THERMOHYDRODYNAMIC INSTABILITY IN SYSTEMS WITH NATURAL CIRCULATION OF A BOILING HEAT CARRIER IN PIPES

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A description is given of possible regimes of thermohydrodynamic processes in a closed natural-circulation loop including a heat exchanger with vertical steam-generating pipes in which water boils within the pressure range 8-90 kPa.

A good deal of attention has recently been paid to the design of heat exchangers with the natural circulation of a heat carrier boiling in vertical pipes [1-4]. The amount of heat removed by such units is limited by the magnitude of the limiting thermal loads associated with heat-transfer crises or the onset of unstable boiling regimes. Analysis of the causes of instability in the operation of heat exchangers with a boiling heat-transfer agent in pipes requires knowledge of the frequency, amplitude, and phase characteristics of oscillations of the thermal and hydrodynamic parameters.

This article reports the results of experimental studies of characteristics of oscillations of thermohydrodynamic parameters occurring in natural circulation systems due to unstable water boiling regimes in vertical pipes at pressures of 8-90 kPa.

Figure 1 presents a diagram of the experimental unit. It constitutes a closed natural circulation loop which includes a heat exchanger 1 and a condenser 2. The vertical steam-generating pipes of the heat exchanger 1 are of diameter $d = 6 \times 1$ mm and length $L = 1.52$ m. They are made of stainless steel OKh18N10T. There are 101 such pipes. The hot steam is directed through a nozzle with a supercritical pressure drop, so the steam flow rate is independent of oscillations in saturation pressure P_s in the intertube space. The water levels in the down and overflow pipes were monitored with water-gauging columns. Two "tube-in-a-tube" type heat exchangers were located on the down pipe to heat or cool the heat carrier.

Oscillations of the pressure in the chamber where the hot steam condenses P_s and the pressure above the steam-generating pipes P_k was recorded with MÉD pressure gauges with a measurement range from 0 to 0.1 MPa and 0 to 0.15 MPa. The signal from the gauges was sent through an amplifier to an N115 loop oscillograph. A check of the synchronism of the gauges at frequencies up to 1 Hz showed them to be identical. The gauges were used to determine only phase relations between the fluctuations in the pressures P_s and P_k and their frequency characteristics. The pressure and the amplitude of its oscillations were determined from standard vacuum gauges with graduations of 0.49 kPa.

The scheme shown in Fig. 2 was used to obtain oscillograms of the level oscillations in the down pipe. The transducer here consisted of two parallel electrodes supplied with a direct voltage of about 1 V. Fluctuations in the liquid level in the pipe lead to changes in the circuit current which are recorded by the oscillograph. The total thermal load Q_Σ recorded during boiling in the steam-generating pipes of heat exchanger 1 was determined from the consumption of coolant water through the condenser and the temperature difference at the condenser inlet and outlet. The error of Q_Σ was not more than 5%. The completed studies established the existence of four characteristic regimes of operation of the experimental unit with a change in Q_Σ from 0 to the limiting (maximum possible) thermal load $Q_{\Sigma *}$. The thermal load on one steam-generating pipe was determined as $Q = Q_\Sigma/101$. At low thermal loads and low pressures inside the loop, we observed stable oscillations not only of the pressure P_k, the temperature of the heat carrier, and the liquid level in the down and overflow pipes, but also of the saturation pressure in the condensation chamber P_s. The latter

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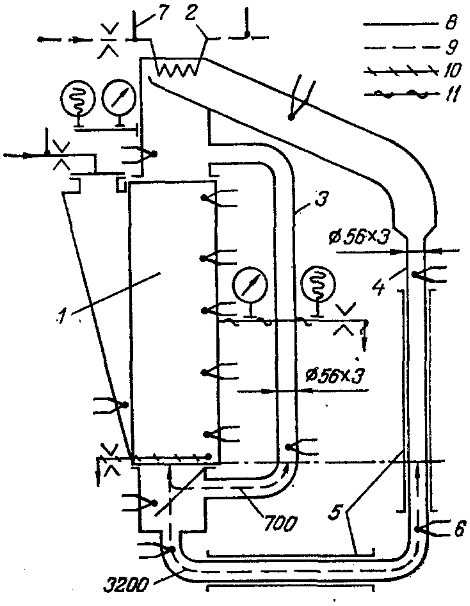

