AN EXPERIMENTAL INVESTIGATION OF THE DETERIORATION OF THE HEAT-TRANSFER CONDITIONS IN THE VAPOR-GENERATING CHANNELS OF A REFRIGERATION SYSTEM

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Experimental data are presented on the characteristics of the temperature pulsations of the walls of coiled channels under conditions of deteriorated heat transfer.

During the vaporization of refrigerants the vapor content at the outlet of a channel approaches unity. In this case a deterioration of the thermal conditions occurs in the heating zone, and this is accompanied initially by the development of temperature pulsations in the walls of the channel, and as the vapor content subsequently increases further, by a monotonic increase in the wall temperature. This deterioration in heat transfer is classified in the literature as a heat transfer crisis of the second type. In this type of crisis low-frequency wall temperature pulsations are observed over quite a wide range of local vapor contents of the mass flow rate: from x_y corresponding to the onset of the temperature pulsations to x_{gr} corresponding to the heat-transfer crisis.

A knowledge of the conditions in the regime with temperature pulsations preceding the heat-transfer crisis and its internal mechanism makes it possible to correctly select the conditions of heat transfer depending on the requirements presented by the object being refrigerated.

The deterioration in heat transfer connected with the temperature pulsations in the vapor-generating channels has been noted during investigations of the boiling crisis of the second type for various materials: water [1, 2], potassium [3], refrigerant-113 [4], etc. Unfortunately, the experimental data given in these papers are piecemeal in nature and not systematic, and the information on the lengths of the pulsation zones, the effects of the operating parameters on their extents and their amplitude—frequency characteristics is very limited. Experimental investigations of the deterioration of the thermal conditions have therefore been carried out by the writers on a test loop, the flowsheet for which has been described in detail in [5].

The vapor-generating channel being investigated consisted of a flat copper coil of rectangular cross section 3.0 × 4.9 mm consisting of eight linear sections of length 530 mm connected to each other by bends of radius 15 mm. The heat flux to the vapor-generating channel was supplied from rectangular heaters 4.5 × 12.5 mm placed on the lower face of the channel with a pitch of 26 mm. Temperature measurements were carried out near each third heater, so that the temperature field in the vapor-generating channel was quite completely determined. In the outlet zone of the last linear section there was an inspection window of length 100 mm, the construction of which did not disturb the structure of the flow, and which made it possible to take motion-picture photographs of the hydrodynamic flow patterns in the channel.

The experimental investigations for studying the mechanism of the deterioration of heat transfer during the boiling of refrigerant-22 were carried out over the range of boiling pressures P = 0.7-1.0 MPa, specific heat fluxes referred to the total evaporator surface area of q = 2-20 kW/m², mass flow rates $\rho' w$ = 230-700 kg/m²·sec, and vapor contents at the inlet to the vapor generating channel x_{in} varying from 0 to 0.8. The investigations were carried out at three orientations of the channel to the horizontal: 0, 90, 180° (0° corresponds to having the heater placed on the upper face of the channel).

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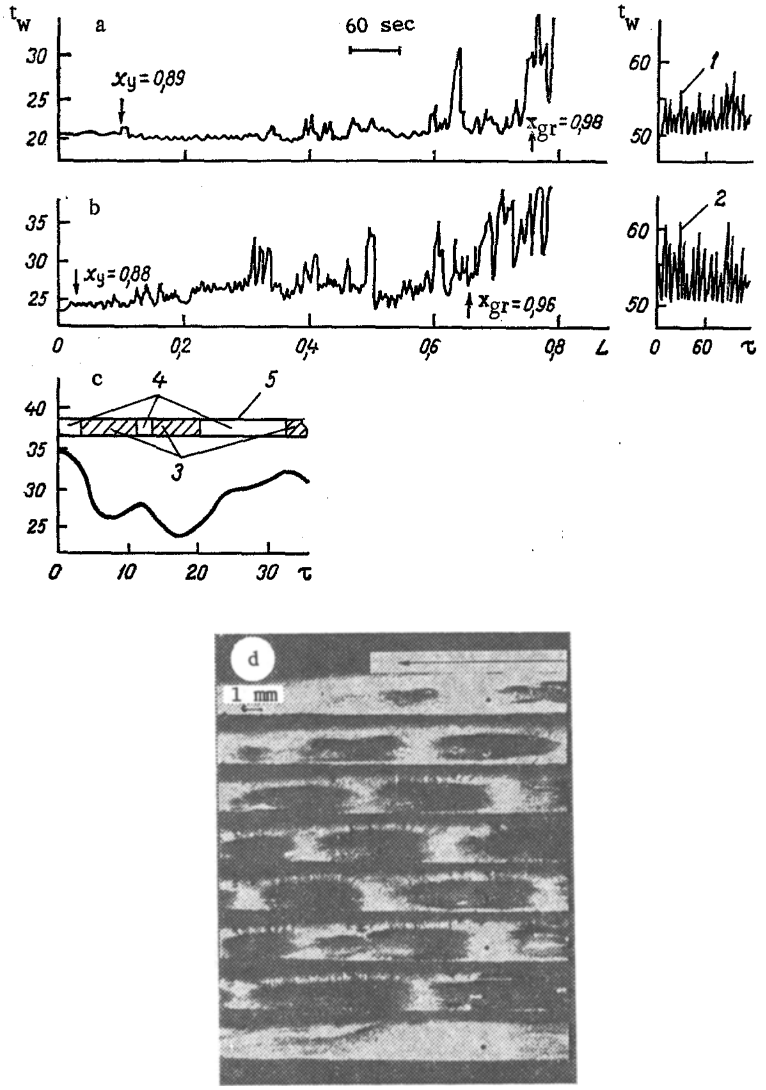

