Heat transfer at boiling on a vertical modified surface

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Abstract. Modification of heat transfer surface through additive technologies (3D printing) is a very promising direction, since it allows organizing surface structures of any complexity with high reproducibility of parameters. This paper presents investigation results on heat transfer at boiling of freon R21 on a flat, vertically oriented brass surface modified with a copper coating using 3D printing. The heat-transfer surface is modified using 0.5 mm thick and 4 mm wide 3D-printed plates. The plates are made of copper spherical granules with an average diameter of 50 μm by laser welding of granules. The plates are fixed on the heat transfer surface by spot soldering. The experiments are carried out under conditions of large volume at a pressure of 0.18 - 0.21 MPa, which correspond to equilibrium temperatures of 25 - 30°C. The heat flux density varies in the range of 700 - 410000 W/m². Experiments are carried out on the heat transfer surface before modification under the same conditions, but the surface is oriented horizontally. The experimental data show that for a modified heat transfer surface in the range of heat flux density from 1.8·10⁴ to 3·10⁵ W/m², the heat transfer coefficient changes little and is approximately equal to 1·10⁴ W/m²K. In the range of heat flux density less than 2·10⁵ W/m², the value of heat transfer coefficient on a modified heat transfer surface is up to 4 times greater than on a smooth horizontally oriented heat transfer surface without coating.

1. Introduction

The achievement and maintenance of temperature conditions at technological facilities in the energy sector, in the chemical, metallurgical, oil and gas, food and other industries are realized by the supply or removal of heat energy from the working environment. This function is performed by heat exchange equipment. Increasing the efficiency of this equipment is possible by creating optimal surface structures that meet the specific requirements of the device. To modify the heat transfer surface, various technologies are used (mechanical cutting, plasma spraying, galvanic deposition, etc.) [1-5]. Experiments carried out with a surface, modified by plasma spraying, show that more intense heat transfer is observed under unsteady heat transfer conditions [6, 7]. The vortex method of heat transfer enhancement, which includes spherical holes, is promising, since at its implementation there is an outrunning increase in the relative heat transfer coefficient in comparison with the increase in the relative resistance coefficient. Holes are made by a relatively simple technology, which does not increase the weight of the structure, and when the walls are thin the protrusions are formed on the opposite wall side, leading to an increase in the heat transfer coefficient on this side of the wall [8, 9]. Experimental results show that the best thermal performance is achieved when the holes with a rounded edge are used upstream the flow as compared to the conventional holes with sharp edges. According to the results of numerical calculations, the flow around the holes on the surfaces can be divided into five zones and each zone has its own unique flow characteristics [10]. A promising direction is modification of the heat transfer surface through additive technologies (3D printing) [11,
This method allows organizing the surface structures of any complexity with high reproducibility of parameters. This paper presents investigation results on heat transfer at boiling of R21 freon on a flat, vertically oriented surface modified with a 3D-printed copper coating.

2. Setup and method description

The experiments are carried out on a setup designed to study heat transfer processes under the conditions of pool boiling. A working volume is shown schematically in Fig. 1a. The research vessel (1) with a diameter of 250 mm and depth of 230 mm is equipped with glass windows (2) for observing and photo-video recording of heat transfer processes occurring on the studied heat transfer surface of the working section, installed in a sealed cylindrical block (3), whose construction is shown in Fig. 1b. To maintain the temperature in the research vessel within the specified limits, there is a heat exchanger (4) through which water circulates from an external thermostat. The research vessel is fixed on the frame, which can rotate within 360° around the horizontal axis, changing the orientation of the heat transfer surface.

![Figure 1](image-url)

**Figure 1.** Schematic diagram of the working volume (a) and working block (b). 1 – research vessel; 2 – glass windows; 3 – working section (a); 4 – heat exchanger; 5 – working section (b); 6 – heating elements; 7 – thermometers; 8 – working section cover.

The working section (5) is made of brass hexagon with 36 mm between the faces. At one end of the working section, three heating elements (6) with a power of 50 W each are installed in the hexagon. The second end is machined to a diameter of 20 mm over a length of 45 mm. The end face of the cylindrical part is the heat transfer surface. The through channels with a diameter of 1.3 mm are drilled from the end face along the cylindrical section at distances of 10, 20, 30 and 40 mm, respectively; semiconductor thermometers (7) are installed in these channels. Heat from the heating elements is transferred to the studied heat transfer surface by thermal conductivity through a cylindrical section with thermometers. The heat flux density and the temperature of the heat transfer surface are calculated by temperature distribution along the cylinder. The thermal conductivity of LS-59-1 brass of the working section is measured in a separate experiment, resulting in a good agreement with the reference data. The side surface of the cylinder and the heating end of the rod are covered with heat-insulating basalt wool and placed in a sealed block. The block cover (8) is made of fiberglass 8 mm
The cylindrical end of the working section is brought outside through the hole in the cover, and heat transfer to the R21 liquid freon is studied at the end of this section.

