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EXPERIMENTAL STUDY OF REGIMES OF LOW-VELOCITY MOTION OF A SUBHEATED LIQUID IN HORIZONTAL ANNULAR CHANNELS WITH A HEAT-TRANSFER CRISIS

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The range of existence of different regimes of flow of a two-phase mixture during initiation of a heat-transfer crisis is determined.

The use of gravitational—evaporative cooling systems with natural circulation of the coolant is promising for certain thermally loaded elements of radioelectronic equipment having annular channels. Such systems make it possible to circulate the coolant at velocities up to 0.6 m/sec at pressures of 0.2-1.5 MPa in the cooling system.

The lack of reliable recommendations on calculating the critical heat flows in the low-pressure region makes experimental study of such processes important. A significant volume of expermental data has been accumulated on the heat-transfer crisis during boiling for systems with vertical heated channels at high coolant pressures (more than 10 MPa [1, 2]). Since the conditions of cooling of the heating surface are different for horizontal and vertical flows at low circulation rates, it is not possible to use the available data on q_{cr} for vertical flows.

As is known [3, 4], the critical heat flux depends mainly on the regime of motion of the two-phase mixture in the channel. Regime diagrams are used to identify different structures. The domestic and foreign literature contains different modifications of such diagrams for vertical and horizontal channels. However, most of these diagrams have been constructed for adiabatic flows. Thermal nonequilibrium connected with the flow of subheated liquid near the heated surface has a certain effect on features of the motion of a two-phase mixture. This is manifested most clearly at specific heat fluxes close to the critical fluxes. There is no data in the literature on the mechanism of occurrence of the crisis in horizontal channels under the conditions typical of gravitational-evaporative cooling systems. It is therefore interesting to study the conditions of occurrence of the heat-transfer crisis in horizontal channels at low pressures ($\rho'/\rho'' \approx 10^3$).

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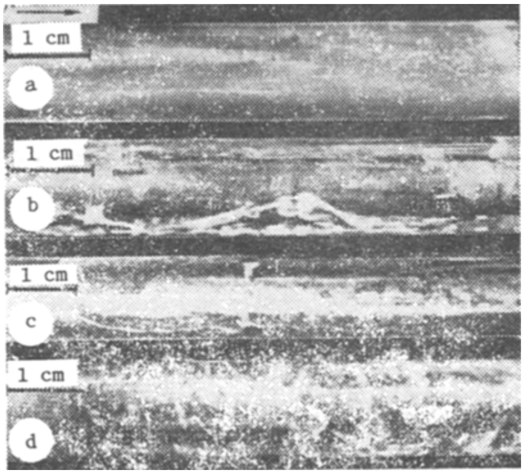


Fig. 1. Flow patterns of a two-phase mixture with the occurrence of a crisis and different regimes: a) nucleate: $\delta = 2.8$ mm; $w = 0.55$ m/sec; $\Delta T_{in} = 22$ K; $q_{cr} = 1.05$ MW/m^2; b) laminar; $\delta = 1.3$ mm; $w = 0.02$ m/sec; $\Delta T_{in} = 51.8$ K; $q_{cr} = 62$ kW/m^2; c) plug: $\delta = 1.9$ mm; $w = 0.19$ m/sec; $\Delta T_{in} = 33$ K; $q_{cr} = 33$ K; $q_{cr} = 689$ kW/m^2; d) emulsion: $w = 0.217$ m/sec; $\Delta T_{in} = 1.3$ K; $q_{cr} = 1.27$ MW/m^2; the arrow denotes the direction of motion of the coolant.

The experimental stand described in [5] was used to study critical heat fluxes and flow regimes of a two-phase mixture. The characteristics of the fuel element: length 100 mm, diameter 4 and 7 mm. The size of the annular gap was changed from 0.6 to 1.5 mm. The regime parameters of the coolant: velocity 0.02-0.50 m/sec, subheating at the inlet 2-85 K.

