9. D. A. Frank-Kamenetskii, Diffusion and Heat Transfer in Chemical Kinetics [in Russian], Moscow (1967).

LIMITING HEAT TRANSFER IN HORIZONTAL TWO-PHASE THERMOSIPHON

M. K. Bezrodnyi and V. M. Podgoretskii

UDC 536.27

Experimental results on the heat-transfer crisis in a horizontal thermosiphon with steam heating are outlined.

The wide use of autonomous heat-transfer devices – closed two-phase thermosiphons – entails comprehensive investigation of their characteristics in different operating conditions. The experimental material accumulated on the thermal and hydrodynamic characteristics of thermosiphons is basically related to the specific conditions of heat supply corresponding to boundary conditions of heat supply corresponding to boundary conditions of the second kind, which are modeled by means of electrical heating. Such rigorous heating conditions do not allow reliable experimental data to be obtained on the maximum heat-transfer capability in investigating inclined and horizontal thermosiphons [1-3], since this leads to premature heating of the evaporator wall along the upper generatrix on account of the stratification of the two-phase flow. To obtain experimental data on the limiting operating conditions of horzontal thermosiphons, investigations are undertaken with heat-supply boundary conditions of the third kind: steam heating.

The experimental apparatus (Fig. 1) includes: steam-generator 1, steam-heating chamber 2, experimental thermosiphon 3, and heat exchanger 4. The steam generator consists of a vertical tube 5 in which heat is liberated on account of direct transmission of a constant current and steam is generated, separation chamber 6, and external discharge channel 7. Heat supply to the thermosiphon evaporator is ensured on account of condensation of the steam ob-

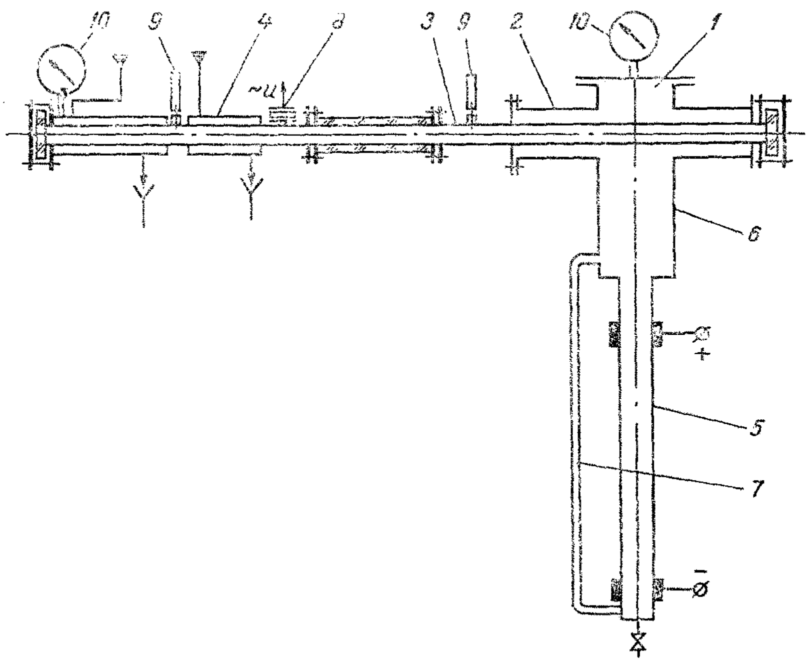

Fig. 1. Experimental apparatus.

Fiftieth-Anniversary-of-the-October-Revolution Kiev Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 58, No. 1, pp. 63-67, January, 1990. Original article submitted July 25, 1988.

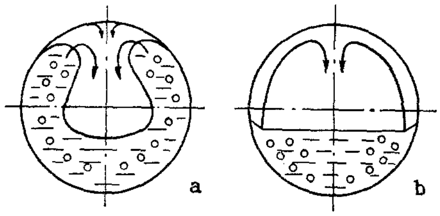

Fig. 2. Visual patterns of phase interface in thermosiphon evaporator: a) boiling of Freon-11 at relatively high pressures; b) boiling of water at low pressure.

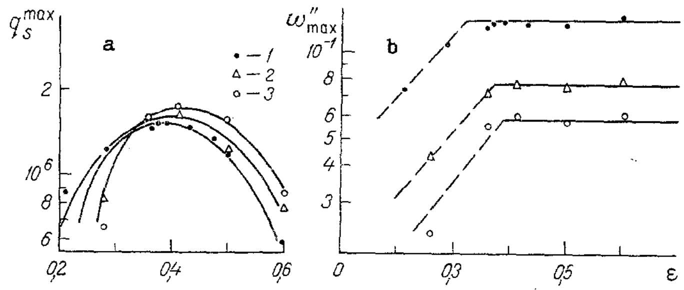

Fig. 3. Limiting characteristics of the heat-transfer capability of the thermosiphon as a function of the pressure and degree of filling (heat carrier: Freon-11): a) for the maximum heat-flux density in the thermosiphon cross section; b) for the critical steam velocity in the steam-flow cross section; P = 0.2 MPa (1), 0.4 (2), 0.6 (3), q_s^{max}, W/m².

