Heat Transfer at Film Cooling of an Array of Horizontal Tubes with an Enhanced Surface

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Abstract. The paper presents investigation results about the influence of various methods of surface treatment on heat transfer enhancement in falling films of R21 Freon on an array of horizontal tubes. The experiments were carried out on the aluminum alloy tubes with a ceramic coating obtained by micro-arc oxidation and on copper tubes with a structured surface, treated by deformational cutting. The experiments were carried out in a regime of turbulent film flow at Reynolds numbers from 400 to 1500. The results of measuring the heat transfer coefficients on the surface of samples with a developed surface and on the standard smooth tube are compared. The highest values of heat transfer coefficients in falling films during nucleate boiling were obtained on a structured surface with semi-closed cavities. Heat transfer enhancement on the surface of a tube made of alloy D16T with the MAO coating of 30 μm thick, obtained in a silicate-alkaline electrolyte, is comparable to heat transfer enhancement on the surface of copper tubes with a microstructure applied by the deformational cutting method.

1. Introduction
Shell-and-tube heat exchangers with horizontal tube arrays are the widely used elements of heat exchange equipment in power engineering, cryogenic and refrigeration engineering, chemical technology, food industry and many other applications. A large number of modern research and reviews are devoted to the study of the fundamental laws of hydrodynamics and heat transfer in film heat exchangers with horizontal arrays of smooth and modified tubes [1-2]. The use of film flows of the working fluid allows reduction in the specific quantity of metal and in dimensions of heat exchangers, as well as reduction in the consumption of the working fluid. Despite the known advantages of using liquid film flows for cooling heat-generating surfaces in various technological applications, the experimental data obtained for film boiling are currently much less than those for pool boiling. This explains the emergence of new systematic experimental studies of heat transfer features during pool and film boiling for heat-transfer surfaces with similar characteristics [3-4].

One of the effective ways to intensify heat transfer during boiling and evaporation is application of capillary-porous coatings on the heat-transfer surface [5-6]. When choosing a method for creating structured surfaces, the decisive factors are reproducibility of characteristics of the created structures and the cost of their mass production. The method of micro-arc oxidation (MAO) is widely used for creating electrical insulating and wear-resistant coatings, protection of the surface of spacecraft from...
plasma jets, and in many other applications [7-8]. In particular, this technology is successfully used for coating the surface of long aluminum conductors for electrical transformers [9]. Micro-arc oxidation technology is very promising and quite affordable for creating reproducible characteristics and stable porous coatings on the outer surface of long tubes for large-scale coil-wound heat exchangers [10].

The method of deformational cutting (DC) is an affordable and effective way of precision machining of plastic materials, based on cutting the surface layer of the workpiece material and its subsequent deformation with formation of macro- and microrelief in the form of ribs, spikes, cells or threaded profiles [11]. This method allows creation of complex surfaces for heat transfer enhancement at nucleate boiling with an increase in the area of the heat-transfer surface by the factor of up to 12. In [12-13], experimental studies on heat transfer intensification were carried out in falling films of refrigerants on vertical and horizontal tubes with a surface structured by the DC method. The experimental results showed that the structure with semi-closed microcavities gives the greatest increase in the heat transfer coefficient in comparison with a smooth surface (more than twice), while the rhomb-shaped structure and its modification with transverse micro-ribbing are less effective.

This paper compares the results of measuring the heat transfer coefficients in falling films of refrigerant R21 on a vertical array of horizontal tubes with a porous coating applied by micro-arc oxidation (MAO) and on the enhanced surfaces obtained by deformational cutting.

