Calculation of heat transfer coefficients for explosive boiling of a liquid under conditions of low pressure

A E Brester¹,², V I Zhukov¹,², D A Shvetsov², and A N Pavlenko²

¹ Novosibirsk State Technical University, K. Marx Prosp., 20, Novosibirsk, 630073, Russia
² Kutateladze Institute of Thermophysics, SB RAS, Lavrentyev Ave., 1, Novosibirsk, 630090, Russia

brester94@gmail.com

Abstract. The paper discusses the problem of determining the temperature head for calculating the heat transfer coefficient during explosive boiling of a liquid on a smooth horizontal surface under conditions of low pressure. The task of the work is obtaining the method for determining the characteristic pressure for calculating the temperature of saturated vapors. As a result, it is found that the difference between the heat transfer coefficients calculated at the pressure specified at the beginning of the experiment and the pressure averaged over time differs on average by 5%.

1. Introduction

Explosive boiling of a liquid is observed in devices such as vacuum diffusion pumps, vacuum evaporators, etc., in which the liquid boils at low pressures. With a decrease in pressure, the critical radius of the vapor nucleus increases, and this leads to liquid overheating. The temperature head of the beginning of boiling increases. Energy is accumulated in the liquid and in the heat-transferring wall and spent subsequently on vaporization at the moment of explosive boiling. In [1], it is shown that under low-pressure conditions, even small overheating of liquid creates great opportunities for the growth of vapor bubbles. Due to the low vapor density, the growth rate of vapor bubbles increases significantly, the process of vapor bubble formation is explosive [2]. In [3], the mechanism of explosive boiling up of liquid in a thin layer at low pressures is described in detail. The destruction of the layer occurred as a result of the development of a disturbance at the upper boundary. The development of explosive boiling is divided into two periods. In the first period, a smooth change in the parameters over time is observed, and then significant pulsations of pressure and other parameters are observed. The graphs of changes in parameters over time are given. At the first stage, the temperature of the heating surface increases, and the heat flux passing through the heating surface decreases. The heat load on the heater remains constant. This means that part of the heat flux in this unsteady process is accumulated by the massive heating surface. With the explosive boiling of liquid, the surface temperature decreases. The energy accumulated by the massive heating surface is spent on liquid evaporation.

This work is devoted to the issue of determining the temperature head for calculating the heat transfer coefficient during explosive boiling of a liquid under conditions of low pressure. The tasks of the work include determination of the method for finding the characteristic pressure during explosive
boiling and determination of deviations in the values of the heat transfer coefficient obtained by different methods.

2. Experiments

The experiments were carried out on a heat exchange vacuum unit operating on the thermosiphon principle. A detailed description of the installation is given in [4].

In the experiments, n-dodecane was used as the working liquid; the heating surface was smooth (roughness $R_z = 3.2 \, \mu m$). Before the start of the experiments, the amount of working fluid required to create a layer of a certain height was poured onto the bottom of the working chamber. Further, the liquid was degassed with a decrease in pressure in the volume of the working chamber. During degassing, characteristic bubbling was observed caused by the removal of dissolved air bubbles. In the course of the experiments, several stationary heat transfer regimes were implemented, at which the temperatures were recorded along with the thickness of the heated bottom, and the pressure above the liquid layer in the volume of the working chamber, and at the same time, the process was filmed with a high-speed video camera. The experiments were carried out at a layer height, $h = 40 \, \text{mm}$, and pressure above the layer $P_S (P_S/P_{cr})$: 133 (7.4·$10^{-5}$), where $P_S$ and $P_{cr}$ are the saturation pressure in the volume of the working chamber above the liquid layer and the critical pressure [Pa], respectively.

The temperature distribution along the bottom height was determined by the readings of five thermocouples located at different heights in the bottom. The temperature gradient in the bottom and the temperature of the heating surface were determined by interpolating the readings of thermocouples, by a straight line using the least-squares method using a linear regression model. The total surface temperature measurement error was about ± 0.3°C. The equation for the temperature distribution obtained after interpolation (1):

$$T = T_w + \frac{\partial T}{\partial x} x,$$

where $T_w$ is the temperature of the heating surface, °C; $x$ is the coordinate, measured from the heating surface, m. The heat flux directed to the bottom was determined using the Fourier equation (2):

$$q = -\lambda \frac{\partial T}{\partial x},$$

where $\lambda$ is thermal conductivity, W/(m·°C). The calculated error was about ± 16% at a heat flux of $10^3$ W/m²; ± 10%, at a heat flux of $10^4$ W/m², and ± 4% at a heat flux of $10^5$ W/m². The higher the heat flux, the smaller the error. The heat transfer coefficient was calculated using the formula (3):

$$\alpha = \frac{q}{T_w - T_s},$$

where $T_s$ is the saturation temperature of vapor, °C. The saturation temperature was determined from the pressure of saturated vapors using the dependence of vapor pressure on temperature, taken from the reference book [5]. Pressure measurement error of the current sensor readings was ± 0.5%.

3. Results and discussion

At a pressure of 133 Pa, the evaporation/boiling process of n-dodecane between convective regime (figure 1) and constant boiling regime (figure 2(f)) has a transient regime characterized by periodic explosive boiling (figure 2(a-e)).
Boiling began in the form of separate short-term boiling-ups (figure 2(a)), which were explosive. At the moment of boiling, the liquid layer was destroyed, accompanied by droplets flying upwards, as a result, a huge amount of vapor was ejected into the chamber volume, which led to an increase in pressure (figure 2(a-e)). Then the liquid returned to a non-boiling state, in which heat transfer occurred in convection regime, and the pressure returned to its original value (figure 2(a-e)).

