When a tube operates in the optimum mode (maximum α_{2m}), then a decrease in $h(w_0)$ at Δt = const or in q at h = const may cause a sharp drop in α_{2m} and an appreciable reduction in α_2 at the tube outlet.

It is to be noted that this crisis in the heat-transfer process is quite specific in nature; it occurs when q decreases. A crisis associated with an increasing q can also occur in a steam generator [3, 4].

In this study the authors' aim was to reveal the characteristics of crisis development in a vertical evaporator system during free circulation and then, based on these characteristics, to derive universal relations for determining the limits of crisis-free operation of steam generators and of evaporators. Both experimental and semiempirical methods were used for this purpose.

The experimental part of the study was done in a test stand consisting essentially of a vertical single-tube circulation system, with the boiler tube made of copper d = 28/32 mm in diameter and l = 5 m long.

During the tests under conditions of free circulation the total temperature drop Δt between the heating vapor and the boiling liquid varied from 5 to 95°C, the mass flow rate of water ρw_0 was varied from 0 to 850 kg/m^2·sec, and the apparent level h from 20 to 160%. The relative error in measuring q, ρw_0, and α_2 at q > 20,000 W/m^2 did not exceed 4.5, 9.0, and 7.0%, respectively.

Low-frequency pulsations were recorded on a model N-700 oscillograph. According to oscillograms of the flow rate and to visual observations through sight windows at the lower-end collector, a development of crisis is necessarily accompanied by a development of low-frequency pulsations. At full crisis, when α_2 is distinctly low in the exit zone, the pulsations become so strong that all the liquid is periodically pushed out of the tube into the space below and large vapor bubbles are expelled at the same time. Known methods of preventing pulsations and thus avoiding crises have not yielded satisfactory results in a vertical free-circulation system.

It must be noted that, under a low pressure, pulsations in two-phase streams were observed at any velocity of the mixture flow [5].

For analyzing the characteristics of crisis development in a vertical evaporator system under atmospheric pressure, we used data from several sources. These data are listed here in Table 1, namely the lengths and the diameters (l, d) of boiler tubes along with the ranges of h, q, w_0, w_0'', and x values at the limits of crisis-free operation.

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TABLE 1. Test Performance Characteristics of Evaporator Systems at the Limits of Crisis-Free Operation

Cited source in the technical literature	Liquid	l, m	d, mm	h, %	$q \cdot 10^{-3}$ W/m²	w_0, m/sec	w_0'', m/sec	x	Designated reference number
Tests by authors of [2]	Water	5	28	60—100	210—240	0,28—0,40	114—131	0,20—0,24	I
	Water	3	33,7	22—37	17—76	0,01—0,05	4,6—21	0,25—0,28	II
	30% sugar solution	3	33,7	36—69	10—63	0,01—0,066	2,7—17	0,138—0,148	III
	60% sugar solution	3	33,7	45—77	10—45	0,02—0,08	2,7—12,2	0,063—0,066	IV
[3,4]	Water	1,5	19	27—100	210—695	0,70—2,35	50—168	0,042—0,043	V
			33	35—100	128—545	0,40—1,85	18—76	0,025—0,027	VI
			45	38—100	90—465	0,30—1,55	9—47	0,019—0,02	VII
	20% NaCl solution	1,5	19	50—100	210—695	0,70—2,35	50—168	0,038	VIII
	60% NH_4NO_3 solution	1,5	19	50—100	210—440	0,70—1,44	50—106	0,036—0,037	IX

The limiting values of these parameters correspond in [3, 4] to conditions where the $\alpha_{2m} = f(q)$ curve for h = const bends sharply, while in [2] they correspond to the point where α_{2m} begins to decrease with decreasing h at q = const or Δt = const. In analyzing the tests performed with a system comprising a boiler tube (d = 28 mm and l = 5 m), the authors noticed a crisis developing slowly at a rate which could be estimated from the shape of the $q = f(\Delta t)$, $\alpha_2 = f(l)$, and $\Delta t_e/\Delta t_i = f(q)$ curves.

According to our data, the curves in Fig. 1 correspond to conditions where the ratio $\Delta t_e/\Delta t_i$ increases sharply, i.e., where the temperature of the tube wall rises appreciably in the exit zone.

