Intensification of heat transfer during pool boiling of nitrogen on surfaces with capillary-porous coatings produced by 3D-printing

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Abstract. The study of heat transfer, critical heat fluxes (CHF) and evaporation dynamics at pool boiling of nitrogen at atmospheric and low pressures in a stationary heat generation regimes was performed. The two flat cooper heaters with porous coatings of various structural parameters obtained by additive 3D-printing as well as smooth one were used as working surfaces. According to obtained results such coatings significantly effect on pool boiling increasing up to six times the heat transfer coefficients (HTC) in comparison with uncoated sample. For all investigated heaters and pressures, visualization of boiling was performed using a video camera from which data on the bubble departure diameters and estimates of the active nucleation site density were obtained.

Introduction
As known, phase changes, including boiling, found their application in industry: in the nuclear power, in the chemical industry, in heat power engineering, at cooling of different electronic devices etc. However, the increasing of heat fluxes which must be removed from energy-intensive surfaces including by reducing the weight and size parameters of equipment stimulate the development of research in the field of heat transfer intensification and increasing the critical heat fluxes at pool boiling of various fluids. One of the most investigate methods in recent years aimed at solving the above problem are methods to creating modified heat releasing surfaces by structuring and creating porous coatings on the micro/nano scale. Today, there are a huge number of technologies for the production of these types of surfaces (mechanical processing, plasma spraying, sintering of particles, electrodeposition, lithography, etc.), which are constantly developing and each of which has its own advantages and disadvantages. In recent years, research has begun to actively develop for creation methods of using additive technology of 3D-printing (selective laser melting/sintering SLM/SLS) to produce modified surfaces which can be used in industry for increasing heat loads of devices. This method is interesting for researchers due to its flexibility in the creation of coatings. Namely it’s able to create solid structures, porous media as well as combined areas from different materials with good reproducibility of microstructural characteristics [1], which allows to analyse the effect of individual coating parameters on the boiling process.

In recent years, the amount of research associated with the influence of individual microstructural parameters of the surfaces with different geometry and material, obtained by the SLM method, on HTC and CHF at nucleate boiling of fluids with different properties and variation of experimental
conditions such as pressure, subcooling etc. is rapidly growing. For example, the authors of [2] studied the aluminum samples with micro-cavity and micro-fin structures during boiling of saturated FC-72 at atmospheric pressure. For all modified working sections, an increase of heat transfer coefficients and critical heat fluxes were observed relative to the smooth one, while the maximum values (70% for HTC and 76% for CHF) were achieved for a micro-ribbed surface with characteristic rib sizes (300-500) microns. In subsequent work [3], this team managed to achieve the high rates of HTC and CHF (up to 3 and 6 times higher respectively) using porous lattice structures relative to the uncoated heater. Similar research results for the same liquid were obtained in the work [4]. The authors used the 3D printing method to create combined structures on the surface of the samples, which are composite porous coatings (0.6 mm micro pores and 2 mm macro pores). It has been shown that composite coatings have the greatest increase in the critical heat flux, both in comparison with a smooth plate and a uniform coating. In this case, an important role is played the thickness of the coating, which significantly affects the value of the CHF. On the other hand the authors of [5] conducted the experiments using water as working liquid (saturated and subcooled) on surfaces with caverns of different geometry and characteristic size of about 1 mm and did not receive any heat transfer intensification. At the same time, the use of re-entrant microchannel structures obtained by the SLM method, as shown in [6], leads to a significant increase in HTC (up to 330%) at boiling of subcooled water. But the authors did not achieve CHF for the modified sample even with a 3-fold excess of the heat releasing power relative to the maximum (critical) heat load for the sample without modification. The influence of microstructural parameters of mesh coatings, obtained by this method, on HTC and CHF during boiling of saturated water was considered in [7]. The authors showed that the increasing of grid width in the rage from 0.5 mm to 1.3 mm significantly decreased the heat transfer coefficient and may cause to be even lower than HTC for plane surface. The maximum CHF values were obtained with a grid width of 1.1 mm (more than 3 times higher than CHF for the uncoated plate). Issues related to the intensification of heat transfer both during boiling and evaporation of n-dodecane were considered in the works [8, 9]. The experimental data were obtained at different pressures and thickness of working fluid layer. As shown in these studies, the use of porous coatings in the form of regular ridges on the surface of the heater, obtained by the SLM method, can lead to a 5-fold increase in the heat transfer coefficients relative to the uncoated one. The above studies show the promise of using the SLM method to create effective heat exchange surfaces for industrial applications, as well as the relevance of studying various forms and parameters of structures in relation to specific operating conditions (type of fluid, pressure, subcooling etc.) to identify optimal one.

