Heat transfer enhancement at evaporation and boiling of liquid on capillary-porous surfaces created by 3D printing

O A Volodin, N I Pecherkin, and A N Pavlenko

Institute of Thermophysics SB RAS, Lavrentyev Ave. 1, Novosibirsk 630090, Russia

*E-mail: volodin_o@mail.ru

Abstract. The paper presents the results of experiments on measuring heat transfer in laminar-wave films of R114/R21 refrigerant mixture flowing down a vertical plate (70 × 80 mm). The experiments were carried out on the saturation line at a pressure of 2 bar. To enhance heat transfer, a porous copper coating with a flat layer thickness of 400 μm and a porosity of 45% was applied to the heat-transfer surface by 3D printing. The effectiveness of the application of the technique used for the heat transfer enhancement is demonstrated: an increase in the boiling heat transfer coefficient is obtained up to three times in comparison with the reference smooth surface, as well as two-fold increase in heat transfer coefficient in the evaporation regime. Based on the obtained experimental results and analysis of the research data of other authors, the geometric structure of promising multiscale porous enhancing coating is proposed for further research.

1. Introduction

Additive manufacturing (AM) also known as 3D printing or Additive fabrication is the process of combining a material (by melting, sintering, etc.) to create an object from its digital 3D model, as a rule, layer by layer, as opposed to “subtractive” manufacturing technologies (milling, etc.) [1]. The AM has a number of advantages over traditional technologies, such as: customization of the created elements, reduction in the weight of the detail (since details with internal channels can be created), a decrease in the number of details of an industrial element and a small amount of waste. Currently, there is a process of intensive development of additive manufacturing. General Electric predicts a 50% decrease due to the use of AM in traditional gas turbine engine parts in 10 years, and NASA predicts in 5-10 years the possibility of printing the entire space satellite [1]. Also development of additive manufacturing will promote the creation of environmentally-friendly (smart) devices. For example, the authors of [2] have made a fully 3D printed disposable paper supercapacitor, maintaining a high capacitance of active material at an operating voltage of up to 1.2 V entirely from renewable, non-toxic materials.

Although, there are still few examples of using the AM for the enhancement of boiling heat transfer [3-8], such studies, allowing quick creation of single prototypes of enhancing surfaces and variation in their parameters with high accuracy, seem to be very promising.

Ho et al. [3] used selective laser melting (SLM) to manufacture micro-fin surfaces (with semicircular form of the fin tops) and micro-cavity surfaces. Pool boiling experiments at atmospheric pressure and saturated conditions were conducted with FC-72 as a test fluid. Heat transfer coefficient (HTC) and critical heat flux (CHF) were increased by 70% and 76%, respectively. Later, Wong et al. [4] manufactured more complex 3D structures for studying the heat transfer enhancement at pool boiling of saturated FC-72 under atmospheric conditions. Nine porous lattice structures were
fabricated using the SLM technique. The best performing substrate was “Octet-3.0C-5.0H” having an average HTC of 1.35 W/cm²K, which was about 3 times higher than that of the plain surface. The highest CHF was achieved by “Octet-5.0C-5.0H” at 107 W/cm², which was about 6.11 times more than that of the plain surface.

Zhang et al. [5] fabricated 3D wall grid structures also by the SLM technique. The authors used stainless steel powder for manufacturing two groups of samples with different wall height: “thin” (0.75 mm wall height) and “thick” (1.5 mm wall height). Grid pitch varied from 0.4 to 1.3 mm. The grid wall thickness was equal to 0.1 mm for all created samples. The experiments were carried out on the ceramic heater (12×12×2.5 mm) with samples pressed to the heater by two crossed stainless steel wires. As a result, it was shown that HTC decreases with mesh pitch increasing from 0.5 to 1.3 mm. The mesh with 0.5 mm pitch (“thin”) was most effective at ΔT varied from 4 to 11 K and meshes with pitch ranges from 0.7 to 1.1 mm (all “thick”) were effective at ΔT variation from 11 to 22.5 K: all resulting in about 2-3 times HTC enhancement as compared to the plain surface. The CHF value for the “thick” mesh with 1.1 mm pitch (best performing) was increased more than 3 times as compared with CHF obtained for the plain surface.

