HEAT EXCHANGE IN THE BOILING OF MIXTURES IN STRONG GRAVITATIONAL FIELDS

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UDC 536.423.1

Results are presented from an experimental study of heat transfer in the boiling of liquid mixtures in different gravitational (inertial) fields.

Recently there have been several studies published which have investigated features of heat transfer during the boiling of either binary mixtures or pure liquids in different gravitational fields [1-4].

Although, as noted in [5], the empirical data published by different authors on the boiling of mixtures is somewhat contradictory, most of the facts discovered thus far make it possible to conclude that the heat-transfer coefficient α in the transition from the boiling of a pure liquid to volatile solutions first decreases with the concentration C of the low-boiling component, reaching a minimum with a certain mixture composition. It then increases smoothly to a value corresponding to the pure second component. The relation $\alpha(C)$ is somewhat more complex for mixtures having an anisotropic composition, but in this case the value of α for the mixture is generally less than for the pure components. To explain the reasons for the deterioration in heat transfer during the boiling of liquid mixtures, several hypotheses have been advanced [6-8]. However, none of them has received broad acceptance.

As concerns the boiling of pure liquids in different gravitational fields, we note that the coefficient α decreases if acceleration due to gravity a increases compared to the normal value $g(a/g > 1)$. The physical circumstances acting to lower the heat-transfer rate are not completely clear in this case either.

In our opinion, the lack of success of attempts to explain the decrease in α in both cases is connected with attempting to link it with features of the growth and separation of individual vapor bubbles.

Experiments we conducted and their qualitative analysis make it possible to suggest that the deterioration in each transfer in both physically different processes is due mainly to more stringent conditions for the functioning of centers of vapor formation, leading to a reduction in the density of such centers n.

First we will examine the process of bubble growth during the boiling of a binary mixture in an ordinary gravitational field ($a = g$). Let there be an active center on the heating surface in the form of a conical cavity (Fig. 1a). The mechanism of the bubble-generating action of such a center was described in [9]. Growth of a bubble from the cavity begins when evaporation of the heated liquid causes the internal pressure P_i (made up of the pressure of the adsorbed air and the pressure of the vapor) to become greater than the external pressure P_e (representing the sum of the hydrostatic and capillary pressures). As it grows, the bubble is forced from the cavity in the liquid and forms an upward-expanding canopy over the cavity (Fig. 1b). As was shown in [9], at a certain moment a rapidly contracting neck forms in the bubble, and the upper spherical part separates (Fig. 1c and d).

The bubble remaining in the cavity and bounded by the canopy contains only a fraction of the original portion of gas. Nevertheless, the pressure in this bubble P_i immediately after the separation of the upper part continues to balance the external pressure P_e. However, this equilibrium may prove unstable. The point is that after the separation there are two processes occurring at the phase boundary, these processes creating forces which act on the canopy in opposite directions. First, there is evaporation of both components of the mixture, which leads to an increase in the internal pressure P_i above the external pressure

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Stavropol' Polytechnic Institute and the Stavropol' State Pedagogical Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 1, pp. 11-16, January, 1985. Original article submitted July 14, 1983.

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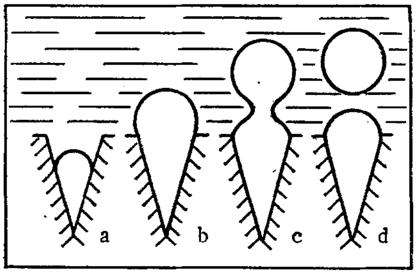

Fig. 1. Growth of a bubble from a conical cavity.

P_e. Second, the rapid growth of the bubble prior to separation leads to compression of the adjacent layers of liquid; now, after separation, the liquid begins to expand, and the potential energy from the compression is transformed into kinetic energy of motion of the liquid toward the canopy, and P_e increases as a result of this head. The latter effect leads to predominance of the external pressure over the internal pressure.

Thus, the state of the vapor—gas bubble remaining in the cavity depends on the relation between the rates of both processes.