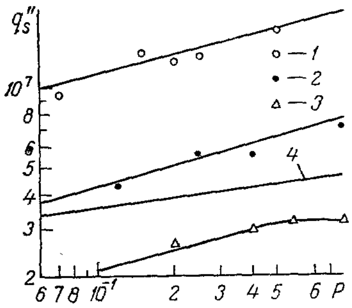

Fig. 4

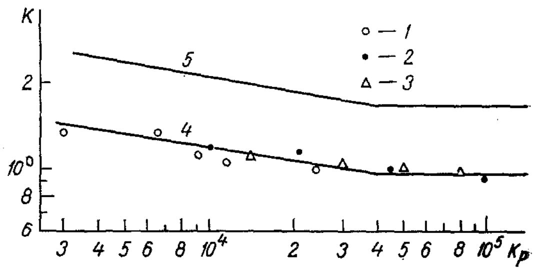

Fig. 5

Fig. 4. Dependence of the limiting thermal load on the pressure with an optimal degree of filling of the thermosiphon: 1) water; 2) propyl alcohol; 3) Freon-11; 4) water [1, 2].

Fig. 5. Dependence of the stability number of the pressure number: 1) water; 2) propyl alcohol; 3) Freon-11; 4, 5) lower and upper limits of "flooding" [5].

tained in the steam generator. The heat extraction from the thermosiphon is by means of cooling water in a sectioned condenser—heat exchanger 4. Glass windows are inserted in the middle and at the ends of the experimental thermosiphon to permit visualization of the flow conditions. Monitoring and identification of the flow conditions in the thermosiphon is by means of photorecording, pressure-pulsation sensor 8, and conductometric sensors for measuring the height of the liquid stream 9. Pressure monitoring in the steam generator and the thermosiphon is by means of standard manometers 10. The experimental thermosiphon is of internal diameter 27 mm and length 2.5 m. The length of the evaporation, transport, and condensation zones is 0.65, 1, and 0.85 m, respectively. The characteristic flow conditions in the thermosiphon are achieved by varying the electrical load in the steam generator, as well as the flow rate and temperature of the surrounding water supplied to the condenser.

The experimental method consists in stepwise change in electrical load in the steam generator. On account of the change in temperature difference between the heat carrier in the first and second loop, the heat flux supplied to the evaporation zone of the thermosiphon changes here. The pressure in the thermosiphon is regulated by changing the flow rate of cooling water, and is maintained constant in each series of experiments.

The results of visual observations indicate the existence of a series of specific structural forms of flow in a horizontal thermosiphon, which are determined by the degree of filling, the thermal load, and the pressure in the thermosiphon. Different visual patterns occur here in the evaporative and transport sections of the thermosiphon.

Visualization of the steam generation in the evaporative section indicates the existence of separate flow conditions of the boiling liquid and the vapor flow, in the general case. However, the form of the interface depends on the process parameters and the kind of liquid, and may vary from plane, which is characterized of purely stratified flow (Freon-11, relatively high pressure) to almost cylindrical, which is characteristic of annular flow conditions (water, low pressure). Swelling of the liquid layer and retreat of the two-phase layer to the generatrix is observed here, with periodic formaiton of crosspieces and the presence of a stable steam rod (Fig. 2a). Increase in pressure leads to change in the pattern of water boiling, to a form analogous to Fig. 2b.

In the transport section, stream flow conditions of opposing steam and liquid fluxes are basically observed, with change in the form of the interface depending on the velocity of the steam flux (thermal load). With increase in steam velocity, the stream surface changes from smooth to undulatory, with the formation of capillary—gravitational waves at the inverted upper layers of the liquid. With sufficient degrees of filling (established below), flow development ends with stability loss of the undulatory structure, breakaway of the liquid film, and the formation of a liquid sample covering the whole thermosiphon cross section, which is entrained in the condenser. Stability loss of the flow has a clearly expressed crisis character, is the upper limit of the "flooding" conditions, and bounds the working region of thermosiphon parameters.

The quantiative characteristics of the limiting heat transfer are investigated on the basis of the dependence of the temperature difference $\Delta T = T_1 - T_2$ between the heat carrier in the steam generator and the thermosiphon on the heat flux supplied. The sharp increase in ΔT in this dependence determines the critical thermal load, which is fixed using a pressure-pulsation sensor. The specific charcteristics of the limiting heat transfer are calculated form the electrical power, taking account of the experimental heat losses in the surrounding medium. The experimental dependence of the limiting thermal load q_s^{max} referred to the total channel cross section on the degree of filling with intermediate heat carrier ε and the Freon-11 pressure is shown in Fig. 3a. As follows from Fig. 3a, the degree of filling of the thermosiphon has a clearly expressed optimum depending on the pressure P. The optimal-filling function $\varepsilon^{opt} = f(P)$ is the boundary between two critical phenomena determining the operating limit of the thermosiphon. Inadequate filling of the thermosiphon with heat carrier leads to drying of the evaporation-zone surface, which sharply reduces its heat-transfer capability. The given conditions of thermosiphon operation have good functions of the thermostabilized thermal diode. Overfilling of the thermosiphon with liquid leads to earlier onset of heat-transfer crisis, which evidently occurs on account of freezing of the channel cross section by the excess of liquid phase. To illustrate these hypotheses, the characteristics of heat-transfer crisis obtained are recalculated for the critical steam velocity in the active cross section of the steam flux corresponding to the part of the channel cross section remaining after subtraction of the liquid-stream cross section; as shown by measurements, this section is approximately equal to $(1 - \varepsilon)$ (Fig. 3b).

