Experimental study of heat transfer during boiling in a thin layer of liquid on surfaces with structured porous coatings

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Abstract. The paper presents the results of the study of evaporation and boiling in a thin horizontal layer of liquid on microstructured surfaces in a wide range of changes in pressure. It is found that the thermal conductivity of materials of microstructured surfaces significantly affects the mechanism of steam removal from the pores and circulation of liquid along the heat transfer surface. It is determined that the pressure change leads to three regimes of heat transfer: evaporation, transition regime, and bubble boiling. The lowest values of the heat transfer coefficients and CHF were obtained in the transition regime; the highest ones were obtained in the bubble regime on both surfaces. Due to the higher thermal conductivity, the higher heat transfer coefficients and CHF were obtained on the bronze coating than on stainless steel over the entire pressure range.

1. Introduction

Boiling processes are widely used in various fields of industry. In this regard, the problem of enhancing heat transfer and increasing critical heat fluxes (CHF) during evaporation and boiling of liquid is one of the key tasks in thermophysics. The nucleate boiling curve is dependent on many parameters, mainly related to the thermophysical properties of the boiling liquid and to the characteristics of the surface on which boiling processes take place. In particular the effect of the surface characteristics such as the thermophysical properties of the material and morphology of surface requires further investigation.

Capillary-porous coatings can significantly intensify heat transfer during evaporation and boiling. One of the methods for creating such surfaces is the additive technology of 3-D printing selective laser melting/sintering (SLM/SLS). The main advantage of the SLM/SLS techniques is the ease in fabrication of complex parts and coatings of required geometries; this eliminates the need for further processing [1]. The study [2] describes a technique of coatings construction by the layer-by-layer SLM. Research results validate that SLM is an effective way to manufacture structured surfaces and control precisely the structure parameters that are important for understanding of the boiling heat transfer mechanism.

Horizontal thin films of the liquid allow the removal of high heat fluxes at low temperature head. In technical devices, horizontal layers of liquid of finite height are used at various relative pressures. It should be noted that the pressure is one of the most important independent parameters affecting heat transfer during evaporation and boiling. With decreasing pressure, the saturation temperature of
boiling liquid decreases, but the temperature head between the heating surface and the saturation temperature increases. The task of reducing the temperature head, that is, enhancing heat transfer, becomes especially important. However, in [3,4], it is shown that the influence of pressure on the CHF during evaporation and boiling on the modified surface has a complex character in a thin layer of liquid. It is found that with increasing pressure, the CHF value decreases. It is also obtained that the curve of the dependence of CHF on the relative pressure has two pronounced minima at pressures of 67 Pa ($P_s/P_{cr} = 3.68 \times 10^{-5}$) and 1 kPa ($P_s/P_{cr} = 5.5 \times 10^{-4}$), where $P_{cr}$ is the critical pressure, Pa.

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 the horizontal heating surfaces with capillary-porous coatings. In the experiments the boiling curves were obtained at different pressures over the n-dodecane layer. The data obtained on microstructured surfaces were compared with each other.

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 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. A 30 – mm thick high heat-conducting brass plate is enclosed between the bottom and a heater to attain uniform heat flux on the heated surface. The gap between the chamber bottom and the plate is filled with a special high heat-conducting paste to reduce contact thermal resistance. 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. An optional coil for heating the chamber walls is fixed below the cooling coil to reduce heat losses due to the leakage along the chamber walls from the bottom and to provide uniform temperature distribution at the chamber bottom. The liquid in the coil for heating the chamber walls is heated in a pumping thermostat. The working chamber is equipped with viewing windows, through which the evaporation and boiling processes taking place in the working chamber are recorded. The detailed description of the experimental setup is given in [5].

Heat transfer at evaporation and boiling in a thin horizontal liquid layer was studied using microstructured capillary-porous coatings. The selected 3-D laser printing technology allowed the formation of structures with a given porosity and form of various materials [6]. Powder was sintered to the surface region by region with the laser beam velocity being smaller than that for the next layers, which provided stable sintering of the first layer with the substrate. Special attention was paid to creating coatings of the same profile, with the same porosity and size of the particles remained in the pores. The parameters of coatings are shown in Table 1.

