Heat transfer at evaporation/boiling in the thin horizontal liquid layer on microstructured surfaces under low pressures

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Abstract. The results of the experimental study of heat transfer during boiling of n-dodecane on a capillary-porous surface are presented. The surface is coated using a 3D laser printer. The dependence of the heat transfer coefficient on the heat flux density under different pressures and liquid layer heights is studied. The obtained experimental data were compared with the values obtained during evaporation/boiling on a plain surface under the same conditions.

1. Introduction
The capacity of technical equipment depends at a larger extent on the cooling system operation under conditions of significant heat flows removal to keep the temperature below the certain level, thereby preventing damages and maintaining performance. At present, two-phase cooling systems using latent heat of vaporization are recognized to be the most efficient. Preference is given to passive cooling schemes, which apply pool boiling of the working liquid [1, 2]. The use of modified surfaces is a practical way to reduce temperature difference and increase critical heat flux (CHF). The techniques of modified porous surface construction are described in [3] and focused on heat transfer intensification at pool boiling. The experiments [4, 5] were carried out to study heat transfer processes in thin liquid films at low pressure on a capillary-porous surface in operating conditions of flat-plate heat pipe systems. The experiments showed the difference between heat transfer regimes under atmospheric and low pressures. For instance, nucleate boiling did not occur under low pressure. Although the steam-saturation temperature was changing, it tended to grow with the increase of the heat flux [4, 5]. In [6], the evaporation/boiling regime on capillary fed copper particle sintered porous wicks is experimentally investigated at the same reduced pressure to compare the heat transfer performance of wicks with a different particle size, particle type and the wick thickness. The experiments were done at constant pressure of 9.6 KPa; that corresponds to the water-saturation temperature of 45°C. The liquid level may have receded into the wick when the heat flux was high enough to induce boiling heat transfer, therefore, the bubble nucleation cannot be observed experimentally. This is particularly true for the case of a large heating area, such as in the study [6]. The experiments described in the studies [7, 8] demonstrate the absence of bubble nucleation boiling under variation of the heat flux, up to crisis phenomena development on the plain horizontal surface of the thin liquid film. The paper [9] presents the systematic study of evaporation and boiling regimes in a thin horizontal layer of the liquid on the
plain surface at large variations of layer heights and reduced pressures. The diagrams of hydrodynamic regimes have been constructed, where the boiling regions or their absence are indicated against each layer height, reduced pressure and the heat flux. This paper presents the results of the heat transfer experimental study of low-pressure evaporation and nucleate boiling in horizontal, different-height layers of n-dodecane on a capillary-porous surface.

2. Experiments
The experimental setup consists of a process chamber, a cooling system, a system for measuring pressure and temperature, a system of collecting and processing test data, and a system of heaters power control and supply. The process chamber was designed as a thermosyphon (figure 1). It is a cylindrical vessel of 12Cr18Ni10Ti steel with the internal diameter of 120 mm, the height of 300 mm and wall thickness of 1 mm. A 30–mm thick high heat--conducting brass plate was enclosed between the bottom and a heater in order to attain uniform of the heat flux on the heated surface. To reduce contact thermal resistance, the gap between the chamber bottom and the plate was filled with a special high heat-conducting paste. There is a cooling coil on the outer surface of the upper part of the chamber. The chamber is cooled by water flowing through the coil. To reduce heat losses due to the leakage along the chamber walls from the bottom to the cooling coil and to provide uniform temperature distribution at the chamber bottom, an optional coil for heating the chamber walls was fixed below the cooling coil. At the top and sides, the process chamber was fitted with the windows for visual observations. To measure the temperature of the heating surface, the copper-constantan thermocouples in stainless capillaries were inserted in five holes of 1.5 mm in diameter into the bottom at different heights. The heat flux was obtained from the temperature gradient measured along the centerline of the upper portion of the bottom using a linear fit from the output of five thermocouples by Fourier equation. The calculated uncertainty was about ±16% at heat flux of \( q = 10^3 \) W/m\(^2\), nearly ±10% at heat flux of \( q = 10^4 \) W/m\(^2\), and ±4% when the heat flux was \( q = 10^5 \) W/m\(^2\). The higher the heat flux, the lower is the uncertainty. The surface temperature was determined by linearly extrapolating the measured temperature profile to the surface. The overall uncertainty in the surface temperature measurement was found to be about ±0.3°C at 200°C. The pressure in the process chamber was measured by a deformation-ionization vacuum gauge and maintained constant. The uncertainty of the measured pressure is ±0.5% of the reading. A capillary-porous coating (figure 2(a)) was applied to the
bottom of the process chamber using a 3D laser printing SLS – method (selective laser sintering) technology [10]. The similar technique of surface coatings production is described in [11]. However, opposed to the technique in [11], solid melt of powder particles was not used in the present study. Judging by its properties, the capillary-porous coating is close to the coating made from a sintered metallic powder. The bottom of the process chamber (figure 2(b)) was 12 mm thick and used as a heating surface with the diameter of 120 mm.