As was noted in [9], in the case of boiling of a pure liquid the rate of entry of gas into the bubble is fairly high, so that the canopy supports the hydrodynamic head of the liquid. In these instances, the cavity in the surface of the heater functions as a permanent center of vapor formation. The situation may be different in the boiling of a mixture, since mainly the volatile component is evaporated in the cavity, and the concentration of this component in the adjacent liquid layers decreases as evaporation proceeds. This makes evaporation of this component more difficult, and the rate of increase in internal pressure P_i generally lags behind the rate of increase in external pressure P_e. As a result, the liquid compresses the vapor—gas bubble and penetrates deeper into the cavity than it did before boiling. It is understood that the rate of penetration of the liquid into the cavity is greater, the wider the mouth of the cavity.

The penetrated cavity can now be an active boiling center only in the case of significant superheating of the latter. If the amount of superheating remains unchanged, then after one or two separations the widest cavities will cease to be boiling centers.

Thus, with an unchanged temperature head ΔT, the number n of active centers on the heating surface in the case of a boiling mixture turns out to be less than the number n_0 in the case of a pure liquid. It is understood that the number of deactivated centers $\Delta n = n_0 - n$ depends for a given mixture on its composition.

It is significant that, due to the decrease in the mean width of the active cavities, the separation diameter D_0 of the bubbles also proves to be less during the boiling of a mixture than in the boiling of pure liquids.

Since, according to commonly accepted representations, the heat-transfer coefficient α during boiling is directly dependent on the density n of active centers, the separation diameter D_0, and the frequency of separation f, then it is clear that α, being a function of the composition of the binary mixture, takes values which on the whole are lower than the corresponding values for each component.

Now let us turn to explaining the reasons for the deterioration in heat transfer in the boiling of pure liquids in strong gravitational fields. Here, the key is the mechanism of growth of vapor—gas bubbles in cavities in the heating surface. Experiments conducted in our laboratory (the results of which will be published later) involving high-speed photographing of boiling in a centrifuge unambiguously indicate an increase in the penetration of the liquid into the bubble-forming cavities with an increase in a. It is difficult to offer an exhaustive explanation of this fact at present. The decisive role is undoubtedly played by the hydrostatic pressure, which in our experiments (height of the liquid column $h \sim 0.1$ m) reached about 20% of the external pressure P_e. It is also possible that the observed rising of the liquid in thin cavities in the heater in the case of high speeds of rotation of the vessel stems from the same causes as the well-known Konovalov effect, when capillary tubes experience high-frequency vibrations. One way or another, more superheating is needed with an increase in η so that the bubbles are free to grow and separate. This effect, which im-

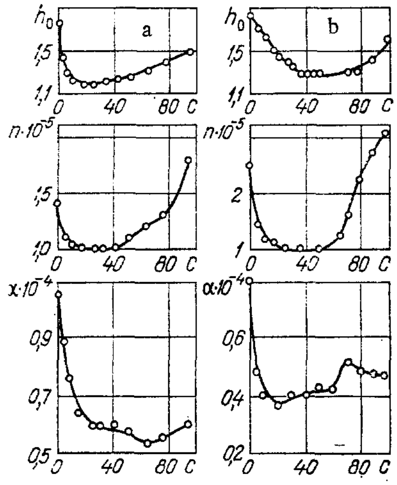

Fig. 2

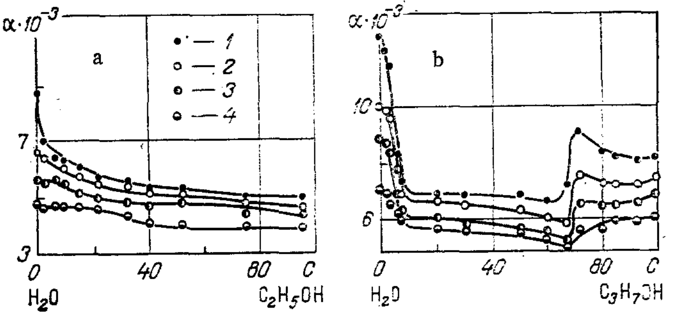

Fig. 3

Fig. 2. Effect of concentration C on mean bubble height h_0, density of active centers n, and heat-transfer coefficient α in the boiling of binary mixtures: a) water—ethyl alcohol; b) water—propyl alcohol. $q = 10^5$ W/m²; h_0, 10^{-3} m; n, m^{-2}; α, W/(m²·K); C, % (wt.).

