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Abstract

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HEAT ENGINEERING

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INVESTIGATION OF THE DISTRIBUTION OF STEAM CONTENTS IN THE BOUNDARY BOILING LAYER BY THE METHOD OF BETA TRANSMISSION

Most studies of boiling processes are devoted to determining the influence of various parameters—heat flux, pressure, temperature, physical properties, and velocity of the liquid flow—on the intensity of heat-transfer processes, as well as the conditions under which the transition from nucleate boiling to film boiling occurs; fewer studies are devoted to investigation of the mechanism of the process. Some essential features of the mechanism of the boiling process and of the crisis can be clarified by investigating the distribution of steam contents near the heating surface. In addition to its independent practical importance, the study of the distribution of steam contents in the boiling layer makes it possible to investigate the quantitative laws of the boiling process at various heat fluxes up to critical ones, and, with an appropriate arrangement and material of the heating surface, also in the postcritical region.

The investigation of the distribution of steam contents in the boundary boiling layer was carried out in the Laboratory of Intra-Boiler Processes of the Power Engineering Institute of the Academy of Sciences of the USSR. The most suitable method proved to be transmission of the medium under investigation by a narrow beam of rays, which makes it possible to measure not only steam contents averaged over the cross section of the channel, but also local values or values averaged over a small segment across the thickness of the boiling layer. For investigating the distribution of steam contents in a boiling layer, only a flat heating surface could be used, since only in this case will the distance from the surface under investigation to the plane of symmetry of the beam of rays remain unchanged. With a uniform distribution of heat flux over the surface and constant liquid parameters, a sufficiently thin beam of rays intersecting the flow at a specified distance from the heating surface, if edge effects are neglected, will pass through a region of practically constant steam content. The displacement of the beam relative to the heating surface when measuring local

Fig. 1. Graphs of the dependence of φ^{loc} on the temperature of the liquid flow.

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steam contents of the boiling layer at different distances from the surface can be carried out either by jointly moving the radiation source and the counter relative to the stationary heating surface, or, with the source and counter stationary, by moving the heating surface itself relative to the beam. In the present work the second method was used. Calculation shows that the smallest errors in determining steam contents are obtained when the medium filling a vessel with plane-parallel walls is transmitted by a thin plane-parallel beam of rays; this beam shape and channel were chosen for the present investigation. The channel width was selected so that, while avoiding almost complete absorption, the path of the ray would not be very large; however, it had to be sufficient to accommodate a heating surface with a large number of vapor-generation centers over a not very great length, so that random elements and edge effects would not exert a large influence. The height of the collimator, which determines the thickness of the beam of rays, must be as small as possible when measuring the distribution of steam contents.

The experimental setup is an ordinary closed circulation loop. Water from the pump, passing through tubes equipped with electric heaters, is heated to the required temperature and enters, through a hydrodynamic stabilization section, the rectangular channel of the experimental section, 4 mm wide and about 20 mm high. From the experimental section the water returns to the pump, after being preliminarily cooled in coolers. In the experimental section the water flows in a flat slit, on the bottom of which a flat heating surface made of strip nichrome, with dimensions 30 × 3.7 × 0.2 mm, is mounted on an elongated movable piston. The plate is heated by alternating current. The piston, on which the heating surface is mounted, can be moved in the slit channel up and down by means of a special mechanism. The piston rod is connected to a displacement indicator. Circular holes are made in the side walls of the channel of the experimental section; into one of them a sleeve filled with lead is inserted. A slit opening 0.3 mm thick and 10 mm wide is made in the lead and filled with powder of the radioactive isotope Sr^{90}. The sleeve has, at its end, a brass window 0.1 mm thick, protecting the isotope from being washed out by water. A narrow slit-shaped beam of β-particles, partially attenuated by the brass foil, penetrates the layer of liquid filling the channel. In the path of the β-particles (and secondary γ-rays) there is installed another collimator sleeve of the same

Fig. 1. Graphs of the dependence of φ^{loc} on the temperature of the liquid flow. $w = 1.3$ m/sec; pressure 1.22 ata. **1, 2, 3** and **5** $-\delta = 0.5$ mm; **4** and **6** $-\delta = 2.7$ mm; **1** $-q = 4.1 \times 10^6$ kcal/m$^2 \cdot$ h; **2** and **4** $-q = 2.8 \times 10^6$ kcal/m$^2 \cdot$ h; **5** and **6** $-q = 1.8 \times 10^6$ kcal/m$^2 \cdot$ h; **3** -2.3×10^6 kcal/m$^2 \cdot$ h; vertical strokes at the lines —crisis.

configuration as the first. This sleeve seals the section and also collimates the scattered beam of rays from the isotope. By moving the piston with the heating plate in the channel, it is possible to vary the distance from the heating surface to the layer being radiographed, thus carrying out in each individual case local radiography of a liquid layer 0.3 mm thick and 10 mm wide, located at various distances from the heating surface (from 0 to 6 mm). To prevent the projecting piston from causing additional disturbances in the liquid flow, a long movable wedge is mounted in the channel in front of it; when the piston moves upward, the wedge moves together with it, stretching a spring.