In [6], a porous structure with a sinusoidal profile was formed from stainless steel powder with spherical particles of 20-40 microns in size using laser layer-by-layer synthesis. The authors carried out an experimental study of heat transfer at boiling and evaporation of thin layers of n-dodecane on the created porous surface under conditions of reduced pressures. It is shown that HTCs on the surface with the studied coating are 3 to 5 times higher than on the smooth surface.

The authors of [7] developed a technology for modifying the heat transfer surface using a porous coating made on a 3D printer. Heat transfer under the conditions of single-phase convection and pool boiling of R21 refrigerant was studied in the pressure range of 0.18–0.21 MPa. The fabricated coating had a thickness of 0.5 mm and was made of copper granules with a diameter of 50 μm. The HTC was measured on both a smooth reference surface and modified capillary-porous surface in the range of heat fluxes from 500 to 400000 W/m². It was shown that at small and medium heat fluxes the boiling HTC on a modified surface was up to 4 times higher than that of a smooth surface. At the pre-crisis regime of heat transfer, the HTCs on both heat transfer surfaces were almost the same.

In [8], the same group of the authors carried out the experiments using the same test setup [7] at reduced pressures (from 0.03 to 0.06 MPa) and at different orientation of test section. The experiments showed that in the region of single-phase convection, a vertically oriented modified surface exhibited more intense heat transfer as compared with a horizontal modified surface. In the region of nucleate boiling at low and medium heat fluxes, a significant (3–7-fold) increase in the HTC is observed. Analysis of the experimental data evidences that rise of the reduced pressure increases the heat transfer intensity at boiling on modified surface.

The aim of this work was to study the heat transfer enhancement in evaporative and boiling refrigerant films, falling down the vertical plate with a capillary-porous coating created by newly developed 3D printing method [6].

2. Experimental setup and procedure

To conduct the study, the sealed experimental column was used, the description of which is given in [9]. The experiments were carried out under saturation conditions at a pressure of 2 bar and the range of variation of the Reynolds film number Re: 400-1400, here Re=4Γ/v. The heat flux density q varied from zero to the critical values. A mixture of R114/R21 refrigerants with a molar concentration of the volatile component of 12% was used as a working fluid; it has a low surface tension that along with high wettability and low viscosity makes it convenient for modeling heat transfer processes for a wide class of fluids (mixtures of ozone-safe refrigerants, cryogenic liquids). Visualization of hydrodynamics and interfacial heat transfer processes in the falling films was carried out using high-speed video shooting by Phantom VEO410.

To create test sample, the complementary layer scanning method developed at the Institute of Automation and Electrometry SB RAS (IA&E SB RAS) was used; it provides the possibility of
forming 3D coatings on substrates of almost any size, with a spatial resolution of the laser beam position of 1-10 mkm, at a high speed of beam movement (1-3 m/s) and the diffraction size of the beam in the processing plane [6]. The liquid film flowed down the vertically oriented test sample: a duralumin substrate (70×80 mm) with a 3D printed copper porous coating, figure 1a. This paper presents the results obtained for the first experiment in the planned series using the simplest (flat) coating with a thickness of 400 microns and a porosity of 45%. Local surface temperatures were measured by six Cu-Kn thermocouples located horizontally in the middle and lower regions of the heated area. The local HTC was determined as the ratio of the heat flux density to the difference between the local wall temperature and saturation temperature \( h = q/(T_w - T_s) \) with relative uncertainty of the HTC not exceeding 16% at \( T > 2^{\circ}C \).

3. Results and discussion

The flow pattern of a boiling film of a binary mixture of refrigerants on modified surface fabricated by 3D printing is shown in fig. 1b. In contrast to experiments with smooth heat transfer sections (see, for example, [9]), a significantly larger number of boiling centers evenly distributed over the heated area was visually observed on the section with a porous coating, starting from low heat fluxes (Fig. 1b).

Figure 2 shows a comparison of experimental data on heat transfer obtained on a coating created by 3D printing with data for a smooth surface, as well as with previously obtained data [9] on surface with semi-close cavities made by the method of deformational cutting (MDC), see its schematic image in figure 3.
Figure 2. The dependences of the HTC on the heat flux for a smooth surface, a surface with a coating created by 3D printing and a surface with semi-closed pores created by MDC; Re \( \approx 430 \) in all cases.