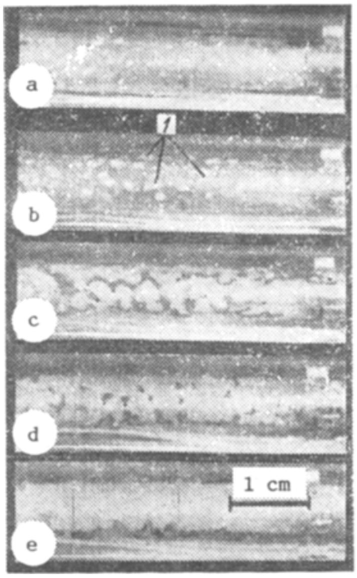
We used horizontal coaxial annular channels in the tests. The test channel was formed by using pins to center the fuel (heating) element inside a glass tube. The pins were made of stainless steel 0.1-0.2 mm thick and up to 2 mm wide. The height of the pins was determined by the size of the gap formed and was checked to within 0.05 mm. The fuel element was a thin-walled tube of steel Kh18N9T soldered with a high-melting solder to current leads. The distance from the channel inlet to the beginning of the heated section was 50-60 mm.

The heat-transfer crisis was fixed from the readings of thermocouples installed on the inside surface of the heated channel. When the temperature of the wall climbed above a specified value, a safety block was activated. The block automatically started a film camera and then shut off power to the heated channel. The film speed ranged from 300 to 2600 frames/sec, depending on the regime of motion of thw two-phase mixture. The plug flow regime was filmed at a speed of 900-1600 frames/sec. The studies yielded photographs of 46 regimes, films (48 frames/sec) of 9 regimes, and high-speed films of 20 regimes. We also recorded flow patterns in the precrisis regime with a "Zenit-B" camera using attachments. A check of the reproducibility of the results in regard to determination of critical heat fluxes and the corresponding regimes showed satisfactory agreement.

One feature of the film studies was that regimes of flow of a vapor-liquid mixture in the channel corresponded to different thermal loads close to the critical load.

Let us examine the character of the films and photographs, considering the fact that the filming was done at heat fluxes differing 4-5% from the critical heat flux. Figure 1 shows photographs of different regimes with flow of a subheated liquid in channels.

In accordance with the character of occurrence of the heat-transfer crisis, it is expedient to group the cnditions of the tests according to flow regimes: 1) velocities greater than 0.5 m/sec, subheatings of more than 20 K; 2) velocities lower than 0.1 m/sec, subheatings of more than 20 K; 3) velocities lower than 0.5 m/sec, subheatings greater than 20 K; 4) subheatings smaller than 20 K.



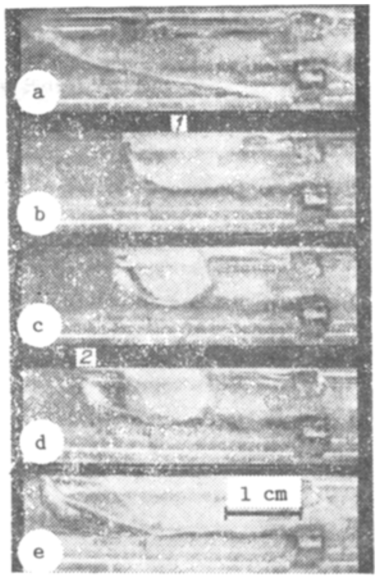


Fig. 2 Fig. 3

Fig. 2. Film of the development of "dry" spots (1) in the plug flow regime ($w = 0.21$ m/sec; $\Delta T_{in} = 34$ K; $q_{cr} = 422$ kW/m²; film speed 48 frames/sec; $\Delta\tau \approx 0.02$ sec): a) formation of spots; b, c) growth of spots; c, d) merging of individual spots; e) formation of a continuous spot in the base of the plug.

Fig. 3. Formation of a superheating zone at the crisis site: 1) phase boundary; 2) superheated part of surface (film speed 1030 frames/sec; $\Delta\tau \approx 1\cdot10^{-3}$ sec); a) exit of plug from channel; b) formation of superheating zone; c) growth of vapor plug in channel; d) growth of superheating zone; e) formation of plug.

A nucleate flow regime is seen along the entire heated channel for the first group (Fig. 1a), vapor content here increasing as the liquid moves. A vapor cavity may form in the rear part of the channel. This cavity may occupy more or less than half of the heated zone, depending on the size of the gap and the velocity.

