A map of regimes of evaporation and boiling in the horizontal liquid layer on the modified surface

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Abstract. The paper presents the results of the study of the evaporation and boiling regimes in thin horizontal layers of liquid on a modified surface in a wide range of changes in the pressure and height of the liquid layer. Depending on the heat flux, pressure, and height of the liquid layer, the formation of various structures was observed. In this paper, maps of the evaporation and boiling regimes are obtained, which show the heat fluxes from the natural convection regime up to the boiling crisis, depending on the height of the liquid layer. The results are compared with the calculation dependencies.

1. Introduction
The evaporation and boiling of thin films of liquid are used in various heat and mass transfer devices (evaporators, distillation columns, heat pumps and pipes, diffusion vacuum pumps, spray cooling systems, air conditioning, etc.). Horizontal thin films of the liquid allow the removal of high heat fluxes at low temperature head. The use of modified surfaces also allows multiplying the heat transfer coefficient.

The aim of the work was an experimental study of heat transfer during evaporation and boiling in a layer of a single-component liquid on a horizontal heating surface with a capillary-porous coating applied in a wide range of changes in the pressure and height of the liquid layer. In the experiments the boiling curves were obtained at different pressure values over the n-dodecane layer. Measurements of the regime parameters were carried out simultaneously with visual observations of the structures formed in the layers. Based on the comparison of the experimental results with the observed structures, maps of the evaporation and boiling regimes are constructed.

2. Experiments
The detailed description of the experimental setup is given in [1]. 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 spiral heater is located at the bottom of the working surface, allowing to evenly heat the bottom of the working chamber. The working chamber is equipped with viewing windows, through which the video recording of the evaporation and boiling processes taking place in the working chamber was carried out.
The capillary-porous coating was made by using the 3D laser printer [2] (figure 1(a)). The coating consists of 15Ni5Cu4Nb powder sintered by SLS (selective laser sintering). The porosity of the coating is \( \varepsilon = 0.44 \), the particle size \((20–40) \mu m\). The 2-D profile of the capillary-porous coating is a sinusoid. Distance between fins \(3.5 \) mm, height of fins \(0.5 \) mm, maximum thickness of the porous coating used \(0.55 \) mm. A photo of the surface is shown in figure 1(a). A more detailed description of the modified surface is presented in [3]. N-dodecane was used as the working fluid. The pressure range in the experiments is \( P = (33 – 20000) \) Pa or reduced pressure values of \( P/P_{cr} = 1.84 \cdot 10^{-5} – 1.1 \cdot 10^{-2} \), where \( P_{cr} \) is critical pressure, Pa. The pressure in experiments was chosen in such a way that the experimental data obtained complied to the pressure range corresponding to the boundaries of intersection of dependences Yagov [4] and Landau [5]. Eq. [4] can be considered for a comparative assessment of the increase in critical heat flux (CHF) on the coating at low reduced pressures. In Landau’s theory, a layer of infinite depth is considered. CHF is independent of the conditions on the heating surface. Eq. [5] should be considered as some limiting case to which CHF can increase. The calculated point, where dependences [4] and [5] cross, corresponds to the n-dodecane saturation temperature of \(38.7\) C° and pressure of \(52\) Pa, \(P/P_{cr} = 2.9 \cdot 10^{-5}\). Experiments with water as a working fluid in the studied pressure range are impossible, since at a pressure of \(P/P_{cr} = 2.736 \cdot 10^{-5}\) water is in the triple point state and intersection of dependences Yagov and Landau is located far beyond the triple point (figure 1(b)).

![Figure 1](image)

**Figure 1.** (a) – photograph of a capillary-porous coating on a heat transfer surface; (b) – the CHF according to the Yagov [4] and Landau [5] dependences: 1 – calculation of [5] for water; 2 – calculation of [4] for water; 3 – [5] for n-dodecane; 4 – [4] for n-dodecane; 5 – the range of pressures and heat fluxes studied in this paper.

The experiments were carried out within the layer height range of \( h = 1.7 – 10 \) mm or dimensionless values of \((h/l_\sigma) = 0.99 – 5.56\), where \( h \) is the layer height, m; \((h/l_\sigma) \) is a dimensionless layer height; \( l_\sigma = \sqrt{\sigma / g(\rho_L – \rho_V)} \) – is Laplace constant, m; \( \sigma \) – is the surface tension, N/m; \( \rho_L, \rho_V \) – are liquid and vapour densities, respectively, kg/m\(^3\); \( g \) – is the gravitational acceleration, m/s\(^2\).

3. Results and discussion

When changing the height of the liquid layer, the pressure in the volume, and the heat flux, the following structures were formed: “funnels”, “craters” and bubble systems. “Funnels” were observed in the 1.7
mm layer in the range \( P_v/P_{cr} = 1.822 \cdot 10^{-5} - 6.623 \cdot 10^{-4} \) from the start of heating to the boiling crisis. “Funnels” look like cavities with a hemispherical bottom on a surface of the liquid layer [1]. It differs in size, and its location is determined by the microstructure of the coating on the heating surface. The number of “funnels” increased with increasing heat flux. “Craters” were observed in the (2.5–4.0) mm layers in the range \( P_v/P_{cr} = 1.822 \cdot 10^{-5} - 7.358 \cdot 10^{-5} \). “Craters” are cavities in a thin layer, but unlike dry spots, there is a residual layer of liquid in the centers of the “craters” [1]. When the pressure increased, single large bubbles formed instead of “craters”. In the pressure range \( P_v/P_{cr} = 2.758 \cdot 10^{-3} - 1.1 \cdot 10^{-2} \) rapid bubble boiling was observed over the entire value of the change in the layer heights even at low heat fluxes. Ranges of the regime parameters of the formation of structures in liquid layers are presented in Table 1. The heat transfer coefficient was calculated by the following expression: \( \alpha = q/(T_w-T_s) \), where \( q \) is the heat flux, W/m²; \( T_w \) is the wall temperature, K; \( T_s \) is the saturation temperature. Shots of the processes observed in different layers of the liquid at different pressures are shown in figure 2.