Figure 3. The sketch of surface with semi-closed pores (frontal view) with characteristic dimensions proportional to the parameters of the real sample [9].

It can be seen from figure 2 that the application of a coating with a thickness of 400 microns with a flat surface of a porous layer leads to a significant intensification of heat transfer, both at the evaporation \((q \leq 1 \text{ W/cm}^2)\) of about two times, and at nucleate boiling of about three times as compared to the reference smooth surface \((R_a \leq 2.5 \mu m)\). Onset of nucleate boiling (ONB) is observed already at 0.6 W/cm², i.e. almost two times earlier than that for the smooth surface. It can also be noted that HTC values for 3D printed porous coating are close or even higher than the HTCs for MDC-surface, which was marked out as the best performing among those studied in [9]. That speaks about the high efficiency of this coating even in its flat initial version. The lack of data on heat flux exceeding the value \(q = 2.18 \text{ W/cm}^2\) in the first experimental series is due to the failure of the heating element (this series is being finalized now).
For implementation of the next stages of research, new experimental sections with a combined (multiscale) coating structure will be prepared, differing both in the characteristics of the microstructure (degree of porosity) and in the geometry of the macrostructure. In particular, based on the results obtained in this work, as well as the results of the study of heat transfer on porous coatings in thin layers of liquid [6], at pool boiling [7, 8] and the study of heat transfer in liquid films falling down a vertical plate with longitudinal grooves [10], for the second series of studies using 3D printing, a combined porous coating with longitudinal finning on a macroscale (vertical grooves) will be prepared, while sintered particles will form a porous internal microstructure of the combined coating.

The final results of a systematic experimental study of heat transfer enhancement on multiscale coatings will be generalized and compared with experimental data and correlations of other authors. The obtained new information on heat transfer will allow expansion of the existing experimental database on heat transfer on combined structured surfaces and offer of recommendations for the selection of optimal new generation surfaces designed to enhance heat transfer in various technical applications.

4. Conclusions

The paper presents the results of studies of heat transfer enhancement in laminar-wave refrigerant films falling down a vertical plate with a flat porous coating made by 3D printing.

The experimental results demonstrate the high efficiency of a porous coating, fabricated by used method, even in its flat initial version. A threefold enhancement of heat transfer was obtained at nucleate boiling of a liquid film in comparison with a smooth surface and approximately twofold in the regime of evaporation. The results obtained on enhancement is comparable with the results of [9] obtained for the best performing MDC-surface among the studied ones.

For the next stage of research, it is planned to perform the experiments on a 3D printed multiscale porous coating with longitudinal finning on a macroscale, while sintered particles will form a porous internal microstructure of the finned layer.

Acknowledgement

This work was supported by the Russian Science Foundation (project No. 19-19-00180).

References

[1] Belosludtsev E V 2021 COURSERA: Additive technologies (3D printing). Introductory course of Peter the Great St. Petersburg Polytechnic University

[2] Aeby X, Poulin A, Siqueira G, Hausmann M K and Nyström G 2021 Adv. Mater. 33 2101328

[3] Ho J Y, Wong K K and Leong K C 2016 Int. J. Heat Mass Transfer 99 107–121

[4] Wong K K and Leong K C 2018 Int. J. Heat Mass Transfer 121 46–63

[5] Zhang C, Zhang L, Xu H, Li P and Qian B 2019 Int. J. Heat Mass Transfer 128 570–580

[6] Bessmeltsev V P, Pavlenko A N and Zhukov V I 2019 Optoelectronics, Instrumentation and Data Processing, 55 (6) 554–563

[7] Pavlenko A N, Zhukov V E and Slesareva E Y 2020 Bulg. chem. communications 52 54–56

[8] Zhukov V E, Slesareva E Y and Pavlenko A N 2021 J. Eng. Thermophys. 30 (1) 1–13

[9] Volodin O, Pecherkin N, Pavlenko A and Zubkov N 2020 Int. J. Heat Mass Transfer 155 119722

[10] Gambaryan-Roisman T and Stephan P 2002 In Proc.s of International Heat Transfer Conference 12 (IHTC-12), 18-23 August, Grenoble, France