The heat flux density \( q \) along the cylinder axis, determined by the Fourier equation in 3 sections between thermometers, differs within 5% in the range of \( 1 \times 10^4 < q < 2.5 \times 10^6 \) W/m². Heat losses in the area of contact with the lid depend on the heat transfer regime and are of the order of 2-3%. When determining the temperature of the heat transfer surface through the Fourier equation, these losses are not taken into account. The total loss of heat generated by the heating element throughout the working block is 10 - 25%, depending on the operating parameters.

The heat transfer surface is modified using 0.5 mm thick and 4 mm wide 3D-printed plates. The plates are made of copper spherical granules with an average diameter of 50 \( \mu \)m by laser welding of granules. The porosity of the plate is 40-50%. The pore size is 20 – 70 \( \mu \)m. A photograph of the surface of a plate made on a 3D printer is shown in Fig. 2a. The plates are fixed on the heat transfer surface by means of spot soldering. At the place of soldering, conical holes with a diameter of 0.2 mm are formed at the surface junction. The point of spot soldering is a vaporization site. The gap between the plate and the end face of the working section is commensurate with the pore size and is an integral part of the system for supplying the vaporization sites with a liquid phase. A photograph of a smooth heat transfer surface before its modification is shown in Fig. 2b, and a photograph of a modified heat transfer surface is shown in Fig. 2c.

![Photographs of the modified heat transfer surface](image)

**Figure 2.** Photographs: a – surface of a plate made by 3D printing; b – unmodified heat transfer surface (without coating); c – modified heat transfer surface.

### 3. Results and discussions

The experiments were carried out at pool boiling in R21 freon at a pressure of 0.18 - 0.21 MPa, which corresponded to equilibrium liquid temperatures (25 - 30)°C. The heat flux density varied in the range of 700 - 410000 W/m². The experiments were carried out with a saturated liquid, the temperature head was determined as the difference between the temperature of the heat transfer surface and the temperature of liquid at the depth of the heat transfer surface. The density of the heat flux through the heat transfer surface was determined from the Fourier equation by the experimental data on temperature distribution along the cylindrical part of the working section.

The photographs of boiling on a modified heat transfer surface with vertical orientation are shown in Fig. 3. Apparently, the vaporization sites are activated as the heat flux density increases. At a high heat flux density \( q = 65760 \) W/m², Fig. 3c, vaporization sites are activated almost over the entire heat transfer surface. Large vapor agglomerates are observed in the upper part of the heat transfer surface, whose proportion increases with approaching the maximum thermal loads of the experiment.
Figure 3. Boiling on a vertical modified heat transfer surface:

\( a - q = 8440 \text{ W/m}^2; \quad b - 18200; \quad c - 65700. \)

The diagram (Fig. 4) shows the heat transfer coefficient \( (\alpha) \) vs. the heat flux density \( (q) \). The heat transfer coefficient on a vertically oriented modified surface is significantly higher than on unmodified heat transfer surface in the range of heat flux densities \( q < 2 \times 10^5 \text{ W/m}^2 \). In the range of small values of the heat flux density \( (q < 2 \times 10^4 \text{ W/m}^2) \), the heat transfer coefficient on a modified heat transfer surface is 3–4 times higher than the heat transfer coefficient on an unmodified heat transfer surface.

Figure 4. Dependence of heat transfer coefficient \( (\alpha) \) on heat flux density \( (q) \). 1 – modified vertical heat transfer surface; 2 – unmodified horizontal heat transfer surface; 3 – Dependence for R21 freon calculated by correlation from [13] Chapter 2.7.2-6 equation (12), \( \alpha = 1.54 q^{0.7} \times 1.129 \).
In the region of high heat flux densities \( q \geq 2 \times 10^5 \text{ W/m}^2 \), the heat transfer intensity is almost the same on both heat transfer surfaces. Apparently, the formation of large vapor sites (conglomerates) blocks the movement of fluid on the scale of surface microstructure, and dynamics of the fluid flow near the modified and unmodified surfaces becomes similar.

**Conclusions**

The processes of heat transfer on a heat transfer surface modified using additive technologies have been studied experimentally. The data on the heat transfer efficiency have been obtained and the heat exchange processes on a modified vertical heat transfer surface have been visualized.

The experimental data show that for a modified heat transfer surface in the range of heat flux density from \( 1.8 \times 10^4 \) to \( 3 \times 10^5 \text{ W/m}^2 \), the value of heat transfer coefficient changes little and is approximately equal to \( 1 \times 10^4 \text{ W/m}^2\text{K} \). In the range of changes in the heat flux density less than \( 2 \times 10^5 \text{ W/m}^2 \), the value of heat transfer coefficient on a modified heat transfer surface is up to 4 times greater than that on an unmodified horizontally oriented heat transfer surface without coating.

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