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Abstract

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HEAT ENGINEERING

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THE INFLUENCE OF NONUNIFORM HEATING ALONG THE LENGTH OF A TUBE ON THE MAGNITUDE OF CRITICAL HEAT FLUXES

In connection with the need to ensure the normal operation of highly forced heat-exchange devices, numerous studies have now been carried out on the conditions under which a boiling crisis arises. Almost all investigations were performed with constant heating along the length of the experimental section; however, in a number of heat-exchange devices the heat flux is distributed nonuniformly along the length of the channel. In this connection the authors carried out an experimental investigation in order to study the influence of this factor on the conditions for the onset of a boiling crisis.

The experiments were conducted with upward motion in tubes of a steam-water mixture and of water subcooled below the saturation temperature, at pressures of 100 and 180 ata and mass velocities of 400, 850, and 2000 $kg/m^2 \cdot sec$.

The experimental installation (its scheme is described in detail in work ([1])) was an open circuit. Superheated steam at a pressure of up to 300 ata and a temperature of up to 600° came from the boiler into a steam cooler with a regulated cooling surface, where it was cooled to the required heat content, and the working medium was directed into the vertical experimental section; then, after throttling to atmospheric pressure, it entered the condenser and measuring tank.

The pressure and mass velocity in the experimental section were regulated either by a valve located before the steam cooler or by a valve located near the inlet to the heated tube. In the first case, between the throttling element and the heated tube there are sections of the circuit filled with an elastic compressible medium; this creates conditions for the free development of pulsations of the working-medium flow rate under the influence of pressure fluctuations arising in the process of steam formation in the heated tube. In the second case, when

Fig. 1. Comparison of values $q_{\text{cr}}^{\text{un}}$ with values $q_{\text{cr}}^{\text{non}}$, obtained in experiments with an increase of heat flux along the flow of the working medium ($p = 100$ ata). *A*—under conditions of restricted development of pulsations; *B*—under conditions of free development of pulsations. Solid lines—nonuniform heating; dashed lines—uniform heating. a—$W_\rho = 400$ kg/m^2·s; b—850 kg/m^2·s; v—2000 kg/m^2·s.

Figure 1: Fig. 1. Comparison of values $q_{\text{cr}}^{\text{un}}$ with values $q_{\text{cr}}^{\text{non}}$, obtained in experiments with an increase of heat flux along the flow of the working medium ($p = 100$ ata). *A*—under conditions of restricted development of pulsations; *B*—under conditions of free development of pulsations. Solid lines—nonuniform heating; dashed lines—uniform heating. a—$W_\rho = 400$ kg/m^2·s; b—850 kg/m^2·s; v—2000 kg/m^2·s.

water subcooled to t_s entered the inlet section of the heated tube $\left(x = \frac{i - i'}{r} < 0\right)$, the sections of the circuit between the tube and the throttling element were filled with an incompressible medium, i.e., regimes with limited development of pulsations occurred.

The experiments were conducted both with uniform and with nonuniform heating along the length of an experimental tube 160 mm long and with an internal diameter of 6 mm, made of stainless steel grade 1Kh18N9T. Heating of the experimental section was effected by passing alternating electric current through it. To produce heating nonuniform along the length, tubes were used whose wall thickness varied along the length; in this case the outside diameter of the tube changed linearly.

Two types of nonuniformly heated tubes were used in the experiments. This article presents data obtained in experiments with tubes for which the ratio of the maximum heat flux to the mean was 2.3, and to the minimum 4.9.

The occurrence of the crisis was recorded visually by the appearance of local reddening of the wall on the tube. The critical heat flux was taken to be the local value of the specific heat flux at the point where the crisis occurred; it was determined from the measured current, the known electrical resistance of stainless steel at the given mean wall temperature, and the geometrical dimensions of the tube at the point where the crisis occurred.

Fig. 1. Comparison of values $q_{\text{cr}}^{\text{un}}$ with values $q_{\text{cr}}^{\text{non}}$, obtained in experiments with an increase of heat flux along the flow of the working medium ($p = 100$ ata). *A*—under conditions of restricted development of pulsations; *B*—under conditions of free development of pulsations. Solid lines—nonuniform heating; dashed lines—uniform heating. a—$W_\rho = 400$ kg/m^2·s; b—850 kg/m^2·s; v—2000 kg/m^2·s.

