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Research Paper

Structured capillary-porous coatings for enhancement of heat transfer at pool boiling

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HIGHLIGHTS

- Novel capillary-porous coatings are developed by directional plasma spraying technique.
- The developed coatings significantly intensify the heat transfer at boiling of water and LN2.
- Maximum enhancement factor on the coated surfaces is observed at low heat fluxes.
- The enhancement mechanisms differ depending on the liquid properties and morphology.

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ABSTRACT

Pool boiling heat transfer in capillary-porous coatings was experimentally studied using two coolants (water and liquid nitrogen) at atmospheric pressure. The unique type of capillary-porous coatings with different thicknesses (400–1390 µm), morphology and with high porosity (up to 60%) were fabricated by the directional plasma spraying technique. The study shows that the use of capillary-porous coatings leads to significant enhancement of heat transfer up to 4 times at boiling of liquid nitrogen and up to 3.5 times at boiling of water in the region of low heat fluxes. Based on the analysis of high-speed video, it is shown that the mechanisms of heat transfer enhancement can differ substantially depending on the properties of liquid and morphology of coatings. The enhancement factor for the developed capillary-porous coatings is compared with the results of previous studies obtained using the structured surfaces with re-entrant cavities, microchannels and coatings fabricated by the gas-thermal methods.

1. Introduction

Boiling is the most efficient process of interfacial heat and mass transfer, so it is frequently encountered in a wide spectrum of thermal engineering systems. Nevertheless, the increasing heat power of the energy-intensive devices as well as reduction of mass-size parameters of heat and mass transfer equipment creates a necessity for improvement of the boiling process: reducing superheating, enhancement of heat transfer and increasing critical heat fluxes. To date, the most popular and effective methods for improvement of boiling performance are the passive methods associated with modification of the heat transfer surface. Modification is carried out both by microstructuring the original surface (the so-called finned surfaces and surfaces with re-entrant cavities and channels) and by deposition various micro- and nanoporous coatings [1–7]. The structured surfaces with high density of re-entrant channels such as Gewa [8–11], Thermoexcel [9,12] and Turbo tubes [10–14] have become very popular in practice. One of the first studies dealt with heat transfer enhancement at boiling of Freon R11, nitrogen and water on the structured surfaces composed of interconnected internal cavities in the form of tunnels and small pores connecting the pool liquid and the tunnels was a series of research presented by Nakayama et al. [15,16]. In these studies, it was shown that evaporation of liquid films and menisci, covering the walls, particularly in the corners, during the growth of vapor phase in the internal tunnels, plays an important role in increasing the heat transfer rate. Later, in numerous works [8,17–22] devoted to investigation of the boiling performance on the structured surfaces with re-entrant channels, the effect of the shape (circular, triangular and rectangular) and

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Nomenclature

A	area [m^2]
C	specific factor
D	diameter [mm]
I	current [A]
l	length [mm]
NSD	nucleation site density [cm^{-2}]
q	heat flux [W·cm^{-2}]
R_a, R_z	roughness parameters [μm]
T	temperature [K]
U	voltage [V]
h	heat transfer coefficient [W·m^{-2}·K^{-1}]
m	mass [g]

Greek symbols

δ	thickness [μm]
ε	porosity
λ_m	modulation wavelength [μm]

Subscripts

CHF	critical heat flux
K-Z	Kutateladze–Zuber
sat	saturation
h	heater
0	smooth surface

geometric parameters of the internal tunnels (height and width of tunnels) as well as the pore diameter and pore pitch, heat flux density and reduced pressure on heat transfer and local characteristics at boiling of coolants with different physical properties (freons, water, organic and dielectric liquids) were studied. A detailed reviews and systematization of these studies are presented in [10,23]. One of the promising techniques for fabricating the surfaces with external micro-fins in the form of re-entrant channels is the hybrid technology based on deforming and cutting suggested by Zubkov [24]. Experimental studies of boiling performance, presented in [25], show that the use of structured surfaces produced by the multitool deformation and cutting leads to significant enhancement of heat transfer at water boiling under the atmospheric pressure.

