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Pool boiling of refrigerant on a flat modified surface

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Improving the efficiency, reliability and energy intensity of heat exchangers is an urgent task in various fields of industry. One of the ways to increase the heat transfer efficiency and the critical heat flux is to modify the heat transfer surface. In our research, surface modification was carried out using 3D printing. This paper presents the results of a study of heat transfer on modified and unmodified surfaces during boiling under conditions of free convection. The working liquid is freon *R*21. The experiments were carried out at two working sections made of LS59 brass. The experimental blocks were in the form of cylinders with a diameter of 20 mm. Heat was released at one end of the cylindrical section and transferred to liquid from the opposite end of horizontal orientation. Thermometers were installed along the length of the cylinder, which measure the temperature distribution along the cylinder from the heat source to the heat transfer surface. According to thermometers, the temperature of the heat-transfer surface and the density of the heat flux through this surface were determined. In one section, the heat transfer surface was polished; in another section, a 0.5 mm thick coating of spherical copper granules with a diameter of 50 μm was applied to the heating surface using a 3D printer. Heat transfer under the conditions of single-phase convection and pool boiling of liquid *R*21 freon on the saturation line before the boiling crisis was studied. The studies were carried out in the pressure range of 0.18 - 0.21MPa.

Keywords: pool boiling, heat transfer coefficient, modified heat-transfer surface, vaporization sites, refrigerant

INTRODUCTION

Heat exchangers are the devices designed to transfer heat from one coolant to another or to the environment. This is one of the most common devices for all types of power plants and engines. The efficiency and reliability of heat exchangers are of great importance for various industries, including intensively developing microelectronics, therefore, much attention is paid to promising developments for their improvement all over the world. Improvement of heat exchange equipment should make it possible to reduce the consumption of expensive materials for newly created heat exchangers, reduce their dimensions, facilitate the layout as a whole, and significantly increase their efficiency. One of the ways to increase the heat transfer efficiency and critical heat flux is to modify the heat-transfer surface using various technologies [1-6]. One of the latest technologies for modifying a heat-transfer surface is the technology of applying various structures *via* 3D printing [7, 8]. To obtain comparatively generalized experimental data on heat transfer characteristics and dynamics of crisis phenomena on various types of heat-transfer surfaces modified by 3D printing, the authors of this paper are performing a number of experimental studies. This paper presents investigation results about heat transfer intensity on horizontal smooth and 3D-modified heat-transfer surfaces at pool boiling *R*21.

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EXPERIMENTAL SETUP AND TECHNIQUES

The experiments were carried out using a setup, whose schematic diagram is shown in Fig. 1.

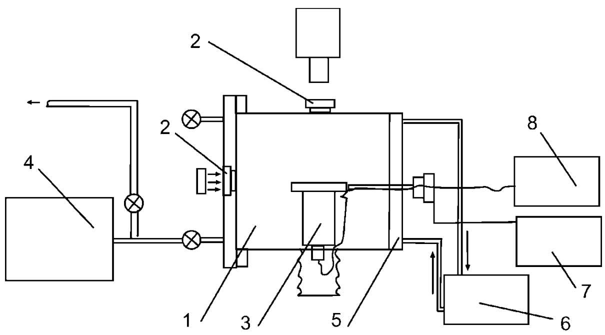


Fig. 1. Scheme of experimental setup. *1* – working vessel; *2* – windows; *3* – working section unit; *4* - filling tank; *5* – heat exchanger; *6* – thermostat; *7* – DC source; *8* – ADC.

The setup is a sealed cylindrical vessel (1) with a diameter of 250 mm and height of 250 mm. The vessel is equipped with glass windows (2) with a diameter of 60 mm for observation and photo-video recording of the processes on the heat-transfer surface of the working section (3). To fill the vessel with freon and evacuate freon from the vessel, a filling tank (4) with a system of overflow and vacuum pumping channels is used. A 50-W LED assembly is used to illuminate the object during photo and video shooting. The vessel is designed to operate at pressures of up to 0.4 MPa.