![Figure 2](image)

**Figure 2.** Heating surface of the experimental facilities. (a) The photograph of the microstructured capillary-porous coating; (b) The bottom of the process chamber of the experimental setup with the microstructured capillary-porous coating.

The study of heat transfer at evaporation and boiling in thin horizontal liquid layers was conducted with the use of microstructured 2D modulated capillary-porous coatings, which contour could be approximated by the equation:

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

where \(z\) – a vertical coordinate, m; \(x\) – a horizontal coordinate, m; \(A = \delta - \delta_0 = 0.5 \cdot 10^{-3}\) – the rib height, m; \(\delta\) – maximum height of the coating, m; \(\delta_0 = 50 \cdot 10^{-6}\) – thickness of the continuous coating without contouring or shaping, m; \(\lambda_m = 2l_\sigma = 3.5 \cdot 10^{-3}\) – distance between the ribs, m; \(l_\sigma = (\sigma / g(\rho_l - \rho_v))^{1/2}\) – Laplace constant, m; \(\sigma\) – surface tension, N/m; \(\rho_l, \rho_v\) – liquid and vapour density, respectively, kg/m\(^3\); \(g\) – acceleration of gravity, m/s\(^2\). The coating was made by applying the powder LPW 155 (15-5PH) from stainless steel, with the particles size of 20-40μm, and porosity \(\varepsilon = 0.44\).

Prior to the experiments, a certain amount of liquid (n-dodecane), required to form a layer of a desired thickness, was poured onto the bottom. When decreasing pressure in the process chamber, the liquid was deaerated; that was recorded by termination of characteristic bubbling caused by removal of bubbles of dissolved air. For more complete deaeration, the working liquid was boiled under vacuum for several hours.

The experiments were carried out at the pressure of \(P / P_{cr}\): 0.133 (7.4·10\(^{-5}\)), 1 (5.5·10\(^{-4}\)), 10 (5.5·10\(^{-3}\)), 20 (1.1·10\(^{-2}\)), where \(P\) and \(P_{cr}\) are pressure and critical pressure, respectively, KPa; \((P/P_{cr})\) – reduced pressure. Studied layer heights \(h (h/l_\sigma)\): 1.4 (0.81), 1.7 (0.99), where \(h\) – layer height, mm; \((h/l_\sigma)\) – dimensionless layer height.

During the experiments, a number of steady heat transfer conditions were achieved. At these stationary regimes, the temperatures over the heated wall thickness, as well as pressure over the liquid layer in the chamber were registered. The data of visual observations were recorded by high-speed
video camera. The CHF was determined by the moment of the sharp increase in the heating surface temperature at a constant heat flux.

3. Results and discussion

The heat flux density \( q \), W/m\(^2\), the temperature of the heating surface \( T_w \), K at constant pressure over the layer were experimentally determined. The saturated-steam temperature in \( T_s \), K was calculated from the steam pressure. The heat transfer coefficient was calculated by the formula \( \alpha = q/(T_w - T_s) \), W/(m\(^2\)·K). The results were compared with the experimental data on heat transfer [9, 12] obtained for the given experimental setup during evaporation/boiling of n-dodecane on a plain surface. Figure 3 presents the results obtained for the regime of nucleate boiling. The curve of nucleate boiling with the negative slope was constructed for the 1.4-mm high layer (see figure 3(a)). The similar type of dependence was traced in most studies; in [11] it was observed for the pool boiling of the liquid. This type of the curve behavior is presented and discussed in the review [1]. The nucleate boiling tends to start at lower heat flux on the surfaces with the capillary-porous coating, compared with the coating-free surfaces. The temperature difference is 3-4 time less for the coated surfaces. Figure 3(b) presents data on heat transfer coefficients on the plain surface and on the surface with a capillary-porous coating for two heights of the liquid layer. It’s a well-known fact that the heat transfer coefficients tend to increase with a rise of pressure on the plain surface. The pressure is seen to have less effect on the heat transfer coefficients on the capillary-porous coating. The heat transfer coefficients are 3-5 times higher on the capillary-porous coating compared with the uncoated surface. As shown in figures 3(a) and 3(b), heat transfer intensification is higher for the lower pressure.

