Study of the effect of three-dimensional capillary-porous coatings with various microstructural parameters on heat transfer and critical heat flux at pool boiling of nitrogen

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Abstract. An experimental study of the effect of capillary-porous coatings obtained by directional plasma spraying on heat transfer and critical heat fluxes during pool boiling of nitrogen under conditions of stationary heat release on copper tubular heaters with a diameter of 16 mm was carried out. It is shown that for the coating with the highest porosity, the maximum increase in the critical heat flux is 1.8 times higher than that for a smooth heater. The maximum heat transfer coefficients were observed on TCP coatings in the region of low heat fluxes, which were up to 3.5 times higher than the heat transfer coefficients on a smooth heater. The effect of the thickness of the residual layer of microstructured capillary-porous coatings on heat transfer during nucleate boiling is shown. Based on the data of high-speed video recording, it was shown that the intensification of heat transfer during boiling on structured capillary-porous surfaces is not associated with an increase in the nucleation site density. Revealed pulsating nature of boiling in the region of high heat fluxes is characterized by the periodic formation and departure of vapor conglomerates along the surface of the heater.

1. Introduction

The problems of enhancing heat transfer and increasing critical heat fluxes (CHF) during pool boiling of various liquids are one of the key tasks in thermophysics. Boiling processes are widely used in various fields of industry, however, increasing heat dissipation capacities of energy-stressed devices and equipment, as well as a decrease in the mass and size parameters of heat exchangers stimulate the development of methods for increasing heat transfer coefficients and critical heat loads during boiling. To date, the most popular and effective approaches are passive methods associated with the modification of a heat transfer surface. The modification is carried out both due to microstructuring of the initial surface and due to the creation of various micro-nanoporous coatings on the heater [1, 2].

High heat transfer coefficients and critical heat fluxes can be actualized on surfaces with microporous coatings obtained by the sintering of highly heat-conducting powders. One of the advantages of these coatings is high porosity, which facilitates the nucleation process, initiates the appearance of a new phase with less overheating, and increases the nucleation site density (NSD). Also, using the sintering method, it is possible to create two- and three-dimensional structures with different geometries evenly distributed over the height [3]. The increased interest is given to the development and study of
Anisotropic and combined coatings obtained based on the sintering method, implemented, for example, in [4, 5]. These coatings provide effective modulation, the structure of the two-phase flow near the wall with the countercurrent movement of liquid and vapor, thereby reducing the hydraulic resistance of vapor filtration and ultimately increasing the heat transfer coefficient during boiling compared to a uniform coating. Despite the efficiency of using porous coatings obtained by sintering, this method also has several disadvantages, which include the complexity of coating on surfaces of various shapes, as well as the difficulty of their manufacture due to the need to create high temperatures and pressures in the process.

An alternative way to create porous coatings is the plasma spraying method. However, coatings obtained by the traditional method of gas-thermal spraying have a significant disadvantage - low porosity. In [6] the directional plasma spraying method was proposed with the formation of a three-dimensional capillary-porous (TCP) structure with a varying inclination angle of the cone axis of the sprayed particles to the surface of the substrate. The uniqueness of the coatings obtained using this method lies in the simultaneous combination of the highly porous coating and the structure of its surface in the form of quasi-ordered ridges and channels. The study of the effect of such coatings on heat transfer and critical heat fluxes during the boiling of liquids with various physical properties (liquid nitrogen, R21 freon, and water) was carried out in a series of works [7, 8, 9]. The authors showed that for heaters with coatings in the region of relatively small heat fluxes, a significant heat transfer intensification (up to 3 times) was observed regardless of the type of liquid under conditions of stationary heat release. Moreover, for all studied coatings, the ratio of the heat transfer coefficient to that for a smooth surface decreases with increasing heat flux. An analysis of the heat transfer intensification mechanisms was conducted, which differ depending on the properties of the liquid and the microstructural characteristics of the coatings. Besides, an increase in the stationary critical heat flux during the boiling of nitrogen was observed on the modified samples, and under the conditions of the pulsed supply of the thermal load, the presence of TCP coating led to the degeneration of unsteady CHF.

