INVESTIGATION OF HEAT TRANSFER DURING BOILING ON A FLAT SURFACE BY A NONSTATIONARY METHOD

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A nonstationary method of investigating heat transfer during boiling on a flat surface is described. The heat flux is determined from the reduction in the intrinsic energy of a massive bar over a definite time interval by graphic integration of the temperature field over the bar length.

Evaporative cooling at high heat-flux densities has been used extensively during the past few years. This has made it necessary to obtain heat transfer data for boiling in the near-critical and transition regions, which are of particular interest for engineering calculations of heat transfer during boiling on nonisothermal surfaces [1, 2]. It is well known that great difficulties are encountered in obtaining such data. Thus, for an electrically heated surface, it is not possible to study heat transfer in the transition region, while steam heating involves unavoidable and uncontrollable surface temperature fluctuations which greatly affect the accuracy of the data obtained [3].

The use of nonstationary heat transfer techniques for this purpose is therefore indicated. Boiling, however, is characterized by intense heat removal, and in order that the process proceed sufficiently slowly, it is necessary to retain large amounts of heat—i.e., to have a massive object made from a material with a high specific heat and to limit the heat transfer area, for example, by insulating a portion of the external surface of the body.

Heat transfer during boiling of a fluid in a large volume on a flat surface can be studied under any conditions, including transient conditions, with the aid of a technique based on a method of determining the amount of heat released by a heated body through any kind of surface from the change in the intrinsic energy of the body. For a thermally insulated bar, one of whose end faces transfers heat to a boiling fluid, the mean specific heat flux passing through the heat transfer area during a time interval $\Delta\tau$ is defined as

$$q = \frac{\rho c}{\Delta\tau} \int_0^L (t_i - t_{i+1})\, dl, \qquad (1)$$

where t_i and t_{i+1} are the temperatures along the bar axis in the states i and (i + 1) separated by time intervals $\Delta\tau$. Equation (1) holds for a one-dimensional temperature profile in the body, which is the case when the bar is properly insulated and the heat transfer at the end face is uniform. During this time interval, the mean surface temperature is

$$\bar{t}^s = 0.5\,(t_i^s + t_{i+1}^s), \qquad (2)$$

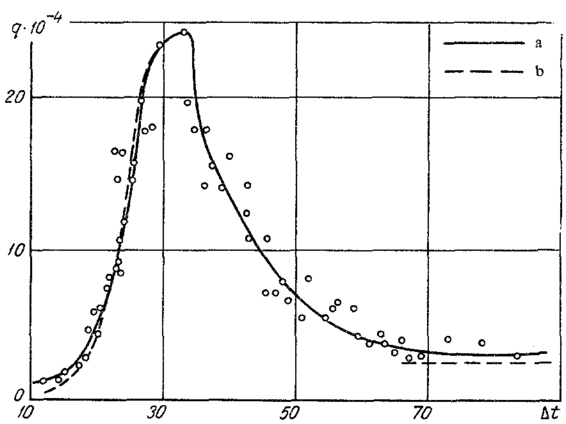
where t_i^s and t_{i+1}^s are the surface temperatures at the instant i and (i + 1).

The reduction in the intrinsic energy was measured for a copper bar 38 mm in diameter and 124 mm long. Its end face was introduced into the lower part of a vertical cylindrical chamber filled with boiling fluid. A heater was mounted on the bar. Six chromel-copel thermocouples were arranged along the bar axis; their readings were recorded by an EPP-09M3 automatic multichannel recorder of the 0.5 class, which at intervals of 0.75 sec recorded the thermoelectromotive force at each point on graph paper.

An N-700 14-channel oscillograph was also used successfully for this pupose.

In the course of the experiment, the bar was heated to $t^s > t_{cr2}$, and the load was then removed and the bar allowed to cool gradually by releasing heat to the boiling fluid. The recordings of the thermocouples were used to plot the temperature variations along the bar versus time, and then to plot the temperature variations at the individual points on the bar for various instants. Extrapolation of the curve $t = f(l)$ with respect to the point $l = 0$ yields the t^s values of the end face of the bar.

The area between the contiguous $t = f(l)$ curves is numerically equal to the integral in Eq. (1). The solid line in the figure shows the relation $q = f(\Delta t)$ for Freon-113 boiling at atmospheric pressure (t_{liq} = = 46.9° C), where the temperature head $\Delta t = \bar{t}^s - t_{liq}$.



Boiling curves of Freon-113 obtained by nonstationary (a) and stationary (b) techniques (q in W/m^2; Δt in °C).

The authenticity of a curve obtained in this way is difficult to assess, because in practice it is not possible to determine quantitatively the error caused by hydrodynamic instability of the fluid, nor is it possible to take into consideration the possible influence of the thermophysical properties of the body itself on the process [5, 7]. To clarify these problems, the heat transfer associated with bubble and film boiling of Freon-113 was studied also by a stationary method under identical conditions.

The copper bar employed in this study constituted the upper part of a massive block, which was continuously heated by electric current. The dimensions of the surface, the method of surface treatment, the method of fixing the surface to the bottom of the chamber, and the chamber itself, whose configuration can substantially influence the test results [8], were the same as in the previous experiment.

The dashed line in the figure shows the averaged results for a large number of test data obtained by the stationary method. The deviation of the solid curve from the dashed curve in the bubble boiling zone does not exceed 10%, but increases to 25% in the film boiling zone; i.e., the data scatter usually observed in investigations of heat transfer during boiling is only slightly exceeded.

The boiling curve was also calculated by the mean temperature method [5]. In spite of the fact that due to the high rate of the process it proved necessary to select short time invervals (for which $Fo < 0.5$), the deviations of the data calculated by this method from the stationary values did not exceed the aforementioned deviations over large portions of the curve. However, the error of this method exceeds 25% in the near-critical zone, where $Fo \ll 0.5$.

Analysis of the results obtained shows that in a system with an inertia as high as the one employed in this work, the boiling process may be considered quasi stationary. Moreover, no influence of the thermophysical properties of the sample on heat transfer was observed. The combined results indicate that the relatively simple method of studying heat transfer, we have described, is well suited for obtaining, within a single test, over a short period of time, a boiling curve for any condition of practical interest.

NOTATION

q is the heat flux density; t is the bar temperature; t_{cr_2} is the second critical temperature; Δt is the heating-surface/fluid temperature difference; t^s is the surface temperature; $\bar{t}^s$ is the mean surface temperature; t_{liq} is the liquid temperature; ρ and c are the density and specific heat of the bar material; τ is time; l is the coordinate; L is the bar length; Fo is the Fourier number.

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