The nucleate boiling was absent in the range of low pressures – \( P (P/P_c) \): 0.133 \((7.4 \cdot 10^{-5})\), 1 \((5.5 \cdot 10^{-4})\) KPa both on capillary-porous and plain surfaces [9]. The liquid evaporated from the surface coating at relatively low heat fluxes. The liquid level over the total surface, apart from the area near the chamber walls, tended to decrease with a rise of the heat flux. The ribs were dampened with the liquid and projected above the surface. The liquid was fed along the troughs between the ribs. At some moment in time, pressure pulsations occurred within the working chamber, the surface became partially dry, the liquid level was falling, and a dry spot emerged. While moving round the surface, the dry spot was shrinking or increasing in size. Large-scale low-frequency pulsations of pressure were observed in the total volume depending on the change of the dry spot size at 10-second intervals. The
pulsation frequency tended to rise with the increase of the heat flux. The heat transfer coefficient increased sharply with the emergence of the dry spot, and the heat transfer intensified by a factor of 4 - 5 (figure 4). When the pressure reached $P = 0.133$ KPa, the heat transfer coefficient increased at the heat flux density of $q = 9.8 \times 10^3$ W/m$^2$. However, at $P = 1$ KPa, the heat transfer coefficient increased at the heat flux density of $q = 2 \times 10^4$ W/m$^2$. The moving objects, called “craters” [7-9], form on the plain surface within this range of pressure variations in the thin liquid layer. The “craters” surface is covered with a residual layer of the liquid. The absence of nucleate boiling in the thin liquid layer on the capillary-porous surface at low pressure was observed in the experiments [4–6] with the use of water as a working liquid. As suggested in these studies, the liquid layer decreased or passed into the capillary-porous coating. The movement of the forming objects was not noticed, because much smaller heating surfaces were used. In [4, 5], the heating surface was a square with a side of 11 mm, and in [6] it was a square with a 30 mm side. In the present study, the diameter of the heating surface with the capillary-porous coating was several times larger.

Figure 5 presents a comparison of the experimental data on the CHF values obtained on the capillary-porous surface in the present study with the results obtained in [9] for the plain surface.

The graphs demonstrate that the CHF value obtained on the capillary-porous surface within the studied pressure range significantly depends on the layer height and reduced pressure. The calculated dependences determined by the Kutateladze [13] and Yagov [14] formulae are given on the graph for comparison. Significant deviations from the Kutateladze calculated dependence for the plain surface within the reduced pressure range are explained by the change of the heat transfer mechanism (absence of nucleate boiling), and by the impact of intensive liquid evaporation from the upper free layer boundary. It also confirmed that CHF for evaporation/boiling on the capillary-porous surface don’t exceed the values calculated by the Kutateladze formula. The change of the heat transfer mechanism was observed in comparison with conditions of pool boiling. It should be noted that the layers of small heights were studied in this research. Consequently before and during the crisis, the liquid on the most portion of the heat transfer surface was inside the capillary-porous coating, where the free boundary of the liquid film was absent. Evaporation processes took place inside the coating and caused some reduction of CHF compared with the evaporation process in the layers with upper free boundary on the plain heating surface. Similar to the process of boiling/evaporation on the plain heating surface, there exists the pressure region, where CHF considerably depend on the height of the liquid layer and
slightly influenced by pressure. This region is biased towards higher pressures for heat transfer on the capillary-porous surface.

4. Conclusion
In this study was fabricated 2D modulated capillary-porous surface for evaporation and boiling heat transfer using 3D laser printing SLS – method (selective laser sintering) technology.

The nucleate boiling tends to start at lower heat flux on the surfaces with the capillary-porous coating, compared with the coating-free surfaces. The heat transfer coefficients are 3-5 times higher on the capillary-porous coating compared with the plain surface. Pressure has less effect on the heat transfer coefficients on the capillary-porous coating.

The CHF value obtained on the capillary-porous surface within the studied pressure range significantly depends on the layer height and reduced pressure.

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