| Table 1. Ranges of the regime parameters of the formation of structures in liquid layers. |
|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| \( h \) | \( h/l_\sigma \) | \( P_v, \text{ Pa} \) | \( P_v/P_{cr} \) | \( q, \text{ W/m}^2 \) | \( \alpha, \text{ W/(m}^2\text{K}) \) |
| 1.7 | 0.99 | 33-1200 | 1.822\( \cdot 10^{-5} \)-6.623\( \cdot 10^{-4} \) | 512-13350 | 82-694 |
| 2.5 | 1.4 | 33-133 | 1.822\( \cdot 10^{-5} \)-7.358\( \cdot 10^{-5} \) | 9628-70140 | 748-2345 |
| 4.0 | 2.32 | 33-133 | 1.822\( \cdot 10^{-5} \)-7.358\( \cdot 10^{-5} \) | 15580-74380 | 514-3260 |
| 1.7 | 0.99 | 5000-20000 | 2.758\( \cdot 10^{-3} \)-1.1\( \cdot 10^{-2} \) | 1740-22280 | 135-1765 |
| 2.5 | 1.4 | 399-20000 | 2.203\( \cdot 10^{-4} \)-1.1\( \cdot 10^{-2} \) | 2391-96330 | 252-8120 |
| 4.0 | 2.32 | 399-20000 | 2.203\( \cdot 10^{-4} \)-1.1\( \cdot 10^{-2} \) | 1515-194800 | 166-25699 |
| 10.0 | 5.56 | 33-20000 | 1.822\( \cdot 10^{-5} \)-1.1\( \cdot 10^{-2} \) | 2409-181200 | 262-22970 |

“Macrolayer” zones were formed with an increase of the heat flux in the layers of (2.5–10.0) mm (figure 3). The presence of such “macrolayer” zones ensures the intensification of heat transfer during evaporation and boiling on a structured surface with a coating. A higher heat transfer in the zones of the “macrolayer” is caused by a significant decrease in the local temperature of the heat-releasing surface [6]. It is convenient to represent the data of table 1 in the form of maps of hydrodynamic regimes of evaporation and boiling. In [1], maps of hydrodynamic regimes were proposed, on which, for each height of the liquid layer, the regions of existence of structures are indicated, depending on heat fluxes and reduced pressure. The authors of [7] proposed maps on which, for a constant pressure above the layer, the regimes of liquid evaporation and boiling are shown depending on the heat fluxes and the layer height. Maps of the hydrodynamic regimes of evaporation and boiling on the modified surface are constructed in this paper. The abscissa axis was chosen as the dimensionless layer height \( h/l_\sigma \) to create these maps. The maps show the regimes from natural convection up to the boiling crisis. Maps of
hydrodynamic regimes are shown in figure 4. Experimental data obtained at different heights of the liquid layer are also compared with the calculated dependences of Yagov [4] and Landau [5].

The maps show that the increase in the layer height from 1.7 mm ($h/l_\sigma = 0.99$) to 4.0 mm ($h/l_\sigma = 2.32$) increases the value of the CHF by an order of magnitude at all operating pressures. At the same time, a further increase in the layer height to 10 mm ($h/l_\sigma = 5.56$) does not significantly affect the increase in the CHF. In a layer of 1.7 mm at pressures up to 1000 Pa and heat fluxes, in which a transition from convection to “craters” or bubbles was observed in thicker layers, the surface was drained [8]. The CHF obtained on the modified surface for layers of 4.0 mm and 10.0 mm are higher than the calculated values according to the Yagov dependence. Deviations from the Yagov dependence are explained by the formation of “macrolayer” zones, which is characterized by a significant difference in the hydrodynamics of the movement of liquid and steam in the wall region on a surface with a capillary-porous coating in liquid layers of finite height compared to the movement of liquid in the wall region on a smooth surface. CHF at very low relative pressures on a capillary-porous coating is limited from above by the Landau dependence, which was obtained for processes without taking into account surface conditions.

![Figure 2. Shots of the structures observed in n-dodecane layers.](image)
Figure 3. A shot of the “macrolayer”: 
\[ h = 4.0 \text{ mm}; \]
\[ h/l_\sigma = 2.32; \]
\[ P = 133 \text{ Pa}; \]
\[ Pv/P_{cr} = 7.358 \cdot 10^{-5}; \]
\[ q = 97230 \text{ W/m}^2; \]
\[ T_w - T_s = 33 \text{ K}. \]

Figure 4. Maps of the hydrodynamic regimes of evaporation and boiling on the modified surface: 1 – “funnels”; 2 – the drying; 3 – convection; 4 – “craters”; 5 – bubble systems; 6 – zones of the “macrolayer”; 7 – CHF according to [4]; 8 – CHF according to [5].
4. Conclusion
The experimental study of heat transfer and crisis phenomena during evaporation and boiling of thin horizontal layers of liquid under reduced pressures on a modified heating surface is performed. In this paper, the dependences of CHF on the height of the liquid layer at different pressures are shown together with the designation of the regimes that were implemented in the heat transfer process. The resulting maps show the regimes of evaporation and boiling from the regime of natural convection up to the boiling crisis. The values of CHF increased by an order of magnitude with an increase in the layer height from 1.7 mm to 4.0 mm, but with a further increase in the layer height, the values of CHF increased slightly.

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