2. Experimental setup and measurement technique

2.1. Experimental setup

The experimental setup for studying heat transfer at evaporation and boiling of liquid under conditions of film irrigation of the array of horizontal tubes is a closed circulation loop. The main element of setup is the evaporator (Figure 1), where a vertical single-row array of horizontal tubes is mounted. Up to 40 tubes with a diameter of 10 mm can be simultaneously mounted in the evaporator with a gap of 2 mm between them. The length of the irrigated part of tubes inside the heat exchanger is 625 mm. The total length of tubes with fittings for supplying and discharging hot water is 1 meter. To perform observation and video filming of flow regimes, the evaporator is equipped with windows. Video filming was carried out with a Phantom VEO 410 high-speed digital video camera with a frequency of (1000-4000) frames/s. Freon R21 was used as a working fluid, the pressure in the evaporator was 3 bar, and the saturation temperature was (40 ± 0.05)°C.

The tubes in the evaporator are irrigated with the working fluid along the full length of the array through a slot distributor consisting of two horizontal stainless steel tubes. The experiments were carried out in the range of film Reynolds numbers from 400 to 1500. The Reynolds number of the falling film was calculated by the liquid flow rate per one half of the tube \( \text{Re} = \frac{G}{2L\mu} \), where \( G \) is the refrigerant mass flow rate, \( \mu \) is the dynamic viscosity, \( L \) is the length of the irrigated part of the tubes. The volumetric flow rate of R21 was measured by a turbine flow meter.

The heat flux is generated by passing hot water inside the tubes. Water flows by gravity from a constant header tank, which eliminates flow rate pulsations. The heat flux magnitude is regulated by changing the water temperature and flow rate. Water flowrate is measured using individually calibrated rotameters installed on the supply lines of each tube of the array. The water flow rates in each tube of the array are chosen so that the corresponding Reynolds numbers are kept equal to about 10,000. The amount of heat supplied to each measuring tube is calculated from the hot water flow rate and the temperature difference at the inlet and outlet of the tested tubes. The hot water temperature at the inlet of each experimental tube was measured with chromel-copel thermocouples. The temperature difference of the water on each experimental tube is measured by LM20 differential semiconductor temperature sensors with a sensitivity of (−11) mV/°C. The maximum measurement uncertainty of the water temperature difference was no more than 2%. The uncertainty in measuring the water temperature by thermocouples is no more than 0.5%. The uncertainty in measuring the heat flux on the surface of tested tubes is no more than 2%. The uncertainty in calculating the heat transfer coefficient averaged over the tube length in the falling film is (7-16) %.
2.2. **Working sections**

To study heat transfer during boiling and evaporation under the conditions of film irrigation of an array of horizontal tubes, the following test sections were made: tubes made of AD-31 and D16T aluminum alloys with porous coatings applied by the MAO method, and tubes made of M1 copper with structured surfaces, created by the deformational cutting method.

The surfaces of copper tubes with an outer diameter of 10 mm and a wall thickness of 2 mm were processed by the method of deformational cutting, resulting in the following structures:

- microstructure with semi-closed cavities;
- rhomb-shaped structure;
- rhomb-shaped structure with micro-ribbing.

The microstructure of the test section surface with semi-closed cavities has the following parameters: ribbing pitch of 100 μm, rib height of 220 μm, and transverse knurling pitch of 318 μm (Figure 2a). The rhomb-shaped structure is composed of rhombuses with an almost horizontal long diagonal with the angles of grooves of 10° and 30° and pitches of 0.8 and 1.2 mm (Figure 2b). The third structure is obtained by applying additional transverse micro-ribbing to the tube surface with a rhomb-shaped structure. Micro-ribbing characteristics: rib thickness of 0.1 mm, rib height of 0.4 mm, and a gap between the ribs of 0.1 mm (Figure 2c).

To apply a porous coating by micro-arc oxidation, tubes made of AD-31 and D16T aluminum alloys with an outer diameter of 10 mm and a wall thickness of 1.5 mm were used. The tubes were coated along the length of the irrigated part. During deposition of coatings, the electrolyte composition, the current supply mode, and the processing time were varied. Coating deposition mode: anodic-cathodic pulse, frequency of 250 and 500 Hz. Application time: from 90 s to 50 min. Surface treatment was carried out in acid or alkaline electrolytes:

- oxalic acid 25 g/l + citric acid 25 g/l;
- KOH 4 and 25 g/l + liquid sodium glass 8 g/l.
Figure 2: Tube surface structures created by deformational cutting (left) and surface morphology of porous coatings deposited by micro-arc oxidation (right).

