Maps of hydrodynamic regimes of evaporation and boiling in the thin horizontal liquid layer on the modified surface

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Abstract. The paper reports the results of the study of evaporation and boiling regimes of a thin horizontal liquid layer on a modified surface. The formation of various structures was observed at the different heat fluxes, pressures, and heights of the liquid layer. The paper presents maps of the hydrodynamic regimes of evaporation and boiling of thin liquid layers on a modified surface. The regions of existence of various structures observed in the layer are indicated depending on the pressure and heat flux. The results are compared with the calculation dependencies.

1. Introduction

Horizontal thin films of liquid are used in cooling and thermal stabilization systems due to the possibility of removing high heat fluxes at low overheats. In [1], maps of hydrodynamic regimes of evaporation and boiling in a thin layer of liquid are presented. At low pressure, structures in the form of “funnels” and “craters” were formed in the layer. “Funels” are recesses with a hemispherical bottom in the thin liquid layer. “Craters” as opposed to the “funnels” have a flat elongated residual liquid layer of finite size at the center of the recess. Low operating pressure reduces the saturation temperature of a working fluid and thus reduces the temperature of a cooling surface. In [2] it is shown that formation of structures in the form of “funnels” and “craters” also leads to an increase in the heat transfer coefficient by ≈ 70% compared to bubble boiling at the same layer height values. However, when thin films are heated, explosive boiling with strong temperature and pressure pulsations may occur. The film also breaks with the formation of dry spots when the critical heat flux (CHF) is reached. The modified surface allows to enhance the heat transfer significantly and increase the value of the CHF.

This paper presents the experimental research findings on the limits of evaporation conditions and bubble boiling in horizontal liquid layers of various heights at reduced pressures on the modified surface. Boiling curves were obtained in the experiments for different pressures over the n-dodecane layer. Measurements of heat transfer characteristics were performed simultaneously with visual observations of structures formed in the layers. The maps of the hydrodynamic regimes of evaporation and boiling on a modified surface are compiled based on a comparison of experimental results with the observed structures. The paper also presents a comparison of the CHF with known calculation dependencies.
2. Experiments

2.1. The experimental setup
The detailed description of the experimental setup is given in [3]. The working chamber is a cylindrical vessel made of 12Cr18Ni10Ti steel with an internal diameter of 120 mm, a height of 300 mm, and a wall thickness of 1 mm. The experimental setup is equipped with observation windows, through them video recording was carried out by a high-speed camera. N-dodecane was used as the working fluid. The experiments were carried out within the layer height range of \( h = 1.7-4 \) mm or dimensionless values of \( (h/l_\sigma) = 0.99-2.32 \), where \( h \) is the layer height, mm; \( (h/l_\sigma) \) is a dimensionless layer height; \( l_\sigma = \sqrt{\sigma / g(\rho_i - \rho_v)} \) is Laplace constant, m; \( \sigma \) is the surface tension, N/m; \( \rho_i, \rho_v \) are liquid and vapour densities, respectively, kg/m\(^3\); \( g \) is the gravitational acceleration, m/s\(^2\). The pressure range in the experiments is \( P = 33-40000 \) Pa or reduced pressure values of \( (P/P_{cr}) = 1.84 \cdot 10^{-5}-0.022 \), where \( P_{cr} \) is critical pressure, Pa.

2.2. The parameters of the modified surface
The capillary-porous coating was made by using the 3D laser printer [4] (figure 1). The coating consists of 15Ni5Cu4Nb powder sintered by SLS (selective laser sintering). The porosity of the coating is \( \varepsilon = 0.44 \). The profile of the capillary-porous coating is a sinusoid, which is approximated by the equation:

\[
 z = A \frac{\sin \left( \frac{2\pi x}{\lambda_m} \right)}{2} + \frac{A}{2} + \delta_0 ,
\]

where \( z \) is a vertical coordinate, m; \( x \) is a horizontal coordinate, m; \( \delta_0 \) is the thickness of a continuous coating without shaping, m; \( \lambda_m = 2l_\sigma \) is the distance between the ribs, m; \( A = l/3 \) is the rib height, m.

3. Results and discussion
In the liquid layers, depending on the height of the layer and the pressure, structures of three main types were formed: “funnels”, “craters” and bubble systems. In a layer with a height of 1.7 mm \( (h/l_\sigma = 0.99) \), “funnels” were formed in the pressure range of \( 1.83 \cdot 10^{-5}-6.62 \cdot 10^{-4} \), and were evenly distributed over the entire surface (figure 1 (a)). As the heat flux increased, the layer thinned until it evaporated completely (figure 1 (c)). At the reduced pressures of more than 0.001 in the 1.7 mm layer bubbles are formed, which merge into a foam with an increasing heat flux (figure 1 (b)). The value of the CHF obtained in a 1.7 mm layer on the capillary-porous surface is significantly lower than the value obtained on a smooth surface [1]. At the reduced pressure of \( 5.51 \cdot 10^{-4} \) the highest value of superheat \( (T_w - T_s) \) was obtained, where \( T_w, T_s \) are wall temperature and saturation, respectively. Also, at the reduced pressure of \( 5.51 \cdot 10^{-4} \), the lowest value of the CHF was obtained due to the transition mode between areas of existence of the “funnels” and bubbles.