Fig. 3. Dependence of the heat-transfer coefficient α on the inertial overloads η in the boiling of binary mixtures of different concentrations: a) water—ethyl alcohol, $q = 10^5$ W/m²; b) water—propyl alcohol, $q = 2 \cdot 10^5$ W/m²; 1) $\eta = 1$; 2) 2.3; 3) 8.7; 4) 20. α, W/(m²·K); C, % (wt.).

pedes the functioning of the centers, is greater, the narrower the cavity (and, accordingly, the greater the capillary pressure). Thus, in a strong gravitational field, an increase in *a* is accompanied by a decrease in the density of active centers mainly due to the thinner cavities.

As a result, in the boiling of a binary mixture in an inertial field, both very broad and fairly narrow conical cavities which usually act as centers of bubble formation on the heater surface become "passive." Consequently, the value of the coefficient α decreases even further.

We conducted several experiments to substantiate the above arguments. The tests were performed in a 0.3-liter vessel with windows for observation and photographing. The boiling surface was a thin nickel plate which served simultaneously as a resistance thermometer. The temperature of the liquid was kept close to saturation at the boiling surface by means of a guard heater and was measured with three copper-constantin thermocouples. The distance from the heater to the axis of rotation was 0.3 m.

For better accuracy, the concentrations of the solutions were determined by two independent methods — from the saturation temperature of the liquid and from their density (by means of a pycnometer).

Before each series of tests we degassed the liquids and "formed" the boiling surface. The process was photographed by a camera located at one window (a diaphragm and photoflash were positioned at the opposite window).

In the first series of tests we studied features of the boiling of different alcohol—water mixtures in an ordinary gravitational field ($a = g$). Special attention was paid here to understanding the dependence of the heat-transfer coefficient α, mean separation height h_0 of the bubbles, and the density n of active centers on the concentration C of the more volatile component. Heat flux q was a parameter in these experiments, so the results of measurements of α(C), n(C), and h_0(C) throughout the concentration range ($0 \leqslant C \leqslant 1$) could be represented as a family of curves with q_i = const.

Examination of the curves (Fig. 2) shows that with an increase in C the density of the centers n and the separation height h_0 initially decrease and reach a minimum. They then increase. It is significant that the curves α(C) behave similarly, but a certain maximum is seen for the propyl alcohol near the azeotropic composition. The other distinctive feature of the dependence of the heat-transfer coefficient on the concentration C is the slower increase in α as $C \to 1$. This is probably explained by the rapid decrease in the heat of vaporization L of the mixture as the alcohol concentration approaches 100%.

On the whole, the completed tests, like the results of earlier [10, 11] measurements, confirm the above proposition that the heat-transfer coefficient α during the boiling of mixtures proves to be less than the coefficient for the pure components, mainly due to a reduction in the density n of active centers.

In the second series of tests the above mixtures were boiled in strong gravitational fields ($a > g$).

The inertial fields were simulated in an S-52 centrifuge containing the test vessel. The rotating and stationary parts of the mechanical and measuring electrical circuits were connected by means of a current pickoff. The heat flux in the tests had one of two values: $q_1 = 10^5$ W/m^2 and $q_2 = 2 \cdot 10^5$ W/m^2. The overloads were changed within the range $\eta = a/g$ = 1-20. A detailed description of the methodology of these experiments was given in [12].

It follows from Fig. 3a and b that an increase in the overloads η is not accompanied by any change in the character of the dependence of the heat-transfer coefficient α on the concentration C of the volatile component, but these curves do move downward. It should be noted that in calculating the coefficient α we determined the temperature head ΔT in two ways: directly, from the temperature of the liquid mixture, and indirectly, from calculated values of its saturation corresponding to different external pressures.* It is significant, however, that the paths of the curves $\alpha(C)$ (with η = const) are similar; yet, the curves $\alpha_2(C)$ lie somewhat above the curves $\alpha_1(C)$ for the same conditions when the second method of calculating ΔT is used. Nevertheless, in both cases all of the points of both curves lie below the limiting values of α of each of the pure components. Figure 3 shows curves $\alpha(C)$ calculated by the first method, since for the construction of the curves $\alpha_2(C)$ we could use only a few points, i.e. the concentrations of the mixtures for which the relation $T_s(P_e)$ has been tabulated.