This work is a continuation of the earlier research [10] and is aimed at studying heat transfer and critical heat fluxes on SLM porous coatings with varying their basic microstructural parameters during nucleate boiling of nitrogen at different pressures.

Experimental facility
Since this work is a direct continuation of earlier studies, a detailed description of all units of the experimental setup (the scheme of which is shown in the figure 1 for clarity), as well as the experimental techniques, is given in [10]. In this section, the main points related to the experimental conditions will be briefly noted.

Liquid nitrogen was used as a working fluid under conditions of saturation at atmospheric and reduced to 0.018 MPa pressures. To achieve subatmospheric pressures, the cryostat is equipped with a system for pumping out the internal volume using a vacuum pump and a fine-tuning valve that regulates the rate of pumping out nitrogen vapours. The current pressure values was directly monitored with precision of 0.01 kgf/cm² using an exemplary vacuum gauge installed in the upper part of the cryogenic tank and by implication according to the measurements of a temperature sensor located at a distance about 5 cm from the investigated surface in the working volume.

The working samples were square plates made of M1 copper with a size (22x22) mm and a thickness of 2.5 mm. The temperature sensor was installed in each sample at a distance of 0.5 mm from the heat exchange surface to minimize the temperature gradient along the heater thickness (the
estimates in this configuration showed that the temperature difference did not exceed 0.1 K at maximum heat fluxes) during data recording. The working surface was heated with a constantan foil, pressed against the sample through a thin insulator and connected to a power supply. To maintain stationary conditions of heat release, after each change in electric power, several minutes were waited until the temperature of the sample surface reached stationary values. It should be noted that hysteresis of the boiling curve was found for all heaters; however, with a decrease in the heat flux density a good reproducibility of the experimental data was observed. In this connection, further analysis of the results was carried out with a decrease in heat load.

Figure 1. Scheme of experimental setup and working area.

To conduct the experiments two copper coatings with different microstructural parameters were created by additive method of selective laser melting/sintering [9] on the working surfaces. The morphology of the coatings was analysed using a BRUKER Contour GT-K1 optical microscope profilometer. 2D/3D profiles of them can be seen in figure 2. The main difference between the modified heater № 1 and № 2 is the significant difference in the width of the channels $l$ and the distance between adjacent ridges $\lambda$. The porosity $\varepsilon$ which was determined by mass method taking into account the shape of the profile of the coating as well as the thickness of uniform porous layer $h$ have close values.

Table. Parameters of the samples.

| Sample № | $\delta$, $\mu$m | $\lambda$, $\mu$m | $l$, $\mu$m | $h$, $\mu$m | $\varepsilon$, % |
|----------|------------------|------------------|-------------|-------------|----------------|
| 1        | 480              | 2010             | 1140        | 70          | 30             |
| 2        | 430              | 3510             | 1820        | 50          | 34             |
Experimental results
The experimental data of the dependence of the heat flux on the overheating of the heat-transferring surface of a smooth and both modified samples with respect to the saturation temperature of liquid nitrogen at atmospheric pressure are shown in the figure 3a. The arrows on the figure indicate the critical heat fluxes for all heaters, which were determined by a sharp increase in temperature with an increase in the heat load and from the visualization of the boiling process. As it can be seen there is a characteristic break of the boiling curve for the smooth heater at a heat flux about 1-2 W/cm², which corresponds to the change of the regimes from the free convection to the dominating nucleate boiling. The value of the CHF for this working section was $q_{CHF} = 16.9$ W/cm² and is in good agreement with the well-known Kutateladze-Zuber model with a coefficient of 0.135. For both modified samples, there are no pronounced kinks in the heat transfer curve which is explained by the presence of boiling at very low heat fluxes until the complete shutdown of the heat release power. In addition, for sample № 1, which is characterized by a smaller distance between adjacent regular ridges, an increase in the CHF is observed by almost 30% relative to the smooth area. For heater № 2, the critical heat flux practically coincides with the $q_{CHF}$ value for a smooth sample. This fact can be explained by the presence of wide zones (more than 1 mm) between the ridges with a quite thin coating layer in which, apparently, local film boiling occurs at high heat fluxes, leading to a heat transfer crisis.