The surface topology of the studied coatings was obtained using Hitachi S-3400N scanning electron microscope. The porous coating shown in Figure 2d, deposited in an alkaline electrolyte, has an average thickness of 120 µm. On the surface of this coating, one can see a developed roughness and a crater with a melted mouth, which can be the outlet of the subsurface cavity. The thickness of the coating applied in an acid electrolyte is 26 µm (Figure 2e). This coating has low porosity and a loose structure of the upper working layer. The coating shown in Figure 2f is deposited in a silicate-alkaline electrolyte and is approximately 30 µm thick. On the surface there is a regular roughness with rare pores of about 2 µm in size, located at distances of (15-20) µm from each other.

The tubes under study, as a rule, were mounted in a tube array in duplicate, to verify the results obtained. The reference values of the heat transfer coefficients on a smooth surface (without coatings) were measured on tubes made of the same materials as the tested tubes. The surface of plain tubes corresponds to technical roughness $R_z \sim (2-3) \mu m$.

3. Results of measuring the heat transfer coefficients in the falling film

The coefficients of heat transfer from the side of the falling film are calculated through the heat transfer coefficients $K$, taking into account heat transfer from the coolant, thermal resistance of tube walls and their coatings. The total heat transfer coefficient was calculated using formula $K = Q/F(\Delta T_w)$, where $Q$ is the amount of heat supplied to the test section, $F = \pi dL$ is the area of the heat-transfer surface of the
tube, \((\Delta T_{ln})\) is the mean logarithmic difference between the coolant temperature and the saturation temperature of freon R21. The thermal resistance of a porous MAO coating is estimated in [10]. The contribution of thermal resistance of the aluminum oxide coating with a thickness of \(\approx 120 \, \mu m\) to the total resistance to heat transfer is \(\approx (3-4)\%\).

Fragments of video of the film flow on horizontal tube arrays with different surface structures are shown in Figure 3. Auxiliary irrigation tubes with micro-ribbing are mounted between the experimental tubes. On all tubes, irrespective of the surface structure and presence of coatings, there is a film flow with annular rolls or jets of boiling liquid spaced regularly along the tube length. The distance between the rolls varies within (1-2) tube diameters. Intense boiling of liquid is observed in the upper part of tubes and in the annular rolls.

![Figure 3](image1.png)

**Figure 3 a.** Film flow on an array of tubes with MAO-coatings: Re = 1000, 
\[ q = 3\times10^4 \, \text{W/m}^2. \]

![Figure 3](image2.png)

**Figure 3 b.** Film flow on an array of tubes with MDC-structures: Re = 590, 
\[ q = 1.7\times10^4 \, \text{W/m}^2. \]

The results of measuring the heat transfer coefficients in the falling film of freon R21 on an array of horizontal tubes with the MAO-coating for the Reynolds number Re = 1000 are shown in Figure 4. Similar data were obtained for the Reynolds numbers Re = 400-600 and Re = 1500. At low heat fluxes of up to \((5-7)\times10^3 \, \text{W/m}^2\) in the regime of heat removal by evaporation, the heat transfer coefficients on a plain tube and tube with porous coatings are almost the same. For coating of 120 \(\mu m\) thickness applied in an alkaline electrolyte (Figure 2d), as well as for a thinner coating obtained in an acid electrolyte (Figure 2e), the heat transfer coefficients at \(q > 10^4 \, \text{W/m}^2\) at nucleate boiling are lower than those on the tube without coating. Deterioration of heat transfer can be explained by the absence of interconnected open-end pores in the coating structure, which can retain the vapor phase and thereby contribute to a decrease in the temperature head required for the beginning of liquid boiling. The greatest heat transfer enhancement in the flowing film was obtained on a tube with a coating thickness of 30 \(\mu m\), deposited in a silicate-alkaline electrolyte (Figure 2f). For this coating, there is no region characteristic of the evaporation regime, where the heat transfer coefficients do not depend on the heat flux. With heat fluxes \(q > 5000 \, \text{W/m}^2\), nucleate boiling is observed. Nucleate boiling begins when the difference between the wall temperature and the temperature of liquid saturation in the film is about 3 K. With developed nucleate boiling, the heat transfer coefficients are (2-3) times higher than the corresponding values for a smooth tube. Perhaps, the higher hydrophobicity of the surface of this porous coating, caused by the high silicon content, is one of the reasons for heat transfer enhancement in the nucleate boiling regime.