Fig. 1

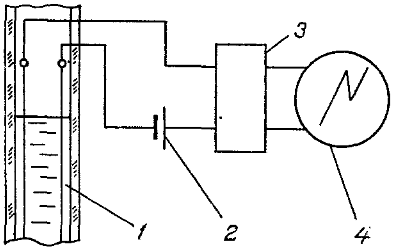

Fig. 2

Fig. 1. Diagram of experimental unit: 1) vertical heat exchanger with steam-generating pipes; 2) condenser; 3) overflow pipe; 4) down pipe, 5) "tube-in-a-tube" heat exchanger; 6) thermocouple; 7) thermometer; 8) hot steam; 9) coolant water; 10) condensate; 11) vapor—air mixture.

Fig. 2. Set-up for obtaining oscillograms of fluctuations in the liquid level in the pipe: 1) gauge; 2) direct voltage source; 3) current divider; 4) loop oscillograph.

is not permitted in several specific technical applications. These oscillations are most pronounced when the loop is initially filled to high levels $h_0/L = 0.8$-1.

Figure 3a shows an oscillogram of the fluctuations in P_s and P_k for mean values $Q = 0.15$ kW; $P_k = 18.1$ kPa; $h_0/L = 0.97$. The amplitude of the oscillations in the range of thermal loads under consideration does not exceed 2 kPa. An increase in thermal load is accompanied by a decrease in the period of these oscillations from 30 to 18 sec. They then die out. It should be noted that the oscillations seen in this range of regime parameters, as in other ranges, exist with a constant steam flow rate and, hence, a constant quantity of heat entering the intertube space of the heat exchanger 1. Thus, they are generated by internal forces in the system and are in the nature of free oscillations.

The second operating regime of the experimental unit is characterized by an absence of oscillatory processes both inside the loop and in the condensation chamber.

In the third regime, where the thermal loads are close to the limiting loads, oscillations with the periods $\tau_1 = 3.5$-5.5 sec and $\tau_2 = 1.9$-2.3 sec are seen. A characteristic oscillogram of the oscillations of P_s and P_k is shown in Fig. 3b for $Q = 0.59$ kW; $\bar{P}_k = 17.7$ kPa; $h_0/L = 0.59$. In this region the amplitudes of the oscillations of P_s change from 1 to 5 kPa, while the range for P_k is from 1 to 3 kPa and the range of the levels in the down and overflow pipes is from 0.05 to 0.3 m. An increase in thermal load and the pressure P_k is initially accompanied by a monotonic decrease in the periods of the oscillations to 3.5-4 sec. This is followed by an almost sudden decrease to 1.9-2.3 sec.

Figure 3c shows an oscillogram of the oscillations of P_s and P_k with the period τ_2 for $Q = 0.67$ kW; $\bar{P}_k = 53$ kPa; $h_0/L = 0.59$. We should note two facts which are typical of this range of regime parameters: first, with oscillations with the period τ_2 there are no fluctuations in the level in the down pipe in the presence of oscillations of P_s and P_k and the level in the overflow pipe; second, in the transition from oscillations with the period τ_1 to those with the period τ_2 and given a constant thermal load, P_s decreases roughly by a factor of two.