Despite on a fairly extensive study of the effect of structures obtained by the directed plasma spraying method on stationary heat transfer during boiling of various liquids, the complexity of the coating morphology does not allow making an accurate comparative analysis of the role of each of the determining parameters (porosity, channel width between adjacent ridges, coating thickness, residual layer thickness, etc.) during heat transfer at pool boiling based on a relatively small number of investigated heat transfer surfaces for one working fluid. Furthermore, all studies investigated cylindrical heaters with a diameter commensurate with coating thickness. This fact leads to the uncertainty of calculating the heat flux density through the heat transfer surface. In particular, when normalizing the power of heat release to the area of a smooth heater (without taking into account the thickness of the coating), the intensification of heat transfer can be significantly higher relative to the presented data. This uncertainty can be solved by minimizing the ratio of coating thickness to the diameter of the smooth samples.

The aim of this work is an experimental study of the effect of TCP coatings obtained by directional plasma spraying on the heat transfer and critical heat flux during nucleate boiling of liquid nitrogen under conditions of stationary heat release on large diameter tubular heaters.

2. Experimental methods

Figure 1 shows the schematic diagram of the experimental setup. Liquid nitrogen on the saturation line ($T_{\text{sat}} = 77.4$ K) at atmospheric pressure was used as a working fluid. The setup was an optical cryostat with an inner diameter of 0.2 m and a height of 1.25 m. To exclude heat influx through the lateral surface of the inner volume of the cryostat, the cryogenic tank was protected by a vacuum cavity, radiation screens, and an external nitrogen bath. A header tank with liquid nitrogen protected the working section from the heat inflows through the cryostat flange. To maintain atmospheric pressure in the working volume the openings on the top cover of the cryostat were provided for the release of excess vapor.

A high-speed video recording of boiling was carried out through the optical windows of the cryostat using a Phantom v.7.0 digital video camera. The recording frequency in the experiments ranged from
2000 to 10000 fps with a maximum resolution of 1 pix. \( \sim 0.02 \) mm. The high spatial and temporal resolution of the camera made it possible to estimate the nucleation site density, as well as to record the growth and departure dynamics of vapor bubbles from the heat-transfer surface, as well as the behavior of the two-phase layer near the surface of the heater at high heat loads.

Figure 1. The schematic diagram of the experimental setup.

Copper cylindrical tubes with an external diameter of 16 mm, the wall thickness of 3 mm, and a length of 50 mm were used as working sections with a smooth heat-transfer surface (without coating). To heat the working areas, a heating element was used which was a constantan tape with 50 \( \mu \)m thick and 3 mm wide, tightly wound on a textolite cylinder with a diameter of 9.8 mm. The ends of the constantan strip were soldered to copper electrodes through which electric current was passed using an EA-PS 8080-60 DT programmable power supply with a maximum power of 1.5 kW. A layer of thin fluoroplastic tape with 90 \( \mu \)m thick was wound over the constantan which served an electrical insulator. The heating element was inserted tightly inside the copper tube. To determine the heat releasing power at a given current value, a potential difference was measured at the current-supplying electrodes. The heat flux was calculated by the formula \( q = UI / (\pi [D + 2\delta] L) \), where \( D \) is the outer diameter of the smooth tube, \( \delta \) is the thickness of the coating, \( L \) is the length of the heat release zone, \( U \) and \( I \) are the voltage and current on the work area.

Figure 2. SEM image, 2D/3D profiles of the sample №16-2.

The coatings on the initial working surface of the above tubes were applied by directional plasma spraying. For spraying a bronze powder of different fractional compositions containing 9% aluminum and 2% manganese was used. Figure 2 shows photographs of the coated working area obtained by Hitachi S-3400N scanning electron microscope, as well as 2D and 3D coating profiles obtained using the BRUKER Contour GT-K1 optical profilometer. It can be seen from the figure that the coatings are
porous ridges and channels quasi-ordered along the surface of the tube. The main microstructural characteristics of the coatings used in the experiments are presented in the table, where $\lambda_m$ is the average distance between adjacent ridges (wavelength of modulation of the structure), $\delta$ is the average thickness of the coatings along the height of the ridges, $h$ is the thickness of the residual layer (layer of uniform porous coating), $l_{\text{char}}$ is the average channel width, $\varepsilon$ is the porosity, $q_{\text{CHF}}$ is the critical heat flux.

