Heat transfer in the falling liquid film on an array of horizontal tubes with MAO coating

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Abstract. The paper presents investigation results on heat transfer of falling liquid films of Freon R21 on an array of horizontal tubes with porous Al₂O₃ coating obtained by the method of microarc oxidation (MAO coating). The microcharacteristics of samples (porosity, thickness, surface roughness) were measured. The results of measuring heat transfer coefficients on the surface of an aluminum tube with a MAO coating and a reference smooth tube were compared. Heat transfer on the surface of the tube with a porous coating was lower than on a smooth reference tube. It was shown that to intensify heat transfer on a surface with a MAO coating, it is necessary to increase the porosity of the coating and decrease its the thermal resistance.

1. Introduction
The shell-and-tube heat exchangers with horizontal arrangement of tube bundles are widespread elements of heat exchanging equipment in the power engineering, cryogenic and refrigeration, chemical technology, food industry, and many other applications. To reduce the mass and dimensions of heat exchangers of this type, intensification of heat transfer is equally important both in terms of the working fluid and heat carrier.

The use of film flows of the working fluid allows reducing the metal consumption, dimensions of heat exchangers and the working fluid flow rates. To increase the thermal cycle efficiency of refrigeration machines and heat pumps, it is important to reduce the temperature difference between the heat carrier and the working fluid, which can be achieved in the regimes of evaporation and nucleate boiling on the enhanced surfaces.

The main volume of liquefied gas is produced using the technology in which the spiral coiled heat exchangers are used as the main heat exchange equipment [1]. The natural gas stream inside the heat exchanger tubes is cooled by a two-phase mixture of refrigerants, i.e. a falling liquid film on the outer surface of tubes with cocurrent vapor flow. The cryogenic heat exchanger of a natural gas liquefaction plant weighs about 250 tons and contains more than 1000 km of tubes [2]. Therefore, improving the efficiency of such heat exchangers is one of the most important tasks of energy saving.

One of the effective ways to intensify heat transfer during boiling and evaporation is the application of capillary-porous coatings on a heat-transfer surface [3]. In [4], the results of a study of intensification of heat transfer at pool boiling of water and liquid nitrogen on the surface with porous coatings are presented. The capillary-porous coatings with high porosity and complex three-dimensional structure studied in this work were made by using a specially developed method [5]. The maximal heat transfer
intensification was obtained on coatings with a thickness of $(810-1330)\ \mu m$ at low heat fluxes $(3-4$ W/cm$^2$). At high heat fluxes, when the developed bubble boiling is achieved on the surface, the surface structure has a less significant effect on the intensity of heat transfer.

When choosing the method of creating structured surfaces, the reproducibility of characteristics of the created structures and costs of their mass production are the decisive factors. It was shown in [6] for nucleate boiling at forced convection of subcooled water on a titanium foil coated with titanium oxide TiO$_2$ obtained by the MAO method (microarc oxidation), reliable intensification of heat transfer was observed. The technology of microarc oxidation [7] is promising for creating a porous aluminum oxide coating on a heat transfer surface. This technology was successfully applied for coating the surface of aluminum conductors when manufacturing transformers. As it was noted above, in the technology of natural gas liquefying, one of the key elements is a spiral shell-and-tube heat exchanger. To produce such heat exchangers, it is very important to develop a technology for manufacturing long tubes with a developed surface both in terms of the cooling mixture and the working medium.

This paper presents the results of measuring the characteristics of porous coatings on the surface of aluminum tubes obtained by the microarc oxidation method, and compares the results of measuring the heat transfer coefficients on the surface of a test sample with a MAO coating and a reference smooth tube.

2. Experimental setup and measurement technique

2.1. Experimental setup

The experimental setup for studying heat transfer during evaporation and boiling of liquid under conditions of film irrigation of tube bundles is a closed circulation circuit. The main element of setup is an evaporator (Figure 1) with a vertically located array of horizontal tubes. In the evaporator, in total up to 40 tubes with a diameter $d$ of 10 mm can be installed with a gap between them of 2 mm. The length $L$ of the measuring part of the tubes inside the evaporator is 625 mm. The total length of the experimental tubes with inlet and outlet fittings for hot water is 1 m. Freon R21 is used as a working fluid, the pressure in evaporator is 3 bar, and the saturation temperature is $40 \pm 0.05^\circ C$.

![Figure 1. The scheme of the evaporator.](image-url)
In the evaporator, the tube bundle is irrigated by the working fluid over the full length through a slot distributor consisting of two horizontal stainless steel tubes: the upper tube with a diameter of 20 mm and a slot of 0.4-mm width and the lower tube with a diameter of 30 mm and a slot of 1.1 mm. Slots are located at the bottom of the tubes along the bundle axis. Under each tube of the distributor, there are drip-of blades. The setup allows conducting experiments at film Reynolds numbers of 500-1 500. The Reynolds number is determined by the irrigation density on each half of the pipe.

