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HEAT-EXCHANGE CRISIS IN THERMOSIPHON CIRCUITS

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The article discusses the analogy and distinguishing features of heat-exchange crises in steam-generating channels of thermosiphon circuits. A chart of the crisis phenomena in channels with natural and forced circulation is presented.

At present various designs of two-phase thermosiphons operating on the principle of closed circulation circuits are widely used. Determining the limits within which these devices are able to operate requires studying the conditions under which heat-exchange crisis originate in two-phase streams with natural circulation of the working medium. Although there is a great variety of applications of the above-mentioned method of circulation, the problem of heat-exchange crises under the given conditions has been studied quite insufficiently.

It is currently assumed that in circuits with natural circulation of the heat-transfer agent (analogously to the case of forced motion) the critical thermal loads have not only to be limited by crises of boiling of the first kind but also by crises of heat exchange of the second kind which are connected with the complete evaporation of the liquid film next to the wall. In addition, the known results of investigations of crises of heat exchange in vaporizer circuits and evaporators indicate that there are considerable quantitative differences between the regularities of crisis phenomena under the given conditions; this is explained by a number of authors by the existence of vibrational instability and low-frequency pulsations in the circuit. The available experimental data on crises of heat exchange in thermosiphons with internal down channel also indicate that the pattern of crisis phenomena is a complex one.

A promising direction in the solution of the above problem may apparently be the successive study of the conditions of the onset of crisis phenomena in the simplest circuits with free convection and their comparison with the basic research of these phenomena under conditions of forced motion. At the first stage it is important to have reliable experimental results on crises of heat exchange where circuits with natural circulation operate in regimes

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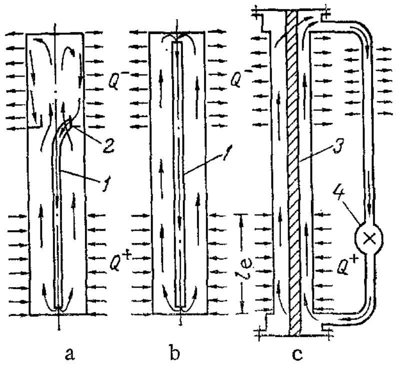

Fig. 1

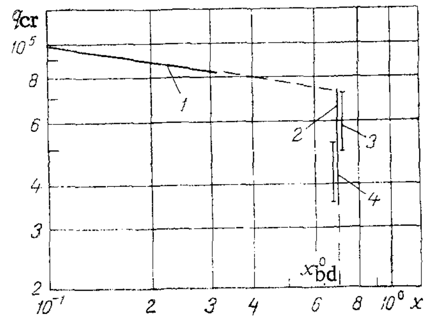

Fig. 2

Fig. 1. Diagram of the experimental thermosiphon circuits: 1) arterial insert (down channel of the circuit); 2) separation pocket; 3) simulator of the arterial insert; 4) turbine-type flow sensor; Q^+) admission; Q^-) removal of heat.

Fig. 2. Identification of the crisis of heat exchange of the second kind in the steam-generating channel of a thermosiphon circuit ($x = x_{bd} = \text{const}$). The heat-transfer agent is Freon-11, $P = 5.5 \cdot 10^5$ Pa, $\rho' w_0 = 200$ kg/m$^2\cdot$sec; 1) linearization of the theoretical dependence [3] for critical thermal fluxes in annular channels with $x \ll x^0_{bd}$; 2) averaging of the experimental data with respect to the crisis of heat exchange of the second kind in the annular channel of a thermosiphon circuit (see Fig. 1c); $l_e = 0.7$–1.2 m, channel: 3) 10×16 mm; 4) 12×16 mm. q_{cr}, W/m^2.

without pulsations. The existing experimental data indicate that similar regimes are implemented in thermosiphon circuits with independent admission of the heat flux and internal down channel. Investigations were therefore carried out to find the regularities of crises of heat exchange in thermosiphon circuits by direct experimental determination of the thermal and circulational limit characteristics of the circuit.

The investigations were carried out on models of thermosiphons (Fig. 1) in which the simplest arrangements of circulation circuits were applied: the evaporating section (a) and also the evaporating and condensation sections (b) were situated in the ascending branch. For convenience of controlling and checking the flow rate of the liquid phase of the heat-transfer agent, thermosiphons with down channel, situated outside the shell of the thermosiphon (c), were used in the experiments. The annular shape of the channel was simulated with the aid of the simulator of the arterial insert. In all cases the required heat was obtained by resistance heating of the pipe wall.

