Heat transfer at evaporation and boiling in thin horizontal liquid layers on smooth and micro-structured surfaces under low pressures

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Abstract. The analysis of the heat transfer investigation results has been carried out at boiling and evaporation in thin horizontal layers of liquid on smooth and structured surfaces. Intensive evaporation of thermal plumes at reduced pressure is considered to be the basic mechanism of heat transfer. The thermal plumes could make a significant contribution in heat transfer under conditions of bubble boiling on micro-structured and ribbed surfaces in the areas where vapour bubbles don’t emerge.

1. Introduction

Horizontal thin liquid films are used in cooling and thermal stabilization systems, diffusion vacuum pumps of special designs [1], contour heat tubes [2], and other types of process equipment. Smooth heating surfaces are usually applied for diffusion vacuum pumps, and surfaces with capillary-porous coatings are common for heat tubes. Papers [3–5] are devoted to the study of heat transfer and critical heat flux (CHF) towards a horizontal layer of vacuum oil under low pressure. The experiments [5] have shown that CHF tends to increase more than by the order of magnitude within a narrow range of variation in the layer height, and in the layers above Laplace constant its value is higher by the order of magnitude in comparison with the estimates obtained by Kutateladze formula [6]. The article [7] presents data on CHF and the areas of different structures emerging due to the conditions of boiling and evaporation in a thin liquid layer when the layer height and reduced pressure tend to vary within a broad range of values. N-dodecane was used as a process fluid in the experiments [7]. The structures in the form of “funnels” and “craters” were formed at low pressures in the layers with the thickness above Laplace constant under the action of the vapor recoil force [3-5, 7, 8]. “Funnels” represent recesses with a hemispherical bottom in the thin liquid layer. “Craters” in contrast to “funnels” have a flat elongated residual liquid layer of a finite size at the center of the recess. The study [8] provides the analysis of the impact which the structures formed owing to evaporation and boiling in thin layers of fluid (n-dodecane) have on heat transfer. It demonstrates that the formation of the structures in the shape of “funnels” and “craters” under conditions of intensive evaporation and low pressure results in
the increase of the surface heat-transfer coefficient by \( \approx 70\% \) in comparison with bubble boiling at the same layer height values.

This paper presents the experimental research findings on the limits of evaporation conditions and bubble boiling in horizontal n-dodecane layers of various heights at reduced pressures on the flat surface. The analysis of the obtained results has been carried out, and the findings have been compared with the estimates of the other studies to determine the basic mechanisms of heat transfer on structured micro-porous heating surfaces.

2. Experiments

The experimental setup is shown in figure 1. It consists of a process chamber fixed to the frame as shown in figure 1(a), a system of collecting and processing test data, a cooling system, a system for measuring pressure and temperature, and a system of power control and supply to heaters. The working chamber was constructed as a thermsyphon in figure 1(b). It is a cylindrical vessel of 12Cr18Ni10Ti steel with the internal diameter of 120 mm, height of 300 mm and wall thickness of 1 mm. The bottom of the working chamber was 12 mm thick and used as a heating surface. A 30 mm

![Figure 1](image)

Figure 1. Experimental facilities. (a) The photograph of the experimental setup; (b) The working chamber of experimental setup: 1 – thermocouples for measuring the temperature of the heated surface, 2 – case, 3 – thermocouples for measuring the cooling water temperature, 4 – branch pipe for securing the pumping system and measuring the pressure, 5 – vacuum inlet, 6 – inspection windows, 7 – cooling coil, 8 – heating coil, 9 – thermal insulation layer, 10 – brass plate, 11 – electric heater, 12 – electric heater cover.
Thick high heat-conducting brass plate was enclosed between the bottom and a heater in order to attain equipartition 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 special high heat-conducting paste. There is a cooling coil on the outer surface of the upper part of the chamber. The distance from the bottom of the chamber to the lower turn of the coil is 100 mm. The chamber was 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 evenly distribute the temperature over the bottom of the chamber, an optional coil for heating the lateral wall of the chamber (not shown in figure 1(b)) was mounted below the cooling coil. This optional coil was connected to the coil designed to warm the lid of the chamber. When mounting an optional heating element, the losses due to leakage, according to the estimated calculations, were not higher than 10% of the total heat flux through the bottom of the working chamber to liquid. At the top and sides, the working 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 $q = 10^4 \text{W/m}^2$, nearly ±10% at heat flux of $q = 10^5 \text{W/m}^2$, and ±4% when the heat flux was $q = 10^3 \text{W/m}^2$. 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. To measure the temperature of liquid, an additional thermocouple on the movable probe was used in the layer. The pressure in the working chamber was measured by a deformation-ionization vacuum gauge and maintained constant. The uncertainty of the measured pressure is ±0.5% of the reading.