Figure 1 presents data obtained in experiments with an increase in heat flux along the flow of the working medium. In these experiments the crisis always

Fig. 2. Same as in Fig. 1 in experiments with decreasing heat flux

Figure 2: Fig. 2. Same as in Fig. 1 in experiments with decreasing heat flux

occurred at the outlet end of the heated tube. For comparison, curves corresponding to conditions of uniform heating of the tubes, all other conditions being equal, are also plotted here. For this purpose, data obtained in the present work, as well as in work ([2]), were used.

From consideration of Fig. 1 it follows that the critical heat fluxes under nonuniform heating of the tube ($q_{\text{cr}}^{\text{non}}$) are approximately twice as high as under uniform heating ($q_{\text{cr}}^{\text{unif}}$) (under analogous conditions at a pressure of 180 ata, the value of $q_{\text{cr}}^{\text{non}}$ was 40–50%). A more complicated dependence was obtained only under conditions of limited development of pulsations at a pressure of 100 ata and mass velocities of 400 and 850 $\text{kg/m}^2 \cdot \text{sec}$. For the latter case, when in the pre-included volume slightly compressible water is replaced by an elastic steam-water

Fig. 2. Same as in Fig. 1 in experiments with decreasing heat flux

mixture, i.e., at $x_{\text{in}} \cong 0$, an abrupt transition occurs from high values of $q_{\text{cr}}^{\text{non}}$ to low ones, as was also observed in experiments with uniform heating. At the same time, for the region $x_{\text{in}} > 0$, when, even in the presence of throttling of the flow near the inlet to the heated tube, flow-rate pulsations could develop, $q_{\text{cr}}^{\text{non}}$ was approximately twice as large as $q_{\text{cr}}^{\text{unif}}$. At $x_{\text{in}} < 0$ the effect of nonuniformity was considerably weaker, and the dependence $q_{\text{cr}}^{\text{non}} = f(x)$ itself differed from that obtained under conditions of uniform heating.

The results of experiments with a decrease of the heat flux along the flow of the working medium are presented in Fig. 2. In these experiments, at $x_{\text{in}} > 0$, the crisis occurred near the outlet section of the tube, where there was a zone of the smallest heat fluxes but the greatest value of the enthalpy of the medium. In this case the value of $q_{\text{cr}}^{\text{non}}$, on the contrary, was two times smaller than under uniform heating. At $x_{\text{in}} < 0$ the crisis occurred near the inlet section of the tube; in this case $q_{\text{cr}}^{\text{non}}$ was considerably higher than $q_{\text{cr}}^{\text{unif}}$. However, in the present case comparison of the values $q_{\text{cr}}^{\text{non}}$ and $q_{\text{cr}}^{\text{unif}}$ is already not legitimate because of the difference in the heated lengths of the pre-included sections of the tube.

The influence of nonuniformity of heating on q_{cr} can be explained as follows. In an unheated tube at a pressure of 100 ata and higher, a two-phase flow acquires an emulsion or core regime of flow. Near the tube wall there is always a layer of water. After the temperature of the wall of the heated tube exceeds the saturation temperature, the process of vapor formation begins in the boundary boiling layer. The steam content of the medium in the boundary layer during its motion inside the intensely heated tube depends mainly on the heat flux in the given section, and also on the steam content of the medium in the pre-included sections of the path. Since the boiling crisis usually arises in the outlet section of the tube, then with an increase in the heat-lower values of q and lower steam contents of the boundary layer occur over the length in the upstream sections of the tube. This circumstance lowers the local value of the steam content of the boundary layer in the outlet cross section of the tube and makes it more difficult for a continuous steam film to arise there, which determines the onset of the boiling crisis. Therefore, an increase in the critical heat fluxes is observed here in comparison with $q_{\text{cr}}^{\text{unif}}$. When q decreases along the length of the tube, the opposite picture is observed, which leads to a decrease in q_{cr}.

It should be noted that the influence of lower heating of the upstream sections extends much farther in the direction of flow than the influence of lower heating of neighboring sections of the tube perimeter ([3]).

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Note: Figure translations are in progress. See original paper for figures.