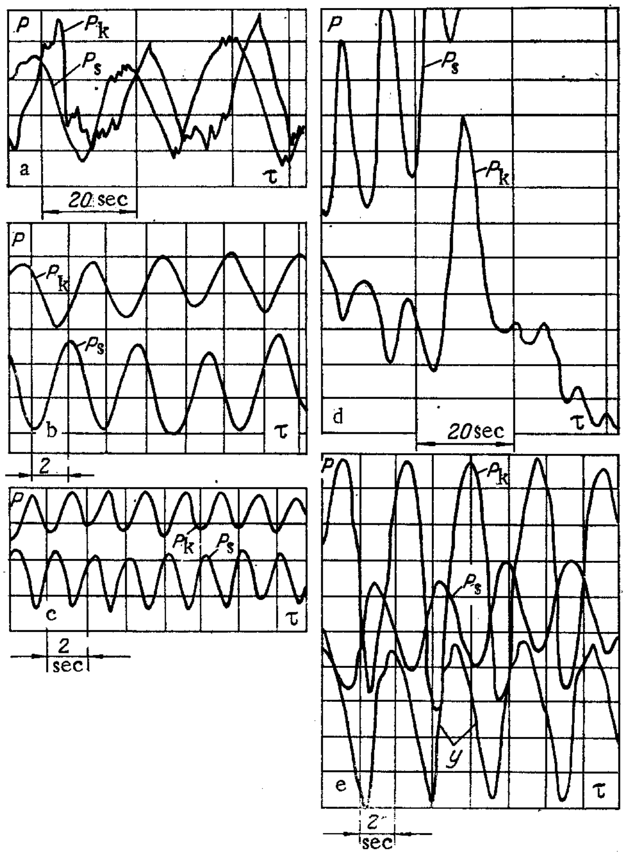

Fig. 3. Oscillograms of fluctuations in pressure above the steam-generating pipes P_k, the pressure in the condensation chamber P_s, and the liquid level in the down pipe y: a) Q = 0.15 kW ($Q_\Sigma \approx 0.2Q_{\Sigma *}$), $\bar{P}_k$ = 18.1 kPa, h_o/L = 0.97; b) Q = 0.59 kW ($Q_\Sigma \approx 0.87Q_{\Sigma *}$), $\bar{P}_k$ = 17.7 kPa, h_o/L = 0.59; c) Q = 0.67 kW ($Q_\Sigma \approx 0.75Q_{\Sigma *}$), $\bar{P}_k$ = 53 kPa, h_o/L = 0.59; d) Q = 0.67 kW ($Q_\Sigma = Q_{\Sigma *}$), $\bar{P}_k$ = 15.2 kPa; h_o/L = 0.59; e) Q = 0.67 kW ($Q_\Sigma \approx 0.83Q_{\Sigma *}$), $\bar{P}_k$ = 35.3 kPa, h_o/L = 0.59.

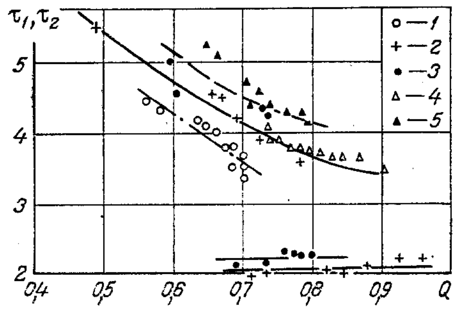

Fig. 4. Dependence of the periods of the thermohydrodynamic oscillations in the natural circulation loop τ_1 and τ_2 (sec) on the thermal load Q (kW) with an overflow pipe: 1) h_o/L = 0.4; 2) 0.59; 3) 0.86; without an overflow pipe: 4) h_o/L = 0.59; 5) 0.86.

