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Abstract

Full Text

HEAT ENGINEERING

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INVESTIGATION OF MASS- AND HEAT-TRANSFER CHARACTERISTICS BY THE “SALT” METHOD

The heat-transfer regime in steam-generating tubes and channels of various shapes, when they are fed with pure condensate, has been studied in sufficient detail and is widely covered in the scientific literature.

According to existing concepts, in a steam-generating tube there are two regions that differ in the mechanism of boiling. In the first region, developed (nucleate) boiling takes place; in the second, there is impaired heat transfer, which, by analogy with boiling in a free volume, has been called film boiling. The boundary between the two regions is a certain steam content of the flow, called critical, which is a function of the heat flux, mass velocity, pressure, channel diameter, and, according to some data, also the relative length of the steam-generating tube. Beginning with the critical steam content, the wall temperature rises sharply.

Despite the large amount of experimental data, the mechanism of the heat-transfer process at the boundary is still insufficiently clear. This is largely explained by the fact that the use only of temperature measurements during operation on pure condensate gives limited information about the processes occurring.

The use of an unsaturated salt solution as feedwater makes it possible to determine the zones of impurity deposition and, from them, to judge qualitatively, and in some cases quantitatively, the mechanism of mass transfer.

For this purpose a special test stand was designed in the form of a single-tube ($d = 10 \times 2$) once-through steam generator with a vertical working section having independent heating (Fig. 1). Along the length (1 m) of the working section, chromel-alumel thermocouples made of 0.5 mm wire were installed at intervals of 50 mm. As feedwater, a sodium sulfate solution with a concentration of up to 1.5 g/kg ($\sim 10\%$ of the saturation concentration) was used. The tasks of the investigation included: determining the influence of salt content on the value of the critical steam content; finding the region of intense salt deposition.

Fig. 1

Figure 1: Fig. 1

Figure 2

Figure 2: Figure 2

Fig. 1. Schematic diagram of the experimental installation.

1 –feed tank, 2 –feed pump, 3 –damper, 4 –regenerator, 5 –refrigerator, 6 –condenser, 7, 8, 9, 10 –regulating valves. I, II, III –heated sections.

In the region of developed boiling, deposition of impurities is unlikely because of the intense mass transfer. However, the degree of influence of salt content on the value of the critical steam content is not obvious. It may be presumed–

assume that the critical steam content may shift toward lower steam contents, for example, if there is a noticeable change in the physical constants of the heat-transfer fluid in the boundary layer. To determine the nature of this shift, it is necessary to know with sufficient accuracy the position of the boundary when the stand is fed with pure condensate. For this purpose special experiments were carried out, although on a limited scale.

Fig. 2. Change in the temperature of the tube wall along the length of the heated section during an experiment. The lines connect points of one cycle; the period between cycles is 2 min.

When working with a salt solution it was found that, in a certain region of the steam-generating tube, impurities are deposited from the unsaturated solution, as evidenced by the continuous rise in the temperature of the tube wall in this region. Figure 2 gives records of the tube-wall temperature made with an electronic potentiometer. Temperature values for one cycle (the period between cycles is 2 min) are connected by a solid line. Figure 3 shows the rate of increase of the wall temperature (and, consequently, of deposits) as a function of steam content at $p = 140$ ata, $w\gamma = 1500$ kg/m² · s, and heat fluxes equal to $250 \cdot 10^3$ and $500 \cdot 10^3$ kcal/m² · h.

As a result of the deposits, the temperature of the outer surface of the wall in this region increases without limit, whereas when operating on pure condensate it remained constant in time and exceeded the saturation temperature (at the given load and mass velocity) by only a few tens of degrees.

Thus, in the steam-generating tube there are three regions: in the first (counting from the inlet) and the third there are no deposits; in the middle (transition) region, on the contrary, intense deposition of impurities takes place. It is quite obvious that the conditions of mass transfer in these regions are different.

Fig. 3. Change in the temperature of the tube wall with time at different steam contents.

Figure 3

Figure 3: Figure 3

Fig. 4. Dependence of the limiting heat flux on steam content at a mass flow velocity of $700 \text{ kg/m}^2 \cdot \text{s}$. a –on pure condensate, b –on salt solution

Figure 4: Fig. 4. Dependence of the limiting heat flux on steam content at a mass flow velocity of $700 \text{ kg/m}^2 \cdot \text{s}$. a –on pure condensate, b –on salt solution

$a-w\gamma = 1600 \text{ kg/m}^2 \cdot \text{s}$, $q = 500 \cdot 10^3 \text{ kcal/m}^2 \cdot \text{h}$; $b-w\gamma = 1500 \text{ kg/m}^2 \cdot \text{s}$, $q = 250 \cdot 10^3 \text{ kcal/m}^2 \cdot \text{h}$.