Other surface modification techniques, which were mentioned at the beginning, are related with a deposition of microstructured and microporous coatings. There is a huge variety of different physico-chemical methods for multiscale modification of surfaces such as sintering [9,10,26–28], electrochemical deposition [29,30], microarc oxidation [31], thermal (plasma) spraying [32–35], etc. The main advantage of the porous coating made of sintered powders and particles is high porosity, which allows not only to increase the effective area of heat exchange surface, but also to facilitate the nucleation process: onset of nucleate boiling at less superheating and an increase in the nucleation site density. In this method there is a possibility to control the pore size and porosity through the selection of particle size and the compression of the powder. In particular, based on the analysis of experimental results on heat transfer at boiling of Freon R134a on High-Flux, Gewa-B, Turbo-CSL and Turbo-BII HP tubes, Ribatski and Thome [10] showed that the maximal enhancement factor (in 4.9–21.3) was achieved using the High-Flux surfaces obtained by the sintering method. Moreover, in many studies, for example in [28,36], it was shown that the use of porous coatings of sintered powders leads to an increase of the critical heat fluxes (CHF) at boiling. Recently, much attention has been paid to the development and investigation of anisotropic coatings obtained on the basis of the sintering method [32,36–39]. Such coatings are either separate geometrically similar sintered 3D microstructures or a system of microchannels entirely composed of sintered powders or when the channel walls are partially covered with sintered particles. These coatings provide effective modulation of the two-phase flow near the wall, thereby reducing the hydraulic resistance of vapor filtration and increasing the heat transfer coefficient at boiling as compared to the uniform coating. In one of the recent papers [39], Deng et al. used the combinations of porous sintering coatings and re-entrant microchannels of a cylindrical shape with the diameter of 0.8 mm to fabricate a functional surface. In this study, it was shown that for the porous coatings with re-entrant channels, the heat transfer coefficient increases in the region of low heat fluxes, and the wall superheat at the onset of nucleate boiling (ONB) can be decreased as compared to those on its solid counterpart at boiling of water and ethanol.

One of the alternative ways of fabricating the porous coatings is the plasma spraying technique. This method has been known for a long time, and now there are several studies devoted to the influence of plasma coatings on heat transfer at liquid boiling [32–35,40–42]. However, the coatings obtained by the conventional method of plasma spraying have some significant disadvantages: low porosity and weak effect on heat transfer and critical heat fluxes at boiling, especially for high wettability liquids. To improve the parameters of the coatings, some authors use the method of plasma spraying with various modifications. For example, Scurlock [33] used a mixture of aluminum/silicon powder and low-melting material-polyester during spraying to increase the porosity of plasma coatings. In another study [32] Andrianov and Malishenko created anisotropic plasma coatings by fabricating in the porous structure the system of channels for vapor escape. In this paper it was shown that with the use of anisotropic coatings, it is possible to achieve a more substantial improvement of heat transfer at boiling than with the use of uniform coatings.

Kalita et al. [43] proposed the method of plasma deposition with formation of three-dimensional capillary-porous (TCP) coating with ridges and cavities by varying the inclination angle of the sprayed particle cone relative to the substrate surface. The advantage of this method in comparison with the traditional one is that it allows to obtain the anisotropic structured porous coatings with maximum porosity (up to 80%), high adhesion and possibility of method scaling for industrial applications. In a previous study by Surtaev et al. [44] in experiments with liquid nitrogen, it was shown that the use of new types of capillary-porous coatings leads to an enhancement of heat transfer at boiling, and also has a significant effect on the development of crisis phenomena at rapid heating. In particular it was found out that for the heaters with capillary-porous coatings, there was degeneration of boiling crisis at rapid heating, when the heat fluxes are $q < q_{\mathrm{CHF}}$. At the same time, data on heat transfer at boiling of liquid nitrogen, presented in this paper, are given only for two samples with coatings. This work is aimed at experimental study and generalization data of pool boiling performance of the anisotropic capillary-porous coatings with different morphology developed by directional plasma spraying technique using liquids with different physical properties (water and liquid nitrogen).

2. Manufacturing of capillary-porous coating

The essence of the traditional method of plasma spraying is as follows: a powder of the deposition material is fed into the high-temperature plasma jet, where it is heated, melted and sprayed in the form of a two-phase flow to the substrate at the angle of 90 degrees. As it was noted in the previous section, the coatings obtained by the conventional method of plasma spraying have a number of disadvantages, including low porosity. In the present study, the method of directional plasma