Figure 4 shows experimental data on oscillation periods in relation to the combined effect of thermal loads Q from 0.49 to 1 kW, pressures P_k from 8 to 90 kPa, and initial levels of filling of the loop h_o/L from 0.4 to 0.86 for the third operating regime. The data on τ_1 and τ_2 in Fig. 4 for different h_o/L is shown as an average by the dashed ($h_o/L = 0.86$), solid (0.59), and dot-dash (0.4) lines. We could not explain the different effects of the thermal load and pressure P_k on τ_1 and τ_2, since for the case $\bar{P}_k$ = const the 10-20% increase in Q_Σ at which the oscillations occur leads to limiting values of the latter. However, it can be concluded from Fig. 4 that the period of the oscillations decreases with an increase in Q and P_k and a decrease in h_o/L.

The crisis phenomena occurring at $Q_\Sigma = Q_{\Sigma *}$ (fourth regime of operation of the experimental unit) are accompanied by a decrease in the quantity of heat removed in the steam-generating pipes with the boiling water and an associated decrease in pressure inside the loop $\bar{P}_k$ with a simultaneous increase in the temperature and saturation pressure of the hot steam $\bar{P}_s$. The fluctuations in the pressures, temperatures, and levels become aperiodic. Figure 3d shows an oscillogram typical of the occurrence of crisis effects for the following regime parameters: $Q = 0.67$ kW; $\bar{P}_k = 15.2$ kPa; $h_o/L = 0.59$.

The complex mechanism behind the phenomena created in the experimental unit is related to different water boiling regimes at low pressures. This was shown by tests conducted on a model of the experimental unit which used a glass tube with an inside diameter $d = 6.2$ mm and length $L = 1.5$ m as the steam-generating section. The pressure above the tube $P_k \approx 7$ kPa. The tube was heated by an electric coil.

At the low thermal loads corresponding to the first regime of operation of the experimental unit, there are time intervals when boiling is absent and the heat supplied to the tube goes mainly into heating it. After a certain temperature difference is reached between the wall and the liquid, a "shell" boiling regime explosively appears (the absence of nucleate boiling of water at $\bar{P}_k$ = 1-5 kPa was also noted in [5]). The vapor "shells" formed here "smear" the liquid in the form of a film over the tube wall. The film evaporation of a liquid with a high heat-transfer coefficient cools the tube wall, and boiling ceases. The time interval when boiling of water occurs corresponds to an increase in the level in the down pipe and an increase in pressure inside the loop. Thus, the first oscillation regime is determined by a nonsteady regime of cooling-heating of the tube wall and the character of boiling of water at low pressures.

The period of time when boiling is absent becomes shorter with an increase in the thermal load, and the vapor shells, alternating with frothed plugs of liquid, begin to follow one another with a frequency which exceeds the natural frequency of oscillation of the liquid column in the U-shaped system comprised of the down pipe and steam-generating channels. Thus, there is almost no fluctuation of the level in the down pipe. This boiling regime probably exists in the steam-generating pipes of the experimental unit when there are no natural oscillations.

The third boiling regime observed in the glass tube is characterized by periodic boiling of water with a frequency near the natural frequency of the water column in the U-shaped system. The liquid boils when its level in the down pipe is close to the maximum position and the pressure in the loop is minimal. With such a boiling regime, the wall of the steam-generating channel is covered for much of the period with a liquid film. This film flows downward after a shell of vapor passes. The existence of natural oscillations in this boiling regime is due to the variable rate of evaporation of the film and the different levels of filling of the channel with liquid. When a shell passes through the steam-generating channel, its entire surface is covered by a liquid film moving together with the shell. The difference between the wall temperature and the saturation temperature in the loop ΔT is maximal. In this period, heat removal from the direction of the boiling heat carrier becomes maximal. After the shell leaves the channel, pressure in the loop increases, ΔT decreases, the liquid film begins its downward flow, and the steam-generating channel is partly filled with water. All this leads to a decrease in the rate of vapor formation. Pressure in the loop decreases and water flows into the down pipe during the oscillation of the water column in the U-shaped system. Here, the water level in the down pipe increases to its maximum value, and the natural oscillation cycle is closed.