Table 1. Parameters of the samples.

| №  | Powder fraction, $\mu$m | $\delta$, $\mu$m | $\lambda_m$, $\mu$m | $h$, $\mu$m | $l_{\text{char}}$, $\mu$m | $\varepsilon$, % | $q_{\text{CHF}}$, W/cm$^2$ |
|----|------------------------|-----------------|------------------|-----------|-----------------|-------------|--------------------------|
| Smooth | 13.1 | 200 | 350 | 50 | 120 | 50 | 18.2 |
| 16-1 | 20-32 | 200 | 350 | 50 | 120 | 50 | 18.2 |
| 16-2 | 20-32 | 350 | 460 | 100 | 240 | 64 | 23.2 |
| 16-3 | 71-100 | 1270 | 1410 | 700 | 450 | 30 | 16.7 |

To measure the temperature of the heat-releasing surface of the copper tube, three pre-calibrated L-type factory-made thermocouples were used. For this purpose, holes with a diameter of 1 mm were drilled in the wall of the cylindrical section, two of which were 13 mm deep located at different ends of the tube, and one, 25 mm deep, was diametrically opposite. This arrangement of thermocouples made it possible to control the temperature both along the length of the tube and along its radius. Cold junctions of thermocouples were placed to the volume of liquid nitrogen far from the heat-releasing surface. The liquid saturation temperature was monitored using a Hel-700 series of platinum resistance thermometer. The collection of experimental data from temperature sensors was carried out with a frequency of 10 Hz using the LTR-114 ADC board and the LGraph software package.

To exclude liquid inflows into the copper samples as well as to thermocouple junctions, all the butt elements of the working section were sealed with epoxy glue. The maximum offset in the measurements of all thermocouples from each other during the experiments did not exceed 0.2 K, which indicated to the uniformity of heating of the working section.

3. Experimental results

Figure 3a shows boiling curves and critical heat fluxes for a smooth copper sample and samples with TCP coatings. The data [10] on heat transfer during boiling of liquid nitrogen on a flat copper heater with a smooth surface, which, as can be seen from the figure, are in good agreement with the results obtained in this work, are also presented. As one can see, the presence of capillary-porous coatings on the surface of heaters No. 16-1 and No. 16-2 leads to a significant increase in the critical heat flux. The maximum $q_{\text{CHF}}$ was observed for the sample No. 16-2 with maximum porosity (64%). For this sample, the value of $q_{\text{CHF}}$ was almost 1.8 times higher than the corresponding value for a smooth tube without coating. It is necessary to note that for samples No. 16-1 and No. 16-2 in the region of high heat fluxes, the pronounced fracture in the boiling curve is observed which is accompanied by significant periodic fluctuations in the surface temperature with an amplitude of (1-2) K and characteristic ripple frequencies (100-200) mHz.
Figure 3. Experimental results: (a) boiling curves, (b) intensification degree.

The processing of experimental data in terms of the degree of heat transfer intensification, obtained as the ratio of heat transfer coefficients on coated heaters to similar values for a smooth area at a given heat flux, is shown in figure 3b. For the samples No.16-1 and No. 16-2, a significant intensification of heat transfer is observed up to 3.5 times in the region of small heat fluxes, which decreases twice for heat fluxes near to $q_{\text{CHF}}$ on the uncoated heater. At the same time, for the sample No. 16-3, an increase in the heat transfer coefficients relatively to the smooth working area was observed only at heat fluxes up to 2 W/cm$^2$. A further increase in the heat load led to very significant degradation of the heat transfer coefficients. For this working sample, the thickness of the residual layer $h$ was about 700 $\mu$m. This important difference apparently leads to a significant increase in hydraulic resistance of vapor filtration from the lower layers of the coating and actually limits the heat transfer intensity by the effective heat conduction regime of the structure provided that it is filled with the vapor phase. The critical heat flux for this sample, at which a sharp and prolonged increase in temperature, was observed was 16.7 W/cm$^2$.