This decrease in the heat-transfer coefficient α is consistent with the above representation regarding the deterioration in the functioning of the active centers in strong gravitational fields. To definitively prove the validity of this hypothesis, the relation $n(\eta)$ should be studied for the boiling of mixtures of different compositions.

The results of the corresponding tests will be published in future articles.

NOTATION

α, heat-transfer coefficient, W(m^2·K); ΔT, temperature head, °K; q, heat flux, W/m^2; C, concentration of the mixture, % (wt.); a, acceleration due to gravity corresponding to the inertial field, m/sec^2; g, normal acceleration due to gravity, m/sec^2; $\eta = a/g$, inertial overload; D_0, separation diameter of bubble, 10^{-3} m; h_0, mean separation height of bubble, 10^{-3} m; f, frequency of bubble separation, sec^{-1}; n_0, density of active centers of vaporization during boiling of the pure liquid, m^{-2}; n, density of active centers of vaporization during the boiling of the mixture, m^{-2}; $\Delta n = n_0 - n$, number of deactivated centers of vaporization, m^{-2}; P_i, internal pressure, Pa; P_e, external pressure, Pa; L, heat of vaporization, J/kg; T_s, saturation temperature of liquid corresponding to the external pressure, °K.

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HELIUM BOILING CRISIS WITH A STEPPED INCREASE IN HEATING CAPACITY

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UDC 536.248.2:546.291

Results are presented from a study of the effect of saturation pressure on the nonsteady critical heat flux during the boiling of liquid helium in a large volume.

Impulsive heat release occurs in superconducting systems [1], and may lead to return of the superconductors to their normal state if adequate cooling is not provided. In connection with this, it is interesting to study the cooling capacity of liquid helium in nonsteady thermal processes.

Several studies have been published [2-5] regarding nonsteady heat transfer during the boiling of helium under conditions of an abrupt increase in power or impulsive heat release. They have shown that when the thermal load increases sufficiently, sheet boiling begins not immediately but after a certain time interval. The nonsteady heat conduction regime in helium is replaced by nonsteady nucleate boiling, and it is only after this that there is a deterioration in heat transfer — connected with the formation of a stable vapor film on the heating surface. Thus, there is a certain time interval τ_{cr} within which the heat-transfer rate remains fairly high after an increase in thermal load.

The character and sequence of occurrence of the nonsteady thermal processes in helium are similar in the case of impulsive heat release. However, if the duration of the thermal pulses is less than τ_{cr} and the time interval between pulses is long enough so that the semiconductor cools to the initial temperature, then it becomes necessary to remove heat from the surface of the superconducting element without its substantial overheating. Here, under certain conditions the magnitude of the impulsive thermal effects may significantly exceed the critical level for pulses of long duration. In the case $\tau_{imp} > \tau_{cr}$, the occurrence of sheet boiling at high thermal loads is unavoidable, so it is of great practical interest to determine the maximum heat flux which when attained will still not lead to a deterioration in heat transfer.

Vapor formation on the heating surface occurs somewhat differently in the case of an abrupt increase in heating than in the case of a slow increase in thermal load [6]. Thus, the critical heat flux $q_{cr.st}$ determined in the quasisteady regime may not agree with the value $q_{cr.ntst}$ characterizing the transition to sheet boiling with a stepped increase in heating. For example, it has been established in studies of the nonsteady boiling of organic liquids that the heat-transfer crisis with an abrupt change in thermal load occurs at heat fluxes $q_{cr.ntst}$ which are less than $q_{cr.st}$. The difference between $q_{cr.ntst}$ and

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 1, pp. 16-18, January, 1985. Original article submitted July 25, 1983.

0022-0841/85/4801-0010$09.50