Fig. 1. Temperature pulsations of the channel wall and structure of the disperse flow during deterioration of the heat-transfer conditions: a), b): oscillograms of the temperature pulsations: a): $p = 0.77$ MPa, $q_{cr} = 7.96$ kW/m², $\rho'w = 263$ kg/(m²·sec), $x_{in} = 0.34$; b): $p = 0.90$ MPa, $q_{cr} = 11.10$ kW/m², $\rho'w = 499$ kg/(m²·sec), $x_{in} = 0.47$; c): results of synchronous recordings of the temperature pulsations and motion-picture photographs of the process, $P = 0.95$ MPa, $q_{cr} = 5.06$ kW/m², $\rho'w = 259$ kg/(m²·sec), $x_{in} = 0.37$; d) motion-picture photographs of the formation of vapor slugs for conditions a): rate of photography 48 frames/sec; $\Delta\tau \approx 0.02$ sec; the arrow indicates the direction of motion of the heat-transfer medium; the development of the process occurs from the top downwards; 1), 2): data of [4] for $p = 0.1$ MPa: 1): $q_{cr} = 6.0$ kW/m², $\rho'w \approx 150$ kg/(m²·sec); 2) $q_{cr} = 10.5$ kW/m², $\rho'w \approx 170$ kg/(m²·sec); 3): vapor-droplet plugs; 4): vapor plugs; 5) channel wall. Units are: t_w, °C; L, m; τ, sec.

A type N399 recording milliamp-voltmeter was used for recording the temperature pulsations; this made it possible to record temperature pulsations with amplitudes of greater than 0.5°C, and the rate of recording could be varied over the range 0.17-1.5 mm/sec. In order to check the validity of the measurements under unsteady-state conditions, the readings of the N399 instrument were duplicated by an N117 electron-beam oscillograph. Since the recordings of the temperature pulsations obtained on these two instruments practically coincided, most of the characteristics of the temperature pulsations were obtained on the N399 instrument.

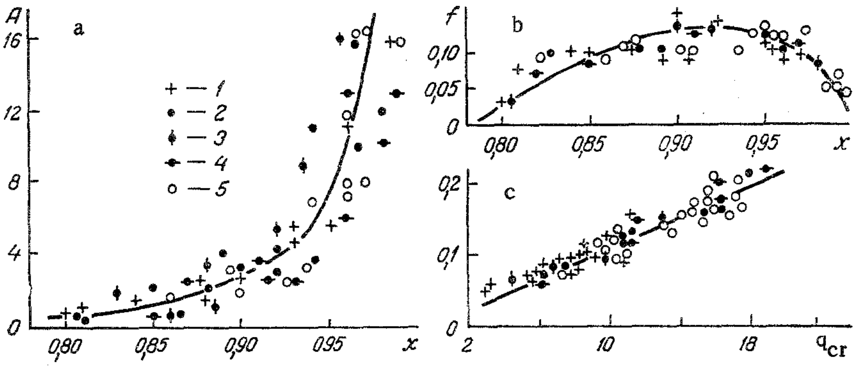

Fig. 2. Dependence of the amplitude/frequency characteristics of the temperature pulsations on the operating conditions of the stream: a), b): dependence of the amplitude and frequency of the pulsations on the vapor content, P ≈ 0.8 MPa, q_{cr} = 12.0 kW/m²; c) dependence of the frequency of the pulsations on the value of the critical heat flux, P ≈ 0.8 MPa; 1) ρ'w = 230 kg/(m²·sec); 2), 3), 4): ρ'w = 460 kg/(m²·sec); 2): heater on upper face of channel (0°); 3): 90°; 4): 180°; 5): ρ'w = 690 kg/(m²·sec). Units are: A: °C; f: Hz; q_{cr} = kW/m².