Figure 4. Nucleation site density.

Based on the analysis of high-speed video data, the nucleation site density was quantified (figure 4) in the heat flux region up to 3 W/cm$^2$, where it was possible to identify individual bubbles. As can be seen, for a smooth heater, an almost linear increase in NSD is observed with an increase in heat flux, while on heaters with TCP coatings this value remains almost constant. The absence of a significant increase in the nucleation site density with an increase in $q$ on modified samples may be one of the reasons for the decrease in the degree of intensification of heat transfer with increasing heat flux. It is also seen that the density of the centers for the smooth heater becomes higher than for the modified samples even at heat fluxes of (1-2) W/cm$^2$. It can be concluded that the nucleation site density is not a
determining mechanism for the intensification of heat transfer during the boiling of liquid nitrogen on TCP coatings obtained by the directional plasma spraying method. It was found that the centers of vaporization during boiling of liquid nitrogen on the smooth heater in the region of low heat fluxes were not stable. So, in particular, there was a periodic deactivation for a long time (relative to the time of growth and departure of the vapor bubble) of individual centers. At the same time, continuous vapor generation was observed on all studied TCP coatings. Pores act as vapor traps and increase the amount of residual vapor after bubble detachment, facilitating the nucleation of a new phase and ensuring the stability of vaporization, which leads to a significant intensification of heat transfer at low heat fluxes.

![Figure 5. Boiling process on a smooth tube at high heat flux and CHF.](image)

In the region of high heat fluxes (q > 7 W/cm² for a smooth working area and q > 12 W/cm² for samples with coatings), the regime of developed bubble boiling is replaced by transitional boiling, which continues until the heat transfer crisis is reached. For example, in figure 5 the frames of a high-speed video recording of nitrogen boiling on a smooth heater at a heat flux of 8 W/cm² are shown, as well as a photograph of film boiling. As one can see, this regime corresponds to the pulsating nature of the boiling. The formation of a large volume of the vapor phase over the entire surface of the heater was observed, after which there was an almost simultaneous departure of the vapor conglomerate along the length of the working area. A large number of bubbles were formed on the surface freed from the vapor, which grew and merged into a new steam conglomerate before departure from the heat transfer surface, after which the process was repeated. The analysis of video recording shows that the frequency of departure of the vapor phase in the transient boiling regime weakly depends on the heat release power and is about (23–28) Hz.

Conclusions
The results of an experimental study of heat transfer and critical heat fluxes on copper tubular heaters with a diameter of 16 mm with structured capillary-porous coatings of various thicknesses and microstructural parameters obtained by the directional plasma spraying method at pool boiling of nitrogen under conditions of stationary heat release are presented. Based on a high-speed video recording of the boiling process the data on nucleation site density were obtained at heat fluxes up to 3 W/cm² as well as the departure frequency of the vapor phase in the transition boiling regime. It was revealed that the microstructural parameters of the coatings significantly affect the heat transfer and critical heat fluxes. The analysis of the results has shown that:

- the maximum increase in the critical heat flux by 1.8 times compared to the smooth heater implemented for the coating with the highest porosity;
- the maximum degree of heat transfer intensification (up to 3.5 times) corresponds to coatings in the region of small heat fluxes;
- significant degradation of the heat transfer coefficient was observed relative to a smooth heater for the thickness of the residual coating layer equal to about 700 μm;
• the nucleation site density on the TCP coatings remains almost unchanged when increasing heat release and with heat fluxes above (1-2) W/cm², and is below the similar values for the smooth sample;
• the departure frequency of the vapor phase in the transition boiling regime weakly depends on the power of heat generation.

Acknowledgment
This research was supported by the Federal Program for Basic Research of State Academies of Sciences for 2013-2020 (theme III.18.2.3, AAAA-A17-117030310025-3).

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