In the case of radiographing the medium by a full-section beam of β-particles, not intersected by the metal of the piston, i.e., at a distance from the plate to the plane of symmetry of the beam greater than 0.15 mm, the value of the void content of the layer being radiographed is determined from the formula

$$\varphi = \ln \frac{N_{\mathrm{cm}} - N_{\phi}^{\mathrm{cm}}}{N' - N'_{\phi}} : \ln \frac{N'' - N''_{\phi}}{N' - N'_{\phi}}, \tag{1}$$

where N', N'', and N_{cm} are the numbers of counts per minute when radiographing a channel filled respectively with water, water vapor, and a steam-water mixture;

N_{ϕ}^{d}, N_{ϕ}^{r}, and N_{ϕ} are the background of the setup per minute, which, in addition to the natural background, includes all radiation recorded by the counter except that which has passed through the collimator. The quantities N', N'', N'_{ϕ}, and N''_{ϕ} are determined directly from calibration data; moreover, calibration in steam may be replaced by calibration in air. The quantity N' is measured directly during the experiment, and the quantity N_{ϕ} is taken equal to

$$N_{\phi} = N''_{\phi} - (N''_{\phi} - N^{d}_{\phi}) \frac{N'' - N}{N'' - N'}. \tag{2}$$

In addition to the main and auxiliary measurements for determining steam contents, the following measurements were made in the experiments: 1) the heat load of the heating surface was determined from the current and the voltage drop across the plate and was referred to its surface; 2) the water temperature at the inlet to and outlet from the section was determined from the readings of thermocouples inserted into sleeves; in addition, the latter was measured with a mercury thermometer; 3) the water velocity in the section was determined from the flow rate, measured by means of an orifice plate and a differential manometer; 4) the pressure before and after the section was measured with control manometers with a scale division of 0.01 kg/cm^2; 5) the distance from the heating surface to the plane of symmetry of the beam was specially set and measured from calibration data.

Fig. 2. Isolines of steam contents in the boiling boundary layer.
A–$q = 1.8 \cdot 10^6$ kcal/m$^2 \cdot$ h, $w = 1.3$ m/sec; –$q = 2.8 \cdot 10^6$ kcal/m$^2 \cdot$ h, $w = 1.3$

Fig. 2. Isolines of steam contents in the boiling boundary layer.

Figure 2: Fig. 2. Isolines of steam contents in the boiling boundary layer.

Fig. 3

Figure 3: Fig. 3

m/sec; $-q = 1.8 \cdot 10^6$ kcal/m^2 • h, $t_B^{93^\circ}$

In each series of experiments the dependence of the steam content, measured at a definite distance from the heating surface, on the temperature of the flow was determined at constant heat load, pressure, and velocity. From Fig. 1, where typical dependences of local steam contents on temperature are presented, it is seen that in the region of high temperatures, when the scanning is performed at a distance from the heating surface smaller than the thickness of the liquid layer in which vapor bubbles are formed and grow, the steam content depends only weakly on temperature. A steeper temperature dependence corresponds to cases when the scanning is performed through a liquid layer pierced by bubbles that have detached from the heating surface and are condensing in the flow.

Figure 2 presents isolines of steam contents for various temperatures, velocities, and heat loads, constructed on the basis of the graphs $\varphi = \varphi(t_B)$. Each isoline represents a curve of the distribution of steam contents near the heating surface at constant flow parameters and heat load. From Fig. 2 *B* it is seen that even with a small difference in velocities (1.0 and 1.3 m/sec), in the region where condensation of the detached ⋯

detached steam bubbles, the influence of velocity takes place. In this region the bubbles that have detached from the heating surface condense the faster, the greater the flow velocity, i.e., the greater the intensity of liquid mixing. With a considerable difference in velocities (0.5 and 1.3 m/sec), the influence of the latter is also manifested in the immediate vicinity of the heating surface.

On the basis of the graphs in Fig. 2, for various heat loads and flow parameters one can determine the thickness of the boiling layer of subcooled liquid, $\varphi_{\text{k.s.}}$, equal to the value δ cut off by each of the epures on the ordinate axis. By measuring the area bounded by each of the epures, one can determine the total amount of steam present at a given moment above the heating surface. The higher the liquid temperature, the greater the heat load and the lower the velocity, the greater the height of the boiling layer and the reduced thickness of the steam film, δ_{pl}, located above the heating surface.

Fig. 3. Graph of the dependence of $\varphi_{\max}^{\text{loc}}$ on the critical heat load q_{cr}. Pressure 1.22 ata.
1 $-w = 0.5$ m/sec; 2 $-w = 1.3$ m/sec

Comparison of the epures of steam content corresponding to regimes in which the flow temperature and heat load are close to critical shows that, at comparatively small heat loads and correspondingly high flow temperatures, the thickness of the boiling layer is comparatively small, while the maximum local steam-content values are very considerable, reaching 0.98. However, the greater the critical heat load and, accordingly, the greater the subcooling below the saturation temperature, the greater the thickness of the boiling layer, and the smaller the maximum local steam contents. From Fig. 3, where the dependences $\varphi_{\max}^{\mathrm{loc}} = \varphi(q_{\mathrm{cr}})$ are presented, it is seen that at low temperatures (especially if the liquid velocity is small) disruption of the supply of liquid to the heating surface, which ensures normal cooling of the latter at high loads, can occur at a very low saturation of the boiling layer by steam bubbles ($\varphi_{\max}^{\mathrm{loc}} = 0.3$). Thus, at small heat loads, when a small quantity of liquid is sufficient to cool the heating surface, the latter can penetrate through the layer of bubbles, even if the passages between them constitute several percent of the full cross section of the boiling layer. At high heat loads, the supply of liquid necessary for cooling the heating surface is disrupted at $1-\varphi = 0.5$, and at low intensity of turbulent pulsations (low flow velocities) even at $1-\varphi = 0.7$. The experimental data presented make it possible to approach the explanation of the mechanism of the boiling crisis differently than has been customary up to now, and in particular refute the widespread notion of a connection between the occurrence of the crisis and the attainment of some constant value of the steam content of the boiling layer.

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