The detailed procedures of the experimental study of the limits of the deterioration of the heat-transfer conditions and information on the treatment of the experimental data and on the experimental errors are given in [5].

Oscillograms of the temperature pulsations for various operating parameters from their onset limit x_y up to the irreversible increase in the wall temperature of the evaporator x_{gr} are shown in Figs. 1a and b; the connecting bends correspond to the coordinate 0.53 m. The figure also shows values of the quantities x_y and x_{gr} which were calculated from the inlet and outlet vapor contents and the experimentally determined coordinate of the deterioration of heat transfer. The curves 1 and 2 in Figs. 1a and b show the pulsation characteristics for refrigerant 113 [4]. The values of the vapor contents for which the pulsation recordings were made are not indicated in [4].

After the connecting bends some decrease was observed in the amplitudes of the pulsations, which is probably related to an improvement in the conditions of wetting the walls of the channel by the liquid.

Figure 2 shows the dependence of the amplitude and frequency of the pulsations of the wall temperature of the evaporation channel on the operating parameters. It follows from Figs. 2a and b that at a fixed heat flux density the amplitude of the pulsation increases sharply as the vapor content increases from x_y to x_{gr} and on exceeding this the pulsations degenerate into an irreversible growth of the channel wall temperature. In this case the frequency of the pulsations varies slightly, and for a given heat flux density remains practically constant in the range of vapor contents 0.85-0.97, and then decreases sharply when $x > 0.97$, which corresponds to the heat transfer crisis accompanied by a sharp increase in temperature.

As the heat flux increases, the curves of the relationship $A = \varphi(x)$ shift to the region of smaller vapor contents, while the relationships $f = \varphi(x)$ shift to the zone of larger frequencies. Figure 2c gives the dependence of the pulsation frequency on the critical heat flux density for the range of vapor contents from 0.84 to 0.97. In a similar way, the heat flux influences the amplitude of the temperature pulsations.

The effects of the operating parameters of the flow and the initial vapor content on the length of the pulsation zone are shown in Fig. 3. The results given in Figs. 2 and 3 are in agreement with those in [1, 2]. Effects of the mass flow rate of the stream, the boiling pressure, and the orientation of the channel relative to the horizontal on the pulsation characteristics were not observed.

In analyzing the dynamic characteristics of the pulsations it was observed that the rates of increase and decrease of the temperature were not the same, and depended on the thermal loading (Fig. 4). Over the investigated range of the operating parameters the rate of decrease

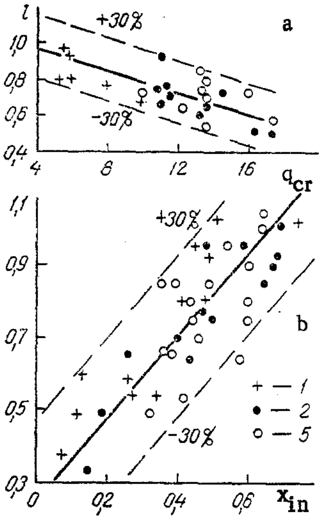

Fig. 3

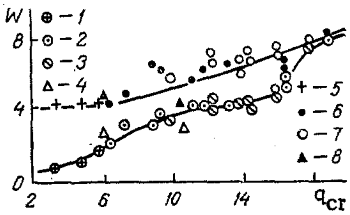

Fig. 4

Fig. 3. Dependence of the length of the pulsation zone on the critical heat flux density (a) and on the initial vapor content (b): $P \approx 0.80$ MPa; a) $x_{in} = 0.4$-0.5; b): $q_{cr} = 12$ kW/m². Symbols are the same as in Fig. 2. The units of ℓ are m.

Fig. 4. Dependence of the rates of increase and decrease of the temperature on the critical heat flux density ($P \approx 0.80$ MPa, $x_{in} = 0.4$-0.5): 1)-4): increase of temperature; 5)-8): decrease of temperature; 1), 5): $\rho'w = 230$ kg/(m²·sec); 2), 6): $\rho'w = 460$ kg/(m²·sec); 3), 7): $\rho'w = 690$ kg/(m²·sec); 4), 8): data of [4]; $P = 0.1$ MPa, $\rho'w \approx 170$ kg/(m²·sec). The units of W are K/sec.

of the temperature was always larger than the rate of increase, and at $q_{cr} > 18$ kW/m² they practically coincided. For a given heat loading the rate of change of the temperature remained constant for the entire length of the pulsation zone.