The heat flux is created by passing hot water inside the tubes. Hot water is fed by gravity from a constant header tank, which eliminates flow pulsations. The heat flux value is controlled by a change in the heat carrier temperature. The water flow rate is measured by flowmeters installed on each tube in the bundle. The water flow rates in each tube of the bundles are selected so that the corresponding Reynolds numbers are maintained equal to approximately 10,000. The amount of heat supplied to each measuring tube is calculated by water mass flow rate and the difference in hot water temperature at the inlet and outlet. Temperature sensors are calibrated before and after each series of experiments.

2.2. Test section parameters

To study heat transfer at boiling and evaporation under conditions of film irrigation of a bundle of horizontal tubes, the following experimental sections were made: two smooth reference aluminum tubes and two aluminum tubes with a porous coating deposited by the MAO method. In this series of experiments, we used the tubes made of aluminum alloy AD-31 with an outer diameter of 10 mm, with a wall thickness of 1.5 mm, and the length of each tube of 1 m. The porous coating was applied over the length of 625 mm. Two test tubes with a diameter of 10 mm, wall thickness of 1.5 mm, and length of 40 mm with a microporous surface were also made to study the structure and properties of the coating. The test tubes were used to determine the microrelief characteristics: porosity, roughness, and wettability of the surface.

To study the morphology of the working surfaces, the method scanning electron microscopy (SEM) was used with the application of microscope model Hitachi S-3400N. The wetting properties were analyzed using a sessile drop method with the help of the KRUSS DSA-100 setup. For the measurements, the “static” drops of distilled water were used at room temperature, i.e. the droplets were formed immediately before the measurement and had a constant volume of (∼ 5 µl) throughout the procedure. The measurement data on the characteristics of the porous coating are shown in Table 1.

| #   | Type of sample       | Diameter, mm | Wall thickness, mm | Length, cm | Thickness of coating, µm | Porosity, % | Roughness Rₐ, µm | Wetting angle, degree |
|-----|----------------------|--------------|-------------------|------------|--------------------------|-------------|------------------|---------------------|
| 1   | smooth reference     | 10           | 1.5               | 100        | –                        | –           | 2.0-6.2          | 60                  |
| 2   | smooth reference     | 10           | 1.5               | 100        | –                        | –           | 2.5-6.5          | 62                  |
| 3   | test tube            | 10           | 1.5               | 4          | 109-124                  | 25-34       | 8                | 41-54               |
| 4   | test tube            | 10           | 1.5               | 4          | 105-173                  | 34-46       | 34               | 37-49               |
| 5   | experimental section | 10           | 1.5               | 100        | 109-124                  | 23-36       | 8                | 40-52               |
| 6   | experimental section | 10           | 1.5               | 100        | 109-124                  | 24-37       | 8                | 39-50               |

Photographs showing the structure of the porous coating of experimental samples No. 5 and 6 with a thickness of (109-124) µm are shown in Figure 2. Below the porous layer boundary in Figure 2a, we can see the metal tube wall, and a protective technological layer located above the boundary. Figure 2b shows the surface structure with a pore in the form of a crater in the central part.
3. Results and discussion
When studying heat transfer on the bundles of horizontal tubes, most researchers calculate the heat transfer coefficient from the working fluid through the overall heat transfer coefficients. In foreign literature, a similar approach by the Wilson method is widely used. If conventional tubes with a smooth surface and constant wall thickness are applied in heat exchangers, these methods provide reliable data on average heat transfer coefficients, since the thermal resistance of the heat carrier and thermal resistance of the tube wall are calculated with good accuracy. When using enhanced tubes to intensify heat transfer, there are some difficulties in calculating the specific characteristic of complex structured outer surfaces, areas of the heat transfer surface, and heat transfer coefficients on the ribbed inner surface. The coating made by the MAO method consists of several layers containing aluminum oxide of various modifications [8]. At this stage, the density, strength, and other characteristics of this coating cannot be determined with accuracy sufficient to calculate the heat transfer coefficients for the falling film on a bundle of horizontal tubes. Therefore, the results of experiments on the aluminum tube with porous coating are shown in Figure 3 in the form of dependence of thermal power $Q$ removed from the test sections, when they are cooled by a falling film, on the temperature of hot water at the inlet to the test sections $T_{w\text{ in}}$. Experiments were carried out without cocurrent vapor flow.

![Figure 3](image)

**Figure 3.** Dependence of the amount of heat, removed from the tube surface by a falling film, on the heat carrier temperature. Re = 1 000.
At low differences between the temperature of heat carrier (hot water) and temperature of Freon saturation, the heat removal on a smooth tube and a tube with a porous coating is almost the same. With increasing temperature of hot water and, accordingly, the heat flux on the surface of the test sections, there is a decrease in the amount of heat removed from the surface of the tube with a porous coating. The heat fluxes of up to 10 kW/m², when the heat is removed through evaporation, correspond to the temperature range of (44-46) °C. The heat fluxes of (10-15) kW/m², when a transition from evaporation to nucleate boiling on a smooth surface begins, correspond to the hot water temperature range of (48-50) °C. When the temperature of the hot water at the inlet of test section is higher than (51-53) °C, the heat fluxes reach 20 kW/m² and more. In comparison with a smooth tube, a significant decrease in the amount of heat removed from the tube surface with a MAO coating begins at higher heat fluxes \( q > 1.5 \times 10^4 \text{ W/m}^2 \), when developed nucleate boiling starts on the surface.