In the investigations we used the traditional temperature method of recording crisis phenomena. The crisis state was determined from the irreversible temperature increase of the outer pipe wall at the end of the evaporation section. The parameters of the limit heat transfer were determined at the steady state preceding the last (crisis) loading. In the experiments we used Freon-11, ethanol, and water as working media. As a result of the investigations we determined the critical values of the het flux densities and mass discharge steam quantities with different values of mass velocity and pressure of the working medium.

An analysis of the obtained data in the traditional system of coordinates $q_{cr} \to x_{bd}$ (Fig. 2) led to the conclusion that beginning at some length of the section of heat admission ($l_e \gtrsim 0.7$ m), the heat flux density on the heating surface is not a characteristic magnitude determining the conditions of origin of crises of heat exchange. Under these conditions, with $\rho w = \text{const}$ and $P = \text{const}$, the crisis of heat exchange is unambiguously characterized by the magnitude of the mass discharge steam quantity x_{bd}. This indicates that under the given conditions it is possible that there exist crises of heat exchange characterized by the conditions of longitudinal heat and mass transfer and called crises of heat exchange of the second kind. However, an analysis of the dependence of this characteristic on the mass velocity of the heat-transfer agent enabled us to establish its substantial deviation from the corresponding dependence for conditions of forced motion. These deviations occur in the region

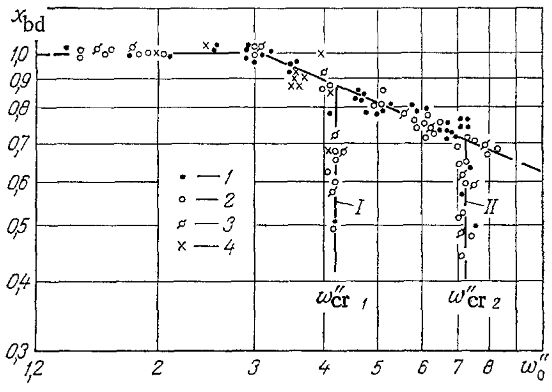

Fig. 3

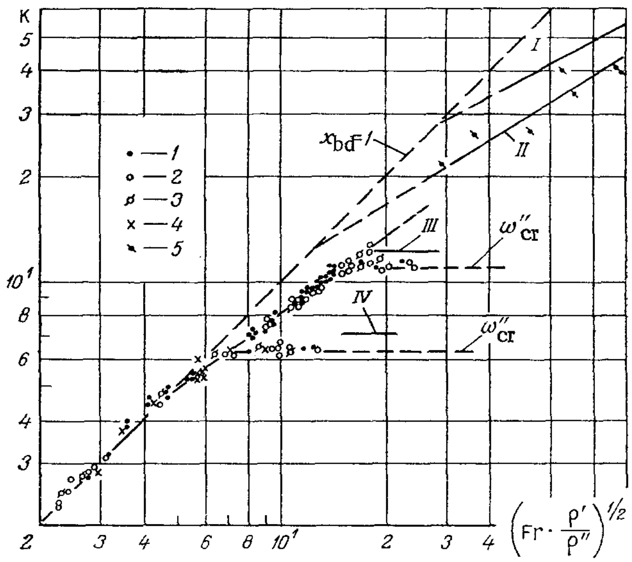

Fig. 4

Fig. 3. Hydrodynamic crisis effects of axial heat and mass transfer in a thermosiphon circuit (see Fig. 1c) with natural circulation of the heat-transfer agent ($w''_0 = w''_{0cr}$ = const). Heat-transfer agent is Freon-11, $P = 5.5 \cdot 10^5$ Pa, channel: 1) 16 × 12 mm, 2-4) 16 × 10 mm; length of the section of heat admission: 1, 2, 4) 1.2 m; 3) 0.7 m; heat removal: 1-3) on the ascending branch of the circuit; 4) on the descending branch of the circuit; I) $\varepsilon_e < 0.75$; II) $\varepsilon_e > 0.75$; $\varepsilon_r < 0.2$. w''_0, m/sec.