The occurrence of crisis phenomena under the above-examined conditions is connected with drying of the descending film of liquid. The sections of the steam-generating surface that are not wetted by the liquid appear primarily in the regions farthest from the outlet of the steam-generating channel.

The similarity between the boiling regimes in the glass tube and the third regime in the experimental unit is confirmed by analysis of the oscillograms on Fig. 3e, showing the oscillations in the pressures P_s and P_k and the liquid level in the down pipe for Q = 0.67 kW; $\bar{P}_k$ = 35.3 kPa; h_0/L = 0.59 (no overflow pipe). When the pressure in the loop P_k is close to minimal and the water level in the down pipe is close to maximal, the liquid boils. This leads to a change in the rate of movement of the free level. The accompanying intensive vapor formation leads to an increase in pressure inside the loop P_k, a decrease in the temperature of the wall of the steam-generating channel and, hence, a decrease in the temperature and saturation pressure P_s in the condensation chamber. The increase in P_k leads to a decrease in heat removal from the direction of the evaporating water film and, thus, to a decrease in P_k, an increase in wall temperature, and an increase in P_s. It should be noted that for the natural oscillations in question the change in P_s is shifted in phase relative to P_k by about 180-240°, while the change in level in the down pipe is 30-50° ahead of the change in P_k.

The periods of the above natural oscillations can be compared with the period of natural oscillation of the water column in the U-shaped systems: steam-generating section—down pipe (SS—DP) and steam-generating section—overflow pipe (SS—OP). The period of natural oscillation for the U-shaped system SS—DP changes from 2.7 to 3.5 sec, while that of the SS—OP system changes from 1.5 to 2.6. The exact period depends on the fullness of the loop. Friction increases the period of natural oscillation τ_0, while the generating force arising during boiling of the liquid and having period close to τ_0 can either increase or decrease this period, depending on the moment it acts on the natural oscillations of the water column [6] and the duration of its existence.

The connection between the periods of natural oscillation and the natural frequency of the water column is confirmed by experimental data: a) the natural oscillations have two periods τ_1 = 3.5-5 sec and τ_2 = 1.9-2.3 sec; b) the transition from natural oscillations with the period τ_1 to natural oscillations with the period τ_2 occurs almost abruptly; c) during natural oscillations with the period τ_2, there are no oscillations of the level in the down pipe; d) natural oscillations with the period τ_1 were not observed in the loop without an overflow pipe (see Fig. 4); e) heating of the water at the inlet of the steam-generating pipes to the saturation temperature from 0 to 20°C and superheating the steam from 0 to 20°C do not affect the period of oscillation.

Thus, natural oscillations with the period τ_1 can be linked with natural oscillations of the liquid column in the SS—DT system, while natural oscillations with the period τ_2 can be connected with oscillations of the liquid column in the SS—OP system.

LITERATURE CITED

1. Wallace and Hisley, "Oscillations in two-phase flows," Teploperedacha, No. 3, pp. 166-174 (1961).
2. R. I. Kalinin et al., "Study of the dynamics of natural circulation of a heat carrier in a closed loop," Teplofiz. Teplotekh., 37, 54-60 (1979).
3. A. P. Simonenko, "Experimental study of heat transfer in the evaporative part of a natural-circulation loop," Sixth All-Union Conference on Heat and Mass Transfer, Summary of Documents, Vol. 4, Pt. 2, Minsk (1980), pp. 136-141.
4. O. O. Mil'man, "Limiting thermal loads during boiling in heat exchangers with vertical pipes," All-Union Conference on the Thermophysics and Hydrodynamics of Boiling and Condensation Processes, Summary of Documents, Vol. 1, Riga (1982), pp. 186-188.
5. O. N. Koban'kov and V. V. Yagov, "Experimental study of heat transfer to a vapor—liquid flow at low pressures," Teploenergetika, 16, 67-69 (1980).
6. B. V. Bulgakov, Vibrations [in Russian], Gosizdat, Moscow (1954).