In Fig. 1 we have plotted, according to the data by various authors, the boundary curves which separate crisis and crisis-free operation of the system during free circulation.

Crisis begins to develop when the parameter values fall below the range marked by these curves. In order to effect a crisis according to curves 1-3 for $dh/dq < 0$, it is necessary that one of the two parameters h and q or both simultaneously decrease.

A crisis according to curves 4-9 for $dh/dq > 0$ can occur if h and or q increases.

The combined effect of changes in q and h can vary, depending on both static and dynamic system characteristics. At the same time, the cause of a crisis development within the ranges of $dh/dq < 0$ and $dh/dq > 0$ curves is the same: a breakdown of the contact between boiling liquid and heating tube wall.

The simplified concepts which have been developed in the technical literature pertaining to crisis development in steam generators and in evaporators (film breakdown by action of the vapor stream, or reduction of liquid supply reserve) do not fully explain the given phenomenon; generalizations on the basis of these concepts alone are limited in scope.

In [6-9 et al.], on the crisis in heat transfer under high pressures, definite conclusions were drawn concerning the effect of pulsations on the critical thermal flux. Under low pressure, when the pulsations are strongest, they simply must be considered in any attempt to analyze the thermal and the hydrodynamic aspects of this process.

In [10] for the first time serious attention was paid to the effect of instability on the thermo-hydrodynamics in boiler tubes of steam generators. In this study here we propose a model of the heat-transfer crisis in an evaporator tube under low pressure during pulsations of the liquid flow rate.

As a rule, the heat-transfer deteriorates first in the exit zone. When this happens during strong pulsations, it can be explained as follows. A change in the flow rate at the tube entrance is in phase

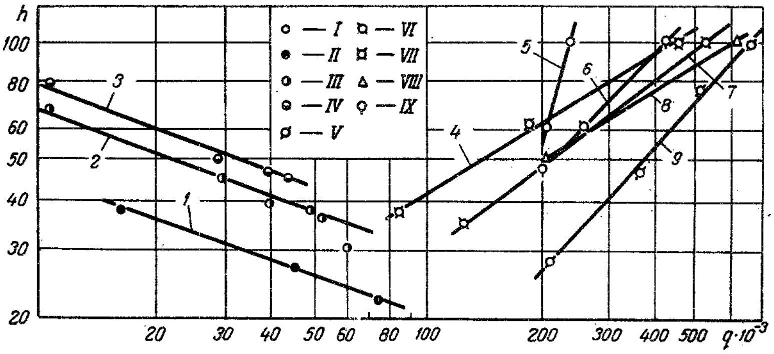

Fig. 1. Curves representing the limits of crisis-free operation, in h (%)–q (W/m^2) coordinates (designated according to the last column in Table 1).

opposition to the change of the flow rate at the tube exit [9]. In view of this, it is valid to assume that waves of increases and decreases in the flow rate travel continuously through the tube.

While such a wave is transmitted, the liquid film at the tube wall may become very thin at the tube exit and, as a result, may break down in some places.

Under low pressure or vacuum the vapor velocity in steam generator or evaporator tubes becomes high. A crisis develops most often when the mixture flows in the film-emulsion mode.

The mass transfer during a film-emulsion flow is shown schematically in Fig. 2a. Along a tentatively singled out tube exit segment of length Δl at time $\tau = 0$ the thickness of the liquid film at the wall is δ_f^0. Through section I–I there flows a volume of liquid V_1 into the film and through section II–II there flows a volume of liquid V_2 out of the film. Liquid evaporates from the film surface at a rate $v = q/(r\rho)$ and amount J_1 in the form of droplets is carried away by the vapor stream, while an amount J_2 in the form of droplets precipitates from the vapor stream into the film.

On this given segment Δl we assume, to the first approximation, the simplified law of change of flow rate V (Fig. 2b). With the time delay taken into account, V_1 and V_2 are related as follows:

$$V_2 - V_1 = \frac{A_V}{T/4}\Delta\tau, \tag{1}$$

where $\Delta\tau$ may be roughly estimated on the basis of the relation

$$\Delta\tau = \frac{\Delta l\,(1-\varphi)}{w_0}. \tag{2}$$

Since Δl represents the length of a definite exit zone in the tube, hence $\Delta\tau$ should be smaller than ϑ by an order of magnitude.