Simultaneously, with the experimental study of the temperature pulsations, an experimental study was also carried out of the two-phase flow by taking photographs and motion-picture photographs. At vapor contents of less than x_y ($x = 0.7$-0.8) flow of a vapor-droplet stream was observed with a constant uniformity over time. On reaching the vapor content x_y the vapor-droplet flow lost its continuity: it broke up into disperse slugs between which there were vapor slugs (see Fig. 1d). The ciné pictures shown in this figure illustrate the process of formation of vapor slugs in the continuous disperse structure of the flow.

The simultaneous visual observations, motion-picture photos, photographs, and the experimental study of the temperature pulsations make it possible to uncover their physical nature. Let us consider the typical experimental data shown in Fig. 1c. It is quite clear that the temperature pulsations arise when the structure of the vapor-droplet flow changes and vapor inclusions are observed in the approximately uniform vapor-droplet flow. This structure of the vapor-droplet flow can be represented as a combination of alternating vapor and vapor-droplet plugs (Fig. 1d). It has been established that at the moment when a vapor-droplet plug passes the wall temperature falls, and that the latter begins to increase when a vapor plug appears in the section in which the temperature pulsations are recorded.

As the vapor content increases up to x_{gr} there is a decrease in the lengths of the vapor-droplet plugs (which were determined in the motion-picture filming process), while the lengths of the vapor plugs increased. Here the frequency and amplitude of the temperature pulsations varied in accordance with Fig. 2. At a vapor content of x_{gr} vapor slugs were observed in the inspection window for the greatest part of the time, with the occasional inclusion of a small vapor-droplet slug. After the passage of the latter a microfilm of liquid was observed on the walls of the channel (and also on the inspection window) which then evaporated completely. Post-crisis heat transfer occurred in the channel when $x > x_{gr}$. The number of vapor-droplet slugs passing through a given cross section of the channel per unit time was determined from the visual observations and the motion-picture photographic data. Comparison of this number of vapor-droplet slugs with the recordings of the temperature pulsations from the data of the oscillograms led to satisfactory agreement.

Thus, in determining the limits for the onset of the condition under which heat transfer deteriorates, which makes itself felt through the development of temperature pulsations, it is necessary to take into account the existence of the mechanism for the development of these pulsations which has been observed in the experiments of the authors. The corresponding overall physical picture can be represented as follows. During the formation of the vapor-droplet flow (disperse regime of flow) the droplet flow density is marked by nonuniformities. The physical reason for the unusual density waves in the vapor-droplet flow may be a variety of perturbations, including those occurring at the bends, at the inlet to the channel, etc.

In order to study the possible effect on the conditions for the onset of post-crisis heat transfer of nonuniformities of heating and of the shape and dimensions of the channel and its orientation, the authors have carried out experimental investigations of x_y and x_{gr} in cylindrical channels with uniform heating having diameters 3.7 and 1.9 mm, with a reduced number of bends. It was found that the dependences of x_y and x_{gr} on the main factors appeared to be the same. To a first approximation it can therefore be assumed that the behavior discussed in the present paper for the onset of precrisis heat transfer in vapor-generating channels is quite general.

With increasing evaporation of the heat transfer medium the moment will arrive when in the zones with reduced densities of the vapor-droplet flow the droplets evaporate completely, leading to the formation of vapor inclusions in a dispersed vapor-droplet flow, which are then converted into vapor slugs. The moment at which the formation of such structures begins also determines the boundary for the onset of the deterioration of the heat transfer conditions which is connected with the development of wall temperature pulsations. In order to successfully generalize the experimental data on the deterioration of the heat transfer conditions it is necessary to set up a theoretical model for adequately describing the experiments.

NOTATION

A, amplitude; L, length of two adjacent linear sections of channel; ℓ, length of the pulsation zone; P, boiling pressure; q_{cr}, critical heat flux; f, frequency; t_w, temperature of channel wall; W, rate of change of temperature; τ, time; $\Delta\tau$, interval of time between photographic frames; $\rho' w$, mass flow rate; x, local vapor content.

Subscripts and superscripts: ′, liquid phase; in, at inlet; y, onset of temperature pulsations; gr, monotonic increase of temperature.

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