| Table 1. The parameters of coatings. |
|-------------------------------------|
| Parameter                           | bronze | stainless steel |
|-------------------------------------|--------|-----------------|
| Powder fraction                     | 40-63 μm | 20-40 μm       |
| Powder material                     | AISI C836000 | LPW 155(15-5PH) |
| Thermal conductivity                | $\lambda \approx 89 \text{ W/(m·K)}$ [7] | $\lambda \approx 20 \text{ W/(m·K)}$ [8] |
| The porosity                        | $\varepsilon = 44\%$ |
| Maximum thickness                   | $\delta = 550 \mu$m |
| Minimum thickness                   | $\delta_0 = 50 \mu$m |
| The rib height                      | $A = \delta - \delta_0 = 500 \mu$m |
| Modulation wavelength               | $\lambda_m = 3.5 \text{ mm}$ |
| Equation of contour                 | $z = (A/2) \sin(2\pi\lambda_m) + A/2 + \delta_0$ |
Notation in the table: \( z \) – a vertical coordinate; \( x \) – a horizontal coordinate.

The porosity was determined by measuring the density of test samples (10×10×5 mm in size) and comparing the results with the density of powder material. The morphology of samples was analyzed using the scanning electron microscope. SEM images of the test samples are shown in figure 1. The scale of the photographs is somewhat different because they were taken with different microscopes. Figure 1 shows that the pores in the coatings are of various sizes and reach several tens of micrometers. Small particles are inside the pores and on the surface of the melted areas.

N-dodecane is used as the working fluid. The pressure range in the experiments is \( P_s = (33 – 20000) \) Pa or reduced pressure values of \( P_s/P_{cr} = 1.84\cdot10^{-5}–1.1\cdot10^{-2} \). The experiments are carried out within the layer height \( h = 1.7 \) mm or dimensionless value \( (h/l_\sigma) = 0.99 \), 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\(^2\).

Figure 1. SEM images of the test samples. (a) – the bronze coating; (b) – the stainless-steel coating.

3. Results and discussion

Three regimes of heat transfer were observed in the liquid layer on microstructured surfaces, depending on the pressure. The first evaporation regime was observed at pressures \( P_s = 33–400 \) Pa \( (P_s/P_{cr} = 1.84\cdot10^{-5}–2.203\cdot10^{-4}) \). The second transition regime was observed at pressures \( P_s = 665–1200 \) Pa \( (P_s/P_{cr} = 3.677\cdot10^{-4}–6.623\cdot10^{-4}) \). The third bubble regime was observed at pressures \( P_s = 5–20 \) kPa \( (P_s/P_{cr} = 2.758\cdot10^{-3}–1.1\cdot10^{-2}) \). Each regime was characterized by its own heat transfer mechanism and crisis phenomena. The thermal conductivity of the material of microstructured coatings significantly affected the removal of steam from the pores, the circulation of liquid on the surface, as well as the structure formation in the liquid layer. For a visual comparison of the operating parameters and coating materials with each other, Figure 2 shows the boiling curves at three most characteristic pressures, as well as the dependence of the heat transfer coefficients on the heat flux. The heat transfer coefficient was calculated using the following expression: \( \alpha = q/(T_w - T_s) \), where \( q \) is the heat flux, W/m\(^2\); \( T_w \) is the wall temperature, K; \( T_s \) is the saturation temperature. The upper points of the boiling curves correspond to the CHF.

In the evaporation regime, which in Figure 2 corresponds to the data at 133 Pa, “funnels” [3] were formed on the stainless steel surface up to the values of heat fluxes \( q = 10 \) kW/m\(^2\). “Funnel" are the depressions with a hemispherical bottom in a thin layer of liquid. Convection without structure
formation was observed on the bronze surface. As a result, the heat transfer coefficients on the stainless steel surface were higher than on the bronze surface. With an increase in the heat flux, the liquid layer on the stainless steel surface evaporated gradually, and the heat transfer coefficient at the same time assumed a constant value in the range of heat fluxes \( q = 10–13.4 \, \text{kW/m}^2 \) until the layer completely evaporated and the dryout crisis occurred. On the bronze coating, when a certain heat flux \( q = 10 \, \text{kW/m}^2 \) was reached, “craters” [3] appeared in the liquid layer. “Craters” are recesses on the surface of a liquid layer; there is a long flat residual liquid layer of finite sizes in the centers of the cavities. This led to the fact that heat transfer in the liquid layer on the bronze microstructured surface continued to higher values of heat fluxes. When the surface temperature became too high, the residual layer of liquid inside the “craters” became a dry spot and the dryout crisis also occurred. The pre-crisis evaporation regimes on bronze and stainless steel surfaces are shown in Figure 3 (a,b). The figures show dry spots and liquid that stops wetting them.