At the reduced pressures below 0.0005, “craters” were formed in layers with the height of 2.5 \( (h/l_\sigma = 1.4) \) and 4.0 mm \( (h/l_\sigma = 2.32) \) (figure 1(d)). With pressure increasing their size decreased but their quantity and occurrence frequency increased. At the reduced pressures of more than 0.0005, bubble boiling occurred in layers with a height of 2.5 and 4.0 mm.
Figure 1. (a) – “funnels” in the layer height of $h = 1.7$ mm ($h/l_\sigma = 0.99$); pressure $P_s = 133$ Pa, $q = 4990$ W/m$^2$, $(T_w - T_s) = 18$ K; (b) – bubbles and foam in the layer height of $h = 1.7$ mm ($h/l_\sigma = 0.99$); pressure $P_s = 5000$ Pa, $q = 18000$ W/m$^2$, $(T_w - T_s) = 12$ K; (c) – dry spots in the layer height of $h = 1.7$ mm ($h/l_\sigma = 0.99$); pressure $P_s = 400$ Pa, $q = 4300$ W/m$^2$, $(T_w - T_s) = 27$ K; (d) – “craters” in the layer height of $h = 4.0$ mm ($h/l_\sigma = 2.32$); pressure $P_s = 33$ Pa, $q = 17900$ W/m$^2$, $(T_w - T_s) = 31$ K.

According to the results of visual observations, it was found that in the range of reduced pressures ($7.35 \times 10^{-5}$–0.011) in the 4.0 mm layer on the surface of the capillary-porous coating, macrolayer zones were formed. The macrolayer is a thin film of liquid that forms in the precrisis heat transfer regimes on a heating surface with a capillary-porous coating (figure 2). An increase in the zones of the macrolayer between fluid volume and heating surface leads to a significant increase in the share of heat transferred due to intensive evaporation. The presence of local zones of the macrolayer provides an enhancing of boiling heat transfer on the modified surface. The smallest values of the heat flux were obtained at the reduced pressure of 0.0005. The macrolayer was observed at those values. The values of heat fluxes, at which dry spots formed due to the evaporation of liquid from the macrolayer, significantly depend on the layer height.
Figure 2. (a) – macrolayer in the evaporation mode with the formation of “craters”, a layer height $h = 4.0$ mm ($h/l_\sigma = 2.32$); pressure $P_s = 665$ Pa, $q = 81800$ W/m$^2$, $(T_w-T_s) = 21$ K; (b) – macrolayer in the bubble boiling mode, a layer height $h = 2.5$ mm ($h/l_\sigma = 1.4$); pressure $P_s = 1200$ Pa, $q = 47300$ W/m$^2$, $(T_w-T_s) = 16$ K.

The maps of hydrodynamic regimes of evaporation and boiling in a thin horizontal liquid layer are shown in figure 3. In figure 4(a), the values of CHFs are compared with known dependencies of Kutateladze [5], Yagov [6], and Landau [7]. In figure 4 (b), the CHFs for the 1.7 mm layer are compared with the heat fluxes of the onset bubble boiling in the 2.5 and 4.0 mm layers.

Figure 3. Maps of hydrodynamic regimes of evaporation and boiling in the thin horizontal liquid layer on the modified surface: (a) 1 – convection; 2 – “funnels”; 3 – the drying; 4 – bubbles; 5 – bubbles with foam; 6 – CHF according to [4]; 7 – CHF according to [5]; (b) 1 – convection; 2 – “craters”; 3 – the macrolayer under “craters”; 4 – bubbles; 5 – the macrolayer under bubbles; 6 – CHF according to [5]; 7 – CHF according to [6]; 8 – CHF according to [7].
Figure 4. Comparison of the CHF: (a) 1 – 1.7 mm \((h/l_σ = 0.99)\); 2 – 2.5 mm \((h/l_σ = 1.4)\); 3 – 4.0 mm \((h/l_σ = 2.32)\); 4 – CHF according to [5]; 5 – CHF according to [6]; 6 – CHF according to [7]; (b) 1 – CHF in the layer height of 1.7 mm \((h/l_σ = 0.99)\); 2 – the onset of boiling in the layer height of 2.5 mm \((h/l_σ = 1.4)\); 3 – the onset of boiling in the layer height of 4.0 mm \((h/l_σ = 1.4)\).

The value of the CHF depends strongly on the height of the liquid layer. Thus, the CHF obtained in a layer with a height of 4.0 mm is higher than the values calculated from the known dependencies of Kutateladze [5] and Yagov [6]. Their value is limited from above by the theoretical Landau dependence [7]. With the layer height of 1.7 mm, the macrolayer was not formed. The value of the CHF obtained in the layer height of 1.7 mm in the range of the reduced pressures \(1.83 \times 10^{-5} - 6.62 \times 10^{-4}\) is close to the value of the heat fluxes at which boiling began in layers with height of 2.5 and 4.0 mm. To start boiling a liquid on the modified surface in this range, the layer height must be at least \((h/l_σ = 1.0)\).

In a thinner layer, a dry spot occurs at low heat fluxes. Also, in the range of the reduced pressures of 0.001 and 0.002 (figure 4(b)), nucleate boiling in layers with height 2.5 and 4.0 mm started at low heat fluxes \((\approx 2000 \text{ W/m}^2)\), while at a lower pressure and heat fluxes about 10000 W/m² the explosive boiling occurred with strong pressure and temperature pulsations.

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