We now consider the change in the quantity of liquid within the time interval from 0 to T/4. At $\tau =$ T/4 there remains in the film

$$\Delta Q_f = \Delta Q_f^0 - \int_0^{T/4}(V_2 - V_1)\,d\tau - \int_0^{T/4} v\pi d\Delta l d\tau - \int_0^{T/4}(J_1 - J_2)\,d\tau, \tag{3}$$

of liquid.

In Eq. (3)

$$\Delta Q_f^0 = \delta_f^0\,\pi d\Delta l, \tag{4}$$

$$\Delta Q_f = \delta_f\,\pi d\Delta l. \tag{5}$$

As soon as $\Delta Q_f = \Delta Q_f^*$ ($\Delta Q_f^* = \delta_f^*\pi d\Delta l$), the film breaks down. After integrating Eq. (3), considering also (1), (2), (4), and (5), we obtain the condition for the start of a crisis:

$$(\delta^0 - \delta_f^*) - \frac{1}{\pi d}\cdot\frac{A_V}{w_0}(1-\varphi) - \frac{J_1 - J_2}{\pi d\Delta l}\cdot\frac{T}{4} = v\frac{T}{4}. \tag{6}$$

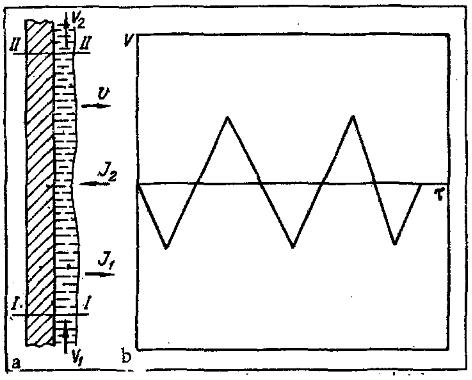

Fig. 2

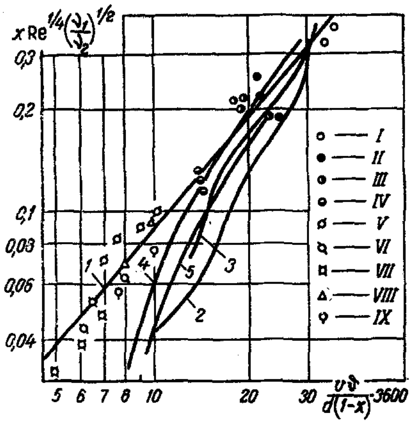

Fig. 3

Fig. 2. Schematic diagram of mass transfer during film-emulsion flow.

Fig. 3. Generalization of crisis data in coordinates $x\mathrm{Re}^{1/4}(\nu_1/\nu_2)^{1/2}$, $v\vartheta/d(1-x)$: 1) generalizing curve (designations according to Table 1); 2) h = 100%; 3) 60%, based on our data; 4) $\Delta t = 20°C$; 5) $\Delta t = 9°C$, based on data in [2].

The quantities on the left-hand side of (6) are little known even under nonpulsating conditions.

Some information about how φ, δ_f^0, δ_f^*, J_1, and J_2 vary under low pressure is given in [11-13 et al.]. On the basis of these data, pertaining to the performance of steam generators and of evaporators, we assume that

$$\left[(\delta^0_f-\delta^*_f)-\frac{1}{\pi d}\cdot\frac{A_V}{w_0}(1-\varphi)-\frac{J_1-J_2}{\pi d\Delta l}\cdot\frac{T}{4}\right]\sim(1-x)\,df\left(x,\ \mathrm{Re},\ \frac{\nu_1}{\nu_2},\ \mathrm{We}\right), \quad (7)$$

and then, according to [9], we estimate

$$\frac{T}{4}\sim\vartheta, \quad (8)$$

where

$$\vartheta=\frac{l(1-\varphi_m)+l_{ec}\varphi_m}{w_0}. \quad (9)$$

The dimensionless complex defining the limit of crisis-free operation is here

$$\frac{(1-x)\,df\left(x,\ \mathrm{Re},\ \frac{\nu_1}{\nu_2},\ \mathrm{We}\right)}{v\vartheta}. \quad (10)$$

The results of test data evaluation (see Table 1) in coordinates

$$x\,\mathrm{Re}^{1/4}\left(\frac{\nu_1}{\nu_2}\right)^{1/2}=f\left[\frac{v\vartheta}{d(1-x)}\right]. \quad (11)$$

are shown in Fig. 3. The Weber number is not included in this generalization, inasmuch as the surface tension σ varied only very slightly in all the tests (see Table 1).