Fig. 4. Generalized comparison of the characteristic of crisis effects in steam-generating channels with natural and forced calculation of the heat-transfer agent: 1-4) thermosiphon circulation circuit, notation analogous to that in Fig. 3; 5) crisis of hydraulic resistance [4]; I) crises of heat exchange of the second kind, $x_{cr} = x^0_{bd}$ [5]; II) crises of hydraulic resistance, $x_{cr} = x_{\Delta p}$ [4]; III, IV) averaging of the experimental data of [1] with respect to crises in thermosiphon circuits type *a* (see Fig. 1).

of relatively large values of ρw, and they indicate that the nature of crises of heat exchange changes when the speed of circulation of the heat-transfer agent increases. To shed light on the possible causes of the above-mentioned deviations, we analyzed the experimental data in different coordinate systems. In addition to x_{bd} and ρw, we used the reduced velocity of the vapor phase w''_0 at the outlet from the heated section of the thermosiphon, which is correlated with x_{bd} and ρw. Representation of the experimental data in the system of coordinates $x_{bd} \rightarrow w''_0$ (Fig. 3) led to the conclusion that there is a range of parameters within which x_{bd} is not a magnitude determining the onset of crises of heat exchange. Under these conditions the origin of crises of heat exchange is unambiguously correlated only with the magnitude of the reduced steam velocity w''_0. This circumstance is a substantial factor indicating a change in the nature of crises of heat exchange in a circuit with natural circulation compared with the known crises of heat exchange of the second kind. The experimentally obtained differences in the level of the critical values of the reduced speed of the steam flow w''_{0cr1} and w''_{0cr2} for the given heat-transfer agent depend solely on the saturation pressure and not on the other parameters of the vapor—liquid system. This shows that in circuits with natural circulation operating in regimes without pulsations, there occur crises of heat exchange unconnected with the complete evaporation of the liquid film next to the wall but due to purely hydrodynamic effects of the phases in two-phase flow which, in the final analysis, lead to local drying of the heat-exchange surface. The crisis phenomena thus established (in comparison with the known crises of the first and second kinds) represent a third group of crises of heat exchange manifesting themselves solely under conditions of unsettled circulation velocities of the working medium and taking place in circuits with natural circulation of the heat-transfer agent. The mechanism of these crisis phenomena requires further study. However, material accumulated by now made it possible to establish the conditions of their manifestation in thermosiphon circuits of various setups and to provide generalized relations for calculating them [1, 2].

A modified generalized representation of the obtained experimental data and their comparison with the dependences for crises of heat exchange of the second kind provide a pattern of the characteristic crisis phenomena taking place in an ascending two-phase stream and manifesting themselves in the dependence on the method of circulation of the working medium (Fig. 4). It can be seen from the figure that the characteristics of crisis phenomena of the second-kind type in channels with natural and forced circulation of the working medium are quite satisfactorily qualitatively correlated with each other. If the speed of circulation in thermosiphon circuits is low, the crisis state of complete evaporation of the working medium (x_{bd} = 1) becomes a reality. On the other hand, the most substantial limitations of effective heat transfer in the range of flow parameters that are specific features of thermosiphon circuits are purely hydrodynamic crisis effects characterized by the conditions w''_{0cr} = const and occurring at relatively higher speeds of circulation. For determining under which conditions some purely hydrodynamic crisis phenomenon manifests itself, there exist empirical estimates (see, e.g., [6] dealing with thermosiphons schematically shown in Fig. 1b). The generalizing importance of the presented processing holds for the range of the practically incompressible state of the working medium: $K_p < 4 \cdot 10^4$.

NOTATION

l_e, length of the section of heat admission of the thermosiphon; w''_0, reduced velocity of the vapor phase of the flow; w_0, speed of circulation of the heat-transfer agent; P, pressure of the heat-transfer agent; q, surface density of the heat flow; x, mass flow rate of the vapor content; $K = w''_{0cr}(\rho'')^{0.5}[\sigma g(\rho' - \rho'')]^{-0.25}$, S. S. Kutateladze criterion of hydrodynamic stability; $K_p = P\delta/\sigma$, criterion of pressure; $\delta = [\sigma/g(\rho' - \rho'')]^{0.5}$, Laplace constant; ρ', ρ'', density of liquid and vapor, respectively; σ, surface tension; ε_e, ε_r, degree of filling of the evaporation section and of the entire lift channel, respectively. Subscripts: cr, critical; bd, boundary.

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