During the experiments, a number of stationary heat transfer regimes were achieved. At these regimes the temperatures over the heated wall thickness, as well as pressure over the liquid layer in the chamber were registered, and video recording of the process was simultaneously carried out with the use of a high-speed video camera. The CHF was fixed by the instant of an increase in the heating surface temperature at a constant heat flux.

### 3. Results and discussion

The first stage of the heat transfer research test was conducted at boiling and evaporation in thin liquid films on a flat surface under conditions of layer heights and pressure variation within a broad range of values. The structures in the shape of “funnels” and “craters” appeared in n-dodecane layers (see in figure 2). The findings of the analysis allow obtaining data used to design micro-structured surfaces with capillary-porous coatings. Figure 3 shows the existence areas of dry spots, “funnels” and “craters”, and the growth of nucleate boiling under two conditions with limited layer heights: $h \,(h/l_n)$: 1.4 (0.81), 1.7 (0.99), where $h$ – layer height, mm; $(h/l_n)$ – dimensionless layer height; $\sigma = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$ – Laplace constant, m; $\sigma$ – surface tension N/m; $\rho_l, \rho_v$ – liquid and vapour density, respectively, kg/m³; $g$ – acceleration of gravity, m/s². The experiments were done within the pressure range of $P = 33 – 10^4 \text{Pa}$ or reduced pressure values of $(P/P_{cr}) = 1.84 \cdot 10^{-3} – 5.5 \cdot 10^{-3}$, where $P_{cr}$ is critical pressure, Pa. Dry spots occurred in the layer with the height less than Laplace constant under reduced pressure (see figure 3(a)), that was caused by the action of thermo-capillary forces. The uppermost points in figure 3 correspond to CHF. Pressure being increased on the surface side without dry spots, nucleate boiling started growing. At higher reduced pressures, the dry spots didn’t appear, and bubble boiling was observed in the entire area. When the layer height was approximately equal to Laplace constant at low reduced pressures, instability arose, and that led to the formation of “funnels” and “craters” (see figure 3(b)). Nucleate boiling was observed under high reduced pressures.
Figure 2. The structures observed in n-dodecane layers: (a) – “funnels”, \( h (h/h_0) \): 2.5 mm (1.45), pressure at volume \( P = 133 \text{ Pa} \ (P/P_{cr}) = 7.4 \times 10^{-5} \), \( q = 6.060 \text{ W/m}^2 \), \( (T_w - T_s) = 22.7 \text{ K} \); (b) – “crater”, 2.5 mm (1.45), 133 Pa \((7.4 \times 10^{-5})\) 12,800 W/m², 20.2 K.

Figure 3. Maps of hydrodynamic regimes of evaporation and boiling in n-dodecane layer: (a) 1 – nucleate boiling; 2 – dry spots in the layer; 3 – dry spots and nucleate boiling observed simultaneously in the layer, 4 – convection; calculated dependences: 5 – CHF according to [6], 6 – CHF according to [9]; (b) 1 – nucleate boiling, 2 – “craters” in the layer, 3 – “funnels” in the layer, 4 – “funnels” and “craters” observed together, 5 – convection. Calculated dependences: 6 – CHF according to [9], 7 – CHF according to [6], 8 – CHF according to [10]; 9 – the boundary between the different regimes of nucleate boiling.