The experiments performed show that on some types of porous coatings deposited by micro-arc oxidation, a significant heat transfer enhancement can be achieved during film flow on an array of horizontal tubes, and the coating method itself can be considered promising for the production of coil-wound heat exchangers in natural gas liquefaction technology [14].
Figure 4. Influence of the characteristics of MAO coatings on heat transfer in a falling film: 1 - plain tube made of D16T aluminum alloy without coating; 2 - coating thickness of ≈120 μm, alkaline electrolyte; 3 - coating thickness of 26 μm, acid electrolyte; 4 - coating thickness of 30 μm, silicate-alkaline electrolyte.

The results of measuring the heat transfer coefficients on an array of horizontal tubes with structured surfaces obtained by the deformational cutting method are shown in Figure 5. As for MAO coatings, the data are presented for Reynolds number Re = 1000 intermediate in the series. Similar data were obtained for Reynolds numbers Re = 400-600 and Re = 1500. It was shown in [13] that the amount of heat removed from the surface of tubes with the studied DC structures is (30-80) % higher than for similar tubes with a smooth surface under the same film flow conditions.

On plain tube at low heat fluxes \( q < 10^4 \text{ W/m}^2 \), heat is removed by evaporation; the heat transfer coefficients in this area do not depend on the heat flux. Nucleate boiling on a plain tube begins at wall-liquid temperature difference \( \Delta T \approx (4-5) \text{ K} \). The temperature difference between the tube wall and the saturation temperature in the region of transition to nucleate boiling for the tubes with a structured surface, depending on the film flow regime, is \( \approx (2-3) \text{ K} \). At heat fluxes of more than \( 2 \times 10^4 \text{ W/m}^2 \), developed nucleate boiling is observed on both plain and structured tubes. Due to the specificity of heating the test sections with hot water, the temperature difference between the tube wall and the saturation temperature does not remain constant along the tube length. This circumstance must be taken into account at definition the temperature difference for the boiling regime of liquid film on the horizontal tubes.

The highest heat transfer coefficients on horizontal tubes treated by the deformational cutting method were obtained on a microstructure with semi-closed cavities (Figure 2a). The parameters of microstructure were selected based on experiments on heat transfer in films of the refrigerants mixture flowing down the vertical cylinder carried out by the authors earlier [12]. This structure is primarily intended for heat transfer enhancement during nucleate boiling. It was shown in [12] that the mechanism of heat transfer intensification during boiling on structured surfaces with semi-closed
subsurface cavities is associated with an increase in the number of active nucleation sites. The results of video filming also confirm an increase in the number of nucleation sites on the surface of horizontal tubes treated by the DC method. The experiments performed show the same heat transfer enhancement in comparison with a plain horizontal tube as on a vertical cylinder.

The rhomb-shaped structure made by the DC method with high accuracy (comparable to laser cutting) is intended to intensify heat transfer in the evaporation regime due to more uniform distribution of liquid over the surface of a horizontal tube, as well as to intensify heat transfer during boiling by creating new active vaporization sites fed by menisci of liquid formed at the intersection of the