It is evident from Fig. 3b that, beginning at a certain value of ε, the critical velocity of the steam is self-similar relative to the degree of filling, which indicates that the conditions of limiting heat transfer are independent of the heat-transfer processes in the evaporator. In this case, the fundamental constraint on the limiting heat transfer in the horizontal thermosiphon is the disruption of stability of the liquid and steam counterflows in the transport section of the device, the characteristic of which is w_{cr}.

The dependences of the limiting heat-transfer characteristics q_s^{max} on the pressure, with optimal filling values, is shown in Fig. 4. Comparison of the experimental data for water with the data of [1, 2], obtained in horizontal thermosiphons with electrical heating, shows that the heat-transfer capability of the thermosiphon is significantly higher with steam heating. It is evident that this difference is explained in that noncritical operation of the thermosiphon is only possible in conditions of electrical heating with reliable immersion of the upper generatrix of the thermosiphon, which requires overfilling of the thermosiphon with heat carrier. On the other hand, the earlier onset of heat-transfer crisis in the conditions of electrical heating is quite probable, on account of the deterioration in heat transfer in the region of the upper generatrix of the tube. The difference in angles of inclination of the curves is explained in that the degree of thermosiphon filling in [2] remains constant and is not optimal for each pressure.

Adopting a physical model of loss of flow stability as sudden increase in wave amplitude at the surface of the stream under the action of the dynamic pressure difference of the opposing steam flux, the ratio of the dynamic pressure difference of the steam flux to the work of large-wave generation at the instant of "flooding" of the flow may be taken as the quantitative characteristic of this phenomenon, i.e., $\rho'' w_{cr}^2/\delta g(\rho' - \rho'')$, where δ is the scale of the wave. Taking the Laplace capillary constant as δ yields the Kutateladze stability number, which is widely used for the characteristics of different critical phenomena in two-phase flows. At the same time, analysis of the conditions of phase interaction in flow of a steam flux around the waves indicates the possibility of breakaway flow of the steam in the descending region. The pressure difference at the crest of the wave arising in boundary-layer breakaway depends on the compressibility of the steam phase. In [4], it was shown that taking account of the influence of compressibility of the gas on the quantitative characteristics of stability loss of such flows is possible by means of the pressure number $K_p = P\delta/\sigma$. Thus, the dependence $K = f(K_p)$ may be used for generalization of experimental data obtained.

The results of generalizing the experimental data on stability loss of the longitudinal transfer in the horizontal thermosiphon are shown in Fig. 5. The experimental data are compared with data obtained in [5] with respect to the lower and upper limits of "flooding" in vertical thermosiphons. It is evident that the present experimental results coincide with the dependence of [5] for the lower limit of "flooding," corresponding to the minimum of hydraulic drag in the steam flux. This indicates that the onset of drop breakaway from the liquid surface, which appears for vertical thermosiphons only as increase in the hydraulic drag of the steam flux, leads to irreversible stability loss for a horizontal counterflow system, resulting in limitation of the heat-transfer functions of the thermosiphon.

The corresponding limiting thermal load may be calculated from the relation $K = CK_p^n$, where $C = 5.72$, $n = -0.17$ when $K_p < 4 \cdot 10^4$; $C = 0.98$; $n = 0$ when $K_p \geq 4 \cdot 10^4$.

NOTATION

ΔT, temperature difference; T_1, T_2, saturation temperature of intermediate heat carrier in steam generator and thermosiphon; q_s^{max}, maximum heat flux referred to total cross section of thermosiphon channel; ε, degree of filling of thermosiphon; P, pressure in thermosiphon; w_{cr}, true critical velocity of steam phase; ρ', ρ'', density of liquid and steam phases; δ, Laplace constant; σ, surface tension; K, Kutateladze stability number; K_p, pressure number.

LITERATURE CITED

1. M. K. Bezrodnyi, S. N. Fainzil'berg, A. I. Beloivan, and N. Yu. Koloskova, Izv. Vyssh. Uchebn. Zaved. USSR, Chern. Met., No. 11, 174-177 (1976).
2. M. K. Bezrodnyi and A. A. Sakhatskii, Teploénerg., No. 3, 75-78 (1977).
3. L. L. Vasil'ev, L. P. Grakovich, and D. K. Khrustalev, Inzh. Fiz. Zh., 46, No. 5, 709-716 (1984).
4. M. K. Bezrodnyi, Khim. Neft. Mashinostr., No. 5, 30-32 (1980).
5. M. K. Bezrodnyi and S. S. Volkov, in: Hydrogas Dynamics and Heat Transfer in Condensed Media [in Russian], Novosibirsk (1981), pp. 121-127.