The enhancement of heat transfer at atmospheric pressure, obtained as the ratio of the HTC on the heaters with coatings to the same value for the uncoated one at a fixed value of the heat flux, is presented on figure 3b. The intensity of heat transfer during pool boiling of liquid nitrogen on the heaters with coatings is much higher in all investigated range of heat releasing power up to the critical value on the smooth sample. The maximum increase in HTC (up to 6 times for the sample № 1 and up to 4 times for the sample № 2) is observed in the zone of low heat fluxes and decreases with increasing heat releasing power.
Decreasing pressure up to 0.018 MPa cause to the lower heat transfer rate both for the smooth and for the modified surfaces on the average 25% relative to the atmospheric pressure, as well as reducing the critical heat fluxes (see figure 4a). At the same time, the calculated Kutateladze-Zuber dependence in this case lies below $q_{\text{CHF}}$ for all investigated samples. As in the case of atmospheric pressure, for both modified samples, there is a significant enhancement of heat transfer compare to the smooth area (figure 4b) in the investigated range heat flux density. The maximum increase in HTC up to 3 times was also obtained for sample № 1 with a smaller distance between adjacent ridges.

The frames of high-speed visualization of boiling for studied pressures at low heat fluxes when the individual bubbles can be determined are shown in figure 5. As shown by the qualitative analysis of the obtained data, at heat fluxes $q <$ 1 W/cm² the active nucleation site density (NSD) on the heaters with coatings is significantly higher than the similar value for the smooth one and boiling occurs in the pores of coating ridges both at atmospheric and at reduced pressures. This is clearly seen in the above figures. Also, the quantitative estimates of the bubble departure diameters for all studied samples at $q <$ 2 W/cm² were carried out. Thus, at atmospheric pressure the departure diameters were (0.1-0.3) mm for the modified heaters (it should be noted that boiling was also observed at extremely low heat fluxes, however, the separation bubble diameters were less than 100 μm and could not be more accurately determined due to the insufficient resolution of the video camera), (0.4-0.7) mm for the smooth heater, and (0.5-1.5) mm, (1.2-4.5) mm at reduced pressure, respectively. An increase in NSD in the zone of low heat fluxes and the increasing of effective heat transfer area due to copper capillary-porous coatings, as well as a restructuring of a two-phase flow with a more ordered character of the
removal of vapour bubbles and liquid supply to the surface are the main factors that can explain increased HTC during nitrogen boiling on such types of coatings obtained by 3D-printing.

Figure 5. Boiling process at low heat fluxes.

Conclusion
In this paper, pool boiling of nitrogen on porous coatings, obtained by the method of additive 3D-printing, with different microstructural parameters was experimentally studied at atmospheric and reduced pressures. The following conclusions can be drawn from this work:

1) For both pressures the presence of such coatings leads to a significant enhancement of HTC (6 and 3-fold respectively) as compared to the plane surface as well as decreasing of bubble departure diameters. This increase of heat transfer coefficients is probably associated to the increased heat transfer surface area, increased NSD and effective liquid supply to the surface.

2) The microstructural parameters of the coatings play an important role in the value of critical heat fluxes. So for the sample №2 the wide zones (more than 1 mm) between the ridges with a quite thin coating layer are the reason for the lack of increase of CHF as compared to uncoated one at atmospheric pressure.

3) Pressure drop up to 0.018 MPa leads to the reduction of HTC and CHF for all investigated samples and higher value of bubble departure diameters.

Acknowledgments
This research was carried out at the Kutateladze Institute of Thermophysics SB RAS with the financial support of the Russian Science Foundation Grant No. 19-19-00180 (experimental study of the heat transfer and critical phenomena during boiling on modified surfaces produced by 3D-printing) and State Contract with IT SB RAS No. 121031800216-1 (debugging the technique for high-speed visualization of non-stationary boiling processes in cryogenic liquids).

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