Heat transfer on a capillary-porous surface during evaporation / boiling of a thin layer of liquid at low pressures

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Abstract. This paper presents experimental data on heat transfer during the evaporation/boiling of n-dodecane on a surface with a capillary-porous coating in a wide pressure range. The obtained data are compared with data on heat transfer during the evaporation/boiling of n-dodecane on a smooth surface. It was found that the regime of bubble boiling occurs on a coated surface at lower pressures than on a smooth surface. It was found that enhanced heat transfer during evaporation/boiling on a capillary-porous surface as compared with a smooth surface is observed only under conditions of bubble boiling ($P \geq 10^3$ Pa).

1. Introduction
Currently, electronics is one of the fastest-growing areas in the world, the main development of which is associated with an increase in power and a decrease in the overall dimensions of devices. Downsizing in turn increases the power density of the losses that need to be removed. Today, air cooling systems are widely used to cool electrical appliances, but the technological capabilities of air cooling are approaching their limit and in some cases cannot provide efficient heat dissipation. The solution to this problem may be the use of liquid cooling. The most effective methods of removing heat from the heating surface using a liquid are processes associated with the use of the latent heat of the phase transition. Constantly increasing requirements for weight, overall dimensions of cooling devices, and improvement of temperature control conditions at high heat fluxes lead to the need to develop more and more effective methods of enhancing heat transfer during evaporation/boiling.

The application of porous metal coatings is one of the most effective methods of enhancing heat transfer. Coatings are prepared by various methods, such as powder sintering, thermal spraying or plasma spraying, vacuum spraying, and electrolytic deposition [1].

In [2], the authors found that the enhancing of heat transfer on a porous surface is due to two factors. Firstly, this is an increase in the density of nucleation of the vapor phase, and secondly, a more uniform distribution of the centers of vaporization on the heated surface. After reaching a certain coating thickness on a porous surface, heat transfer decreases [3]. Thus, the thickness and particle size of the coating are of great importance in enhancing heat transfer processes.
2. Experiments

The experiments were carried out on an experimental setup (see figure 1), the working chamber of which is a cylindrical vessel made of steel 12X18H10T with an inner diameter of 120 mm, a height of 300 mm, and a wall thickness of 1 mm. A cooling coil is located on the outside of the top of the unit. The distance from the bottom of the chamber to the lower coil of the coil is 100 mm. The chamber was cooled by water flowing along with a coil. To reduce heat loss along the walls of the chamber from the bottom to the cooling coil, as well as to more evenly distribute the temperature along the bottom of the chamber, below the cooling coil is an additional coil for heating the side vertical wall of the chamber, connected to a coil designed to heat the chamber lid.

For visual observations from above and from the side, viewing windows had to view windows. To measure the temperature of the heating surface in the bottom at different heights, five holes with a diameter of 1.5 mm were installed in stainless capillaries of the thermocouple. The pressure in the working chamber was measured by a deformation-ionization vacuum gauge and was maintained by constant. The installation is equipped with an automated system for collecting and processing experimental data. A more detailed description of the installation is given in [4, 5].
A capillary-porous coating was applied to the heating surface (figure 2). This coating was obtained using 3D laser printing and had a porosity of 0.44. The size of the sintered particles was in the range of 20-40 μm, the material of the particles was steel LPW 155 (15-5PH). The coating profile is shown in figure 3.

N-dodecane was used as the working fluid. Before starting the experiments, a certain amount of working fluid was poured onto the bottom of the working chamber, which was necessary to create a layer of the required height taking into account the porosity of the coating. With a decrease in pressure in the volume of the working chamber, the liquid was degassed, which was recorded by the termination of characteristic blistering caused by the removal of bubbles of dissolved air. For a more complete degassing, the working fluid was boiled under reduced pressure for several hours. In the course of the experiments, several of stationary heat transfer modes were implemented, in which the temperature was recorded over the thickness of the heated bottom, the pressure over the liquid layer in the volume, and the process was videotaped with a high-speed video camera. In the experiments, boiling curves were obtained at a constant pressure value.

The layer height at which the experiments were carried out was higher than the capillary constant: $h = 2.5$ mm, $(h/l_σ) = 1.45$, here $h$ – the height of the layer, mm; $(h/l_σ)$ – the dimensionless height of the layer, $l_σ = 1.78$ mm – capillary constant.

### 3. Results and discussion

The results obtained on heat transfer during evaporation/boiling on a capillary-porous surface were compared with experimental data obtained on a smooth surface in [5, 6].

In [6], it was shown that on a smooth heating surface at a pressure $P \geq 10^4$ Pa heat transfer occurs in the mode of bubble boiling, and at a pressure, $P \leq 10^3$ Pa bubble boiling was absent in the liquid layers. Heat transfer was carried out due to intense evaporation from the upper liquid layer during the formation in it, under the influence of the vapor recoil force, of structures in the form of “funnels” and “craters”.

The formation of structures in the form of “funnels” and “craters” was also observed on the capillary-porous surface but at lower pressures ($P < 10^3$ Pa). At a pressure of $P \geq 10^3$ Pa, the regime of bubble boiling was observed.

Figure 4 and figure 6 show that in the mode of formation of structures in the form of “funnels” and “craters”, the presence of a capillary-porous coating (dark symbols) does not enhancing heat transfer compared with data obtained on a smooth surface (light symbols).
At the same time, during bubble boiling on a capillary-porous surface, the heat transfer process is amplified by 2–3 times in comparison with the data obtained on a smooth surface (figure 5, figure 7). With the same heat fluxes, with increasing pressure, the temperature head decreases (figure 4–5), as a result of which the heat transfer coefficient increases (figure 6–7). Moreover, the presence of a capillary-porous coating leads to a decrease in the critical heat flux compared to a smooth surface.

In the mode of formation of structures in the form of “funnels” and “craters”, the capillary-porous coating is a buffer thermal resistance due to an increase in the thickness of the residual liquid layer in the zone of the formed “craters”. The heat transfer coefficient in the absence of bubble boiling on surfaces with a capillary-porous coating is lower.
An analysis of the experimental data shows that the evaporation/boiling processes are accompanied by pressure pulsations, the nature of which varies depending on the magnitude of the heat flux. It was shown in [7] that using the flicker-noise spectroscopy method, it is possible to extract useful information in a comparative analysis of pulsations of the noise power spectra of measured parameters (in this case, pressure fluctuations).

4. Conclusion
The mode of bubble boiling on a capillary-porous coating occurs at lower pressures than on a smooth surface.

It was found that heat transfer on a capillary-porous surface is enhanced compared with a smooth surface only in the mode of bubble boiling.

A capillary-porous coating leads to a decrease in the critical heat flux, compared with a smooth surface during the evaporation/boiling of a liquid layer, which was studied in this paper.

The evaporation/boiling processes in thin layers of liquid during the formation of various structures in them are accompanied by pressure pulsations. Processing the pressure fluctuation spectra will allow us to determine the characteristic value of the pulsations for various evaporation/boiling modes.

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