Studies of the properties of the porous coating on samples of AMg-6 aluminum alloy obtained by the MAO method demonstrate that the coatings consist of an external loose layer and an internal denser solid layer of crystalline aluminum oxide [8]. The structure of the pores and their size depends on the technological regimes of surface treatment and coating thickness. The complex structure of the coating with many connected enclosed spaces is observed for the coatings with a thickness of more than 5-10 \( \mu \text{m} \). Thin-layer coatings (up to 20 \( \mu \text{m} \)) have the highest porosity. Pores with a size of 1–3 \( \mu \text{m}^2 \) predominate there; the maximum pore size is up to 395 \( \mu \text{m}^2 \). In thick-layer coatings (up to 60 \( \mu \text{m} \)), the share of pores with an area of (10–20) \( \mu \text{m}^2 \) is 96%, and the maximum pore size is 220 \( \mu \text{m}^2 \). The number of pores decreases with increasing coating thickness. The maximum porosity for the studied samples is about 50%.

In this work, the thickness of the porous coating is (109–124) \( \mu \text{m} \), its porosity did not exceed (20–30) %. According to the photographs of coating cross-sections (Figure 2a), there are no channels connecting pores. In general, the characteristics of coatings studied in this work coincide with those given in [8].

To estimate the thermal resistance of aluminum oxide coating, it is assumed that for heat fluxes corresponding to the evaporation regime, the heat transfer coefficients in the falling film on a smooth tube and on a tube with a MAO coating would be the same for the same Reynolds numbers of the liquid film. Then the difference in heat transfer coefficients on a smooth tube and a coated tube would be caused by a temperature drop in a thin low-heat-conducting layer of a MAO coating. Based on the data obtained in experiments, it is shown that the contribution of thermal resistance of an aluminum oxide layer with a thickness of \( \approx 120 \mu \text{m} \) to the total heat transfer resistance is about 3%. The values of thermal resistance of different components of the process for nucleate boiling regime (\( q \approx 2 \times 10^4 \text{ W/m}^2 \)) are shown in Figure 4.

![Figure 4](image-url)  

*Figure 4. The share of thermal resistance components of the heat transfer process through a cylindrical tube with a MAO coating with a thickness of 120 \( \mu \text{m} \).*
Thermal resistance from the side of the falling film represents almost 60% of the total resistance; therefore, intensification of heat transfer in the falling film can give the most significant effect for increasing the overall efficiency of the heat exchanger. One of the main reasons for the low heat transfer coefficients at boiling in the falling film for the experiments is apparently the fact that the porous structure of the coating is not sufficiently developed to increase the number of nucleation sites and the intensification of nucleate boiling heat transfer. To intensify heat transfer in the regime of nucleate boiling, thin-layer coatings with a large number of interconnected pores in the form of craters with an internal cavity are most preferable (Figure 2b).

Based on the results of determining the thermal resistance of different components of the process, the tube surface temperature and the average temperature drop between the coating surface and the falling film were calculated. The dependence of the heat flux on the temperature difference between wall and saturation temperature is shown in Figure 5. In spite of significant roughness of the surface of the coated tube, the superheat of the tube surface for nucleate boiling incipient on this tube increased as compared to the tube with smooth surface. Therefore, the heat transfer coefficients on a tube with a coating of low-conductivity aluminum oxide at nucleate boiling with all other things being equal will be lower than on a smooth tube.

Figure 5. Heat flux vs. the surface superheat.

In spite of the relatively small contribution of the thermal resistance of the tube wall with MAO coating to the overall resistance to heat transfer, in order to intensify heat transfer from the side of the falling film, along with increasing porosity of the coating, it is necessary to reduce the oxide layer thickness to at least (40-60) μm, and continue searching for the ways to increase the thermal conductivity of the coating.

Conclusion
The paper presents investigation results on heat transfer in the films falling over an array of horizontal tubes with MAO coating. The characteristics of porous coatings obtained by the method of microarc oxidation surface – roughness, the porosity of the layer – have been determined, and the wetting angles of the test samples have been measured.
The results of test experiments on the study of heat transfer in the liquid films falling over a bundle of horizontal tubes show that the amount of heat removed by the falling liquid film on the surface of aluminum tube with specified parameters of MAO coating decrease in comparison with a smooth aluminum tube without coating.

The porous structure of the studied MAO coating with a thickness of (109-124) μm and small porosity is not sufficiently developed for heat transfer intensification in the falling liquid film at nucleate boiling regime.

Based on the results obtained, the parameters of porous coating modification for intensifying heat transfer in the falling film are proposed for future experiments: reducing the coating thickness to (40-60) μm and less, increasing porosity to 50%, and increasing the effective thermal conductivity of the oxide layer.

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