On the inlet side of the tube, the transition region borders on the region of developed boiling; the steam content corresponding to this boundary is the first limiting steam content (X_1). On the outlet side, the transition region is separated by the second limiting steam content (X_2). The first question that arises in connection with the detection of the transition

zone concerns the determination of its boundaries. To clarify this, experiments were carried out on pure condensate while keeping the other parameters in each series of experiments the same as when operating with the solution.

Figure 4 gives a comparison of the values of the first limiting steam content obtained with the solution and with pure condensate at 140 atm and $w\gamma = 700 \text{ kg/m}^2 \cdot \text{s}$. As can be seen from the figure, with a sufficient degree of accuracy these values may be considered coincident in the region of heat fluxes below $400 \cdot 10^3 \text{ kcal/m}^2 \cdot \text{h}$. At higher heat-flux values some stratification of the experimental points is observed; in the experiments with pure condensate the values of X_{gr} are 3-2% greater than in the experiments with the salt solution.

Experiments at mass velocities of 1200 and $1550 \text{ kg/m}^2 \cdot \text{s}$ also gave differences of 5-7% between the points obtained with condensate and with solution.

To determine the stability (constancy in time) of the first boundary of the transition region, long-duration experiments were carried out ($P = 140 \text{ atm}$, $w\gamma = 1500 \text{ kg/m}^2 \cdot \text{s}$, $q = 500 \cdot 10^3 \text{ kcal/m}^2 \cdot \text{h}$, Na_2SO_4 concentration 1.2 g/kg). During the experiments, at the outlet of the steam-generating tube a steam content was maintained amounting to about 95% of the value of the limiting steam content. Experiments lasting up to 27 hours showed that there were no deposits of impurities in the region of developed boiling even at steam contents very close to critical values.

Fig. 4. Dependence of the limiting heat flux on steam content at a mass flow velocity of $700 \text{ kg/m}^2 \cdot \text{s}$. a –on pure condensate, b –on salt solution

To determine the second limiting steam content, the boundaries of the transition region outlined according to the wall temperature and according to the deposition zone were compared. As a first approximation, it may be assumed

that the second limiting steam content (which fixes the end of the deposition zone) coincides with the steam content corresponding to the maximum value of the wall temperature.

The existence of three regions with different relationships to the salt contained in the unsaturated solution indicates different mass transfer in these regions.

In the region of developed boiling, as was to be expected, mass transfer is very intense; therefore there are no deposits in it.

At the boundary of this region the intensity of mass transfer drops sharply. With an impurity content in the water (allowing for evaporation of the solution) of 3 g/kg and a concentration of a saturated sodium sulfate solution of 17 g/kg, a five- to sixfold evaporation corresponds to a circulation ratio in the boundary layer of about 1.25. Thus, in the transition zone the inflow of liquid is small; it exceeds the amount of steam formed from it by only a few tens of percent. It may be considered that in this region only part of the surface is in contact with the liquid. It is possible that such contact occurs periodically.

A different mechanism of mass transfer takes place in the third region. The absence of deposits (or, in any case, very small deposits) indicates that in this region only steam is in contact with the wall. Liquid drops thrown onto the wall as a result of turbulent pulsations do not reach it. They evaporate in the layer of superheated steam washing the wall.

The absence of direct contact between moisture droplets and the wall may be explained by the action of two forces: the excess pressure in the gap between the droplet

and the wall, and by reactive forces. When approaching a strongly overheated wall, an excess pressure is formed in the gap between the droplet and the wall, analogous to that which occurs in spheroidal boiling. On the other hand, during the immersion of a droplet into the boundary layer, intense vapor formation takes place from the surface of the droplet, more intense on the side facing the wall. As a result, the resultant component of the reactive forces is directed toward the core of the flow. The indicated forces are greater the smaller the distance from the droplet to the wall. Thus, when a droplet approaches the wall to a certain extent, forces always arise that are capable of extinguishing the droplet's momentum.

From the mechanism of flow motion in the third region considered above, the convective character of heat exchange in it becomes understandable; this heat exchange is intensified by the evaporation of droplets in the boundary layer, and this region may be called the region of convective heat exchange.

The salt method makes it possible not only to detect regions with different mechanisms of mass transfer, but also to record the values of the limiting vapor contents at low values of heat load and high mass velocity. When working with condensate, such boundaries could not be detected, since the observed rise

in wall temperature is extremely small and difficult to determine. Thus, this method expands the experimenter' s possibilities.

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

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