The second group is characterized by lamination of the phases, and intensive vaporization occurs at the phase boundary (Fig. 1b). Analysis of the observations shows that the lamination of the flow is determined mainly by the circulation velocity and that subheating has little effect. The heat flux corresponding to the beginning of lamination of two-phase flow is limiting (critical) throughout the subheating range, which also determines the lower level of the unit loads ($5\cdot10^3$-$2\cdot10^4$ W/m²·K).

A plug regime of flow (Fig. 1c) is realized in a broad range of the investigated velocities (0.1-0.5 m/sec) for the third group of conditions. Analysis of the films showed that this group is characterized by the formation of vapor cavities and plugs in the channel. The "depth" of propagation of the plug counter to the flow as it propagates in the channel changes in relation to the amount of subheating. The velocity of the liquid in the channel inlet determines the degree to which the plug fills the cross section. At velocities lower than 0.2 m/sec, vapor-phase plugs are located near the top generatrix of the fuel element. At velocities greater than 0.2 m/sec, gravitation has almost no effect.

An emulsion regime of motion is typical of the fourth group of conditions (Fig. 1d) in the investigated velocity range with subheatings of less than 20 K. The critical heat fluxes here reach $1.6\cdot10^6$ W/m²·K.

It can be seen from Fig. 1c that the front of a plug may propagate considerable distances from the outlet section. The pulsative character of motion of the plug is determined by its development in the following stages: 1) cooling of the surface by the heated liquid and the formation of boiling centers; 2) nucleate boiling on the surface of the fuel element and the formation of vapor plugs in the outlet section of the channel; 3) growth of the plug to the maximum size, accompanied by the formation of "dry" spots in the base of the plug; 4) departure of the plug from the channel and "flow" of the dry spots on the surface of the element.

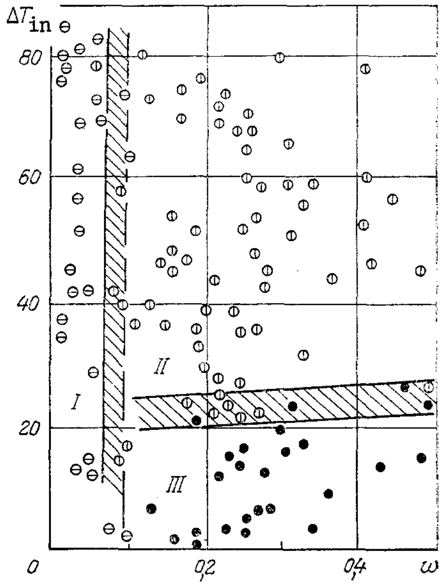


Fig. 4. Flow regime diagram of a two-phase mixture in horizontal annular channels with occurrence of a crisis: I) laminar; II) plug; III) emulsion. ΔT_{in}, K; w, m/sec.

The films show that in every case of plug growth on the surface of the element, "dry" spots form (Fig. 2). The dry spots typically appear simultaneously at different points on the heating surface (Fig. 2a). Vaporization of the liquid film covering the surface of the fuel element leads to growth of the spots until the surface has completely dried. If the heat fluxes on the surface are below the critical value, then the liquid completely washes the element as the plug leaves the channel. Such cooling conditions leads to fluctuations in the temperature of the surface. When some part of this surface is superheated above the temperature corresponding to the metastable state of water, then as the plug leaves the channel it is covered by a vapor film. This corresponds to the critical heat flux regime (Fig. 3).

The tests showed that the period of pulsation of plugs in the channel under the conditions investigated is on the order of 0.1-0.3 sec. If this time is sufficient to form a continuous "dry" spot in the base of the plug, then the crisis begins ($q_{cr} \approx 3\text{-}7 \cdot 10^5$ W/m²·K).

Figure 4 shows combinations of independent regime parameters and regions of existence of flow regimes obtained in tests with the occurrence of a crisis.

NOTATION

q_{cr}, critical heat flux; ρ, density; w, corrected velocity; T, temperature of coolant; $\Delta T = T_s - T$, subheating; δ, size of annular gap; $\Delta\tau$, time interval between frames. Indices: ', liquid phases; ", vapor phase; s, on the saturation line; in, at the inlet.

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