![Figure 2](image)

**Figure 2.** Heat transfer within the range of low relative pressures: (a) – heat flux versus the temperature head; (b) – heat transfer coefficient versus heat flux. Unshaded dots correspond to the data on the bronze surface; shaded dots indicate data on the stainless steel surface.

In the transition regime, which in Figure 2 corresponds to the data at 1 kPa, the highest temperature head and the lowest value of the CHF were obtained on the stainless steel surface. This can be explained by the fact that very small bubbles formed inside the stainless steel coating [6]. Due to the low thermal conductivity of the coating, these bubbles remained inside the coating, but did not come out to the liquid surface. Rows of small bubbles and splashes of liquid could be observed inside the ribs of the coating. At the same time, no large bubbles were formed. As a result, the liquid recharge was disrupted, and the liquid layer was sharply drained at the places of greatest accumulation of these bubbles. This led to an early onset of the dryout crisis. Quite large bubbles formed on the bronze coating, and heat transfer continued at high heat fluxes as compared to the stainless steel surface. At the same time, the CHF value in the transition regime on the bronze coating was also less than in the evaporation regime.

In the bubble boiling regime, which in Figure 2 corresponds to the data at 5 kPa, the increase in heat transfer coefficients values and CHF on the bronze surface as compared to the stainless steel can be explained by an improvement in the uniformity of the structure of steam removal and liquid circulation over the entire heat-releasing surface. This improvement is caused by the greater thermal conductivity of the bronze coating material, which simplifies bubble escape from the ribs of the microstructured coating. Figure 3 (d) shows that rows of small bubbles form on the steel surface, while
the liquid is pushed away from the center to the walls, which leads to a crisis. On the bronze coating, the bubbles are mostly large in size (Figure 3 (c)) and the liquid covers the entire surface until the crisis itself. All CHF values obtained during the experiments are shown in Figure 4.

![Figure 3](image1.png)

**Figure 3.** Pre-crisis regimes of evaporation/boiling on surfaces, $P_s = 400$ Pa; $P_s/P_{cr} = 2.206 \times 10^{-4}$: (a) – bronze: $q = 36.5$ kW/m$^2$; $T_w - T_s = 22$ K; (b) – stainless steel: 12.4 kW/m$^2$; 21 K; $P_s = 5$ kPa; $P_s/P_{cr} = 2.758 \times 10^{-3}$: (c) – bronze: 49 kW/m$^2$; 18 K; (d) – stainless steel: 24 kW/m$^2$; 20 K.

![Figure 4](image2.png)

**Figure 4.** Comparison of CHF on microstructured surfaces in a wide range of reduced pressures: 1 – data obtained on the bronze coating; 2 – on the stainless steel coating; 3 – calculation by the Kutateladze dependence [9]; 4 – by the Yagov dependence [10].
Figure 4 shows the comparison of CHF on microstructured surfaces in a wide range of reduced pressures. According to this graph, it can be seen that the evaporation and boiling regimes on the bronze and stainless steel surfaces have their own local maxima of the CHF values. At the same time, an increase in pressure above 5 kPa ($P_s/P_{cr} = 2.758 \times 10^{-3}$) on the bronze and stainless steel surfaces leads to a decrease in the CHF value. The transition regime is characterized by local minima of the CHF.

In general, it can be seen that the CHF values on the bronze surface are higher than on the stainless steel surface in the entire range of the given pressures. This suggests that with a similar morphology of the capillary-porous coating, the high thermal conductivity of the material can significantly increase the CHF values by improving the removal of steam from the pores and circulation of liquid along the heat transfer surface.

4. Conclusion

The experimental study of heat transfer and crisis phenomena during evaporation and boiling of a thin horizontal layer of liquid at low pressures on microstructured surfaces is carried out. It is determined that the thermal conductivity of materials of microstructured surfaces significantly affects the mechanism of steam removal from the pores and circulation of liquid along the heat transfer surface. Due to the higher thermal conductivity, higher heat transfer coefficients and CHF are obtained on the bronze coating than on stainless steel over the entire pressure range. It is determined that the pressure change leads to three regimes of heat transfer: evaporation, transition regime, and bubble boiling. The lowest values of the heat transfer coefficients and CHF are obtained in the transition regime, the highest ones are obtained in the bubble regime at the pressure of 5 kPa on both surfaces.

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