The pressure in the vessel is maintained at a predetermined level by a heat exchanger (5), where a refrigerant circulates, whose temperature is set by a thermostat (6). The working section is heated by a direct-current source (7). Silicon diodes with high temporal stability, acceptable linearity of calibration in the temperature range of 0–150°C, and higher sensitivity than that of platinum thermometers and thermocouples are used to measure the temperatures in the working volume and temperature distribution over the working section. The temperature sensors were individually calibrated using a Thermo Haake DC30 thermostat with temperature measurement accuracy of 0.1°C and temperature maintaining accuracy of ± 0.02°C. The calibration was carried out in the temperature range of 20 - 110°C. The voltage drop on the thermometers is measured by a 24-bit 16-channel ADC LTR114 (8).

The working section is made in the form of a sealed cylindrical stainless steel block (Fig. 2).

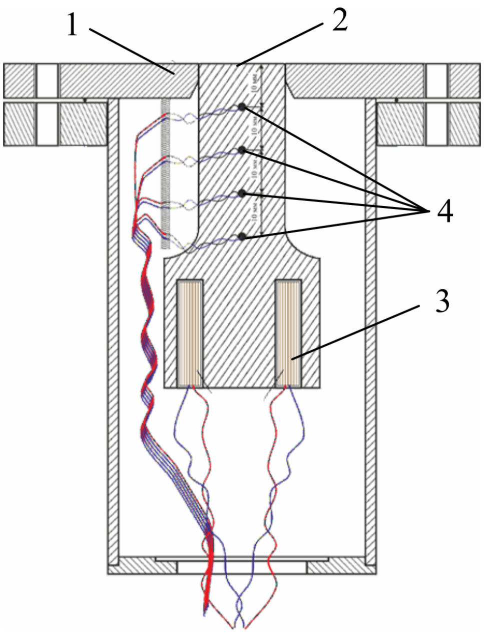
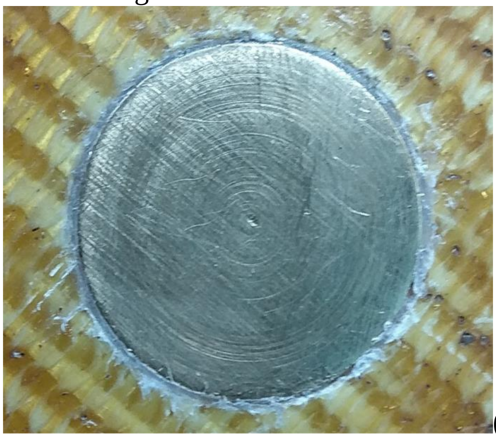


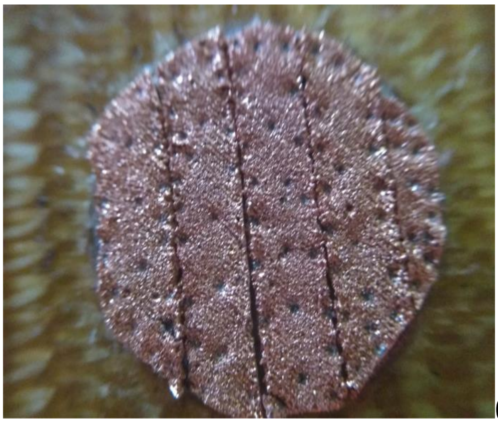
Fig. 2. Scheme of the working section. 1 – section cover; 2 – heat-transfer surface; 3 – heating element; 4 – thermocouples.

The round cover of section (1) is made of fiberglass with a thickness of 8 mm. In the center of the cover there is a hole with a diameter of 20 mm. A 70 mm long cylindrical rod made of LS-59-1 brass is installed in this hole. The end face of this rod (2) is the studied heat-transfer surface and it is installed at the same level with the section cover. The heat is generated by the heating elements (3) mounted on the opposite end of the cylinder. At a distance of 10, 20, 30, and 40 mm from the heat-transfer surface, the holes with a diameter of 1.3 mm are made in the cylinder, where the thermometers (4) are installed. The wires from the section are brought out through a sealed glass connector; the space inside the section is filled with a basalt heat insulator.

Two series of experiments were carried out at the working section. In the first series, the heat-transfer surface was smooth, in the second series, it was modified using 3D printing. Porous strips 0.5 mm thick and 4 mm wide, made on a 3D printer from copper granules with a diameter of 50 μm, were fixed on the heat-transfer surface by spot soldering. In soldering spots, conical holes with dimensions of 0.2 mm at the point of contact were formed. The photos of heat-transfer surfaces used in the first and second series of experiments are presented in Fig. 3.