The test data were processed [4] with regard to the total area occupied by the “funnels” on the fluid surface. In accordance with the obtained estimates the total area occupied by the “funnels” amounts to \( \approx 14\% \) from the entire unoccupied area of the surface liquid layer. If this occurs, about 60 – 66% of the heat will be transferred through the “funnels” surface, i.e. the “funnels” enhance the heat transfer at a
minimum by (2.5–3) times compared to the regime of natural convection in thin liquid layers on a horizontal heated surface. It is demonstrated in [11] that non-stationary heating of the high volume of fluid will result in instability at the top edge of the thermal boundary layer as a consequence, it causes thermals formation. The thermals or thermal plumes cover less than 21% of the horizontal cross-section at the border between the upper thermal boundary layer and the bulk, while they account for about 84% of the mean heat flux [12]. The “funnels” will be certain to form because of the intensive evaporation of the overheated fluid if the thermal plume rises to the unoccupied surface of the horizontal layer. The minimum layer height will be approximately equal to Laplace constant in case it is the reason of instability causing thermal plumes formation at the outer edge of the boundary layer (see figure 3(b)). At low reduced pressures, a contoured capillary-porous coating can be used as a ribbed surface. The research findings of turbulent natural convection on smooth and ribbed surfaces are presented in [13]. The grooved surface consists of parallel V-grooves with the groove height of 10 mm and groove width of 20 mm. The line plumes, which move randomly, are the dominant mechanism of heat transport for the smooth surface. Hotter fluid accumulated in the grooves between the ribs on the grooved surface. A part of the hot fluid was moving along the rib towards the top where the thermal plumes tended to form and tear from the ribs. The authors [13] believe that the enhanced heat transport on the grooved surfaces is due to both a larger surface area and change in the plume dynamics.

Nucleate boiling influences the heat transfer intensity in thin horizontal layers at higher pressure. The highest intensity was attained on the surface with 1390 μm thick coating when the experiments on [14] investigation of pool bubble boiling on the surfaces with structured capillary-porous coatings were carried out in figure 4(a). The most intensive bubble boiling occurred in the grooves between large ribs where the enhanced fluid flow through the micro-porous structure was observed in figure 4(b). The study presents the analysis of the optimal parameters for the micro-structured capillary-porous coatings which were applied in research tests on heat transfer at evaporation and boiling in thin horizontal liquid layers under low pressures. Capillary-porous micro-structuring of the surface was carried out with the use of a 3-d laser printer [16]. A relative contribution in the intensity of heat transfer evaporation and boiling is certain to depend on reduced pressure and heat flux density under low pressures. With regard to the parameters of micro-structuring, we should optimally consider the specifics of boiling and evaporation mechanisms development for porous coatings under the determined conditions. When conducting the experiments [14], the distance between the ribs was estimated at \( \lambda_m = 2\ell_\sigma \), and the ribs height was approximately equal to Laplace constant. The value of \( \lambda_m = 2\ell_\sigma \) is known to be the minimum distance, which is sufficient to lead to instability, which

![Figure 4](image_url)

**Figure 4.** Pool nucleate boiling of liquid nitrogen on the coated surface (a) boiling curves, (b) contour of the coated surface with the thickness of 1390 μm.
must be a reason of thermal plumes formation above the ribs surface in order to avoid the overlapping of fluid heating areas from each rib. The study of heat transfer at evaporation and boiling in thin horizontal liquid layers was conducted with the use of micro-structured capillary-porous coatings, which contour could be approximated by the equation:

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

where \( y \) – a vertical coordinate, \( m \); \( x \) – a horizontal coordinate, \( m \); \( \delta_0 \) – the thickness of a continuous coating without contouring or shaping, \( m \); \( A = \delta - \delta_0 \) – the rib height, \( m \).

One of the main research objectives is considered to be the dependence of heat transfer and crisis phenomena development on the height values of the liquid layer and the ribs heights of the structured capillary-porous coating.

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