In generalizing, besides the earlier known dimensionless parameters, we have introduced a new parameter $K_p = (1-x)d/3600v\vartheta$ characterizing the development of a crisis under pulsating conditions.

The deviation of most test points from the averaging curve does not exceed ±20%. Two points fall outside the range of this generalization, namely those corresponging to q = 10,000 W/m^2, $w_0'' = 2.7$ m/sec, for 30 and 60% sugar in water [2].

In this case the flow in the tube becomes ballistic and the entire process pattern differs from our model. Furthermore, increasing the pulsation period has a marked effect on the crisis development only up to a certain length of this period [8]. The dwell time of liquid in the tube at q = 10,000 W/m^2 for 30 or 60% sugar in water ($\vartheta = 45$ or 32 sec, respectively) exceeds appreciably a certain limiting pulsation period (T = 6 sec) indicated in [8].

Curves 2 and 3 (our test data with d = 28 mm and l = 5 m) in Fig. 3 correspond to h = const and, as q increases, they approach the universal curve 1 and intersect it at certain values of q. Curves 4 and 5 (according to the data in [2]) correspond to Δt = const and, as h decreases, they approach curve 1 and intersect it at certain values (optimum) of h.

When

$$x\,\mathrm{Re}^{1/4}(\nu_1/\nu_2)^{1/2}K_p^{1.2} \gtrsim 0{,}0054 \qquad (12)$$

then crisis effects occur in the evaporator system and develop to the extent that they can be recorded by techniques shown here earlier. Relation (12) is valid when the system operates along curves on the left and on the right side in Fig. 1.

It must be noted, in conclusion, that our crisis model explains the causes of a reduced α_2 in the exit zone in boiler tubes of steam generators and of evaporators when the reserve of liquid supply seems far from critical [1, 2].

Relation (12) agrees qualitatively with the test data which pertain to operation without low-frequency pulsations [6-9]. In this case there occur only high-frequency pulsations with a period shorter by an order of magnitude. In accordance with (12), crisis occurs at a higher thermal flux level when the pulsation period T decreases.

In (12) the period T is expressed in terms of ϑ.

NOTATION

τ	is the time, sec;
T	is the period of flow rate pulsations, sec;
ϑ	is the dwell time of liquid in the boiler tube, sec;
ρ	is the density of liquid, kg/m^3;
ν_1, ν_2	are the kinematic viscosity of liquid and of vapor, respectively, m^2/sec;
r	is the latent heat of evaporation, J/kg;
α_{2m}	is the mean-over-the-length coefficient of heat transfer from tube wall to liquid, W/m$^2\cdot$deg;
Δt	is the temperature drop from the heating vapor to the boiling liquid, °C;
Δt_i, Δt_e	are the temperature drop from the tube wall to the boiling liquid in the initial boiling zone and in the exit zone, respectively, °C;
w_0	is the circulation velocity, m/sec;
w_0''	is the referred velocity of vapor at the tube exit, m/sec;
A_V	is the amplitude of flow rate pulsations in the liquid at the exit, m^3/sec;
l_{ec}	is the length of economizer zone, m;
δ_f, δ_f^0, δ_f^*	are the thickness of liquid film along segment Δl at τ = T/4, at τ = 0, and at the instant of breakdown, m;
ΔQ_f, ΔQ_f^0, ΔQ_f^*	are the volume of liquid in the film along segment Δl at τ = T/4, at τ = 0, and at the instant of breakdown, m^3;
x	is the mass vapor content at the tube exit;
φ	is the true volume content of gas at the tube exit (segment Δl);
φ_m	is the mean-over-the-length (boiling zone) volume content of gas;
$\mathrm{Re} = w_0 d/\nu_1$	is the Reynolds number;
We	is the Weber number.

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