Figure 1. Time dependence of pressure in the convection regime of n-dodecane at a layer height of 40 mm and operating pressure in the chamber of 133 Pa and a heat flux of $1.8 \times 10^3$ W/m$^2$.

The duration of boiling periods and pauses between them depended on the heat flux: at low values (figure 2(a, b)), the duration of boiling periods was measured in seconds (about 10 s), and the pauses between them could reach several minutes. With increasing load, the duration of boiling increased, and the pauses, on the contrary, decreased in duration and became rarer (figure 2(c-e)). At loads somewhat higher than 80 kW/m$^2$, the pauses in the process of vaporization disappeared and boiling acquired a relatively even, stable character (figure 2(f)). This boiling regime existed in a narrow range of heat loads immediately preceding the crisis.

As a result of strong pressure pulsations (figure 2(a-e)), the problem of calculating the heat transfer coefficient arises, which is associated with the difficulty in determining the temperature head. The temperature head depends on the temperature of the saturated vapor of liquid ($T_S$), which directly depends on the choice of the characteristic pressure. As a result of pulsations, the pressure values change as much as by 2.7 times, and the temperature of saturated vapors of n-dodecane changes by 14.6 K.

When calculating the heat transfer coefficient, the temperature of the heating surface ($T_W$) was used equally to the moment preceding the explosive boiling. The saturated vapor temperature was determined at a pressure close to the value set at the beginning of the experiment (figure 1). When switching to the explosive boiling regime, the pressure in the working chamber was maintained in such a way that the pressure set at the beginning of the experiment was between the pressures corresponding to convection and explosive boiling (figure 2(a-e)). As it can be seen from figure 2, the predetermined pressure of 133 Pa was set closer to the pressure corresponding to the heat transfer regime, the duration of which was longer. So in figure 2(a), the specified pressure is shifted closer to the pressure corresponding to the convection regime, since the convection regime lasts ~ 50 s, and
explosive boiling lasts ~ 10 s. In figure 2(c), the specified pressure is shifted closer to the explosive boiling regime, since its duration is longer.

Figure 2. Time dependence of pressure in the mode of explosive boiling of n-dodecane at a layer height of 40 mm and operating pressure in the chamber of 133 Pa: a) heat flux equal to $2.7 \times 10^4$ W/m$^2$; b) $3.3 \times 10^4$ W/m$^2$; c) $6.7 \times 10^4$ W/m$^2$; d) $7.4 \times 10^4$ W/m$^2$; e) $8.0 \times 10^4$ W/m$^2$; f) $8.5 \times 10^4$ W/m$^2$. 
Figure 3. The heat transfer coefficient during evaporation/boiling of n-dodecane at a layer height of 40 mm and operating pressure in the chamber of 133 Pa, calculated at the saturation temperature of n-dodecane vapor: 1 – with the arithmetic mean of the pressure; 2 – at maximum pressure; 3 – at minimum pressure; 4 – at a pressure of 133 Pa.

Figure 3 shows the graphs of the dependence $\alpha(q)$ calculated at different saturation temperatures. Saturation temperatures were determined at different values of the characteristic pressure. The plots in figure 3 can be divided into three sections, the first section (initial) corresponds to the convective heat transfer regime, the second section corresponds to explosive boiling, and the third corresponds to constant boiling. It can be seen that the heat transfer coefficients depend on the selected characteristic pressure only for the area with explosive boiling (figure 3). For comparison, the heat transfer coefficients were calculated at minimum pressure (figure 3(3)) and at maximum pressure (figure 3(2)), on average, the difference between them was 20%.

In this work, the saturation temperature of n-dodecane vapor at a pressure of 133 Pa was used to determine the heat transfer coefficient (figure 3(4)). The calculated value of the heat transfer coefficient at a given temperature of saturated vapor differed on average by 5% from the heat transfer coefficient calculated from the temperature of saturated vapor taken at the arithmetic mean of the pressure (red line in figure 1(a), figure 2(a-f)).

4. Conclusion

It was found that the evaporation/boiling of liquid at low pressures has a zone with explosive boiling, the frequency, and duration of boiling increase with an increase in the heat flux.

It is shown that the difference between the heat transfer coefficients, calculated from the temperature head at pressures (saturation temperatures) corresponding to the maximum and minimum pressure in area with explosive boiling differ on average by 20%. The heat transfer coefficients in the area with explosive boiling calculated from the temperature at a predetermined pressure, set in the experiments with the duration of time intervals explosive boiling, differed on average by 5% from the heat transfer coefficients calculated from the arithmetic mean of the pressure.
In the region of continuous boiling, the heat transfer coefficients calculated from the temperature head at the pressure (saturation temperature) corresponding to the maximum, minimum arithmetic mean and specified pressure differed by less than 2%.

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References
[1] Labuntsov D A, Yagov V V 1975 MPEI 268 3 (in Russian)
[2] Zijl V, Stralen S J van and Vries D A de 1976 All-union conference on heat and mass transfer 3 1 106
[3] Zhukov V I and Pavlenko A N 2021 AIP Adv. 11 015341
[4] Zhukov V I and Pavlenko A N 2018 Int. J. Heat Mass Transf. 117 978
[5] Yaws C L 1995 Gulf Publishing Company 3 398