(a)



(b)

Fig. 3. Heat-transfer surface. a) heat-transfer surface in the first experimental series; b) modified heat-transfer surface in the second series of experiments.

RESULTS AND DISCUSSION

The experiments were carried out under the conditions of a high volume at a pressure of 0.18 - 0.21 MPa, which corresponds to the equilibrium freon *R21* temperatures of 25 - 30°C. The heat flux density increased from minimum to maximum, then decreased.

The dependence of the heat transfer coefficient (α) on the heat flux density (q) for horizontally oriented surfaces is shown in Fig. 4.

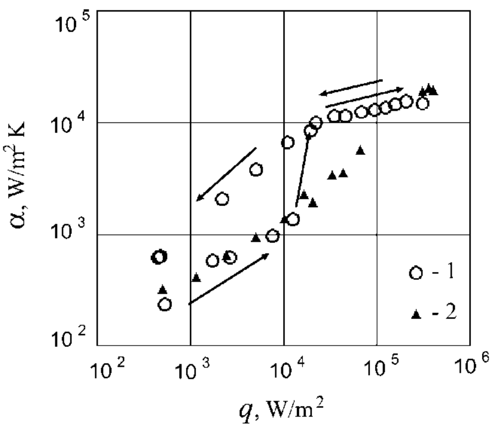


Fig. 4. Heat transfer coefficient (α) vs. heat flux density (q) for horizontal surfaces. P = 0.18 – 0.21 MPa. *1* – modified heat-transfer surface; *2* – unmodified heat-transfer surface.

At low heat flux densities q < 3000 W/m^2 on a smooth and modified heat-transfer surface, vaporization is observed only from microcracks in the sealing layer of the brass cylinder joint with the fiberglass cover of the working section. There is no vaporization at the studied heat-transfer surface; the heat transfer process is carried out by a convective mechanism. On a smooth heat-transfer surface, activation of vaporization sites occurs gradually with an increase in the heat flux density in the range of 3000 < q < 9000 W/m^2. In this range, the vaporization sites extend to the entire heat-transfer surface. With a further increase in the heat flux density, additional vaporization sites are activated and vapor generation at the existing sites becomes more intensive. With decreasing heat flux density, the heat transfer coefficient for a smooth surface without coating is almost unchanged for the same q values. On a modified heat-transfer surface, the presence of active vaporization sites is not observed up to the heat flux density q = 12300 W/m^2, inclusive. In this range of heat flux density, the heat transfer coefficients on smooth and modified surfaces almost coincide. An increase in the heat flux density to q = 19000 W/m^2 leads to an abrupt activation of vaporization sites throughout the modified heat-transfer surface. At that, the heat transfer coefficient on a modified heat-transfer surface (8700 W/m^{2}K) increases more than 4 times relative to the heat transfer coefficients on a smooth heat-transfer surface (1960 - 2200 W/m^{2}K). As it can be seen from the figure, with a decrease in the heat flux density on the modified heat-transfer surface, the vaporization sites remain active up to the minimum values of the heat flux density. The value of the heat transfer coefficient in this case is 3–4 times higher than the value α measured at the corresponding q values on a smooth heat-transfer surface and on a modified heat-transfer surface with inactive vaporization sites.

In the range of 22000 < q < 210000 W/m^2, the heat transfer coefficient for the modified heat-transfer surface increases from 10000 to 15900 W/m^{2}K. In this range of heat loads, the difference in the rate of heat transfer between the modified and unmodified heat-transfer surfaces decreases and it is almost absent in the pre-crisis region (q > 300000 W/m^2).

CONCLUSIONS

A technology for modifying the heat-transfer surface using a porous coating made on a 3D printer was developed. The coating with a thickness of 0.5 mm is made of copper granules with a diameter of 50 µm.

The heat transfer coefficient was measured on a smooth unmodified heat-transfer surface and on a modified heat-transfer surface in the range of heat flux density from 500 to 400000 W/m^2. Unlike a smooth surface without a coating, pronounced hysteresis of the heat transfer coefficient was observed on the modified heat-transfer surface for different directions of the change in the heat load. In the range of small and medium values of the heat flux density under the conditions of activated vaporization sites, the heat transfer rate at boiling on a modified heat transfer surface was up to 4 times higher than the heat transfer intensity on a smooth heat transfer surface. In the pre-crisis region, the heat transfer rate at nucleate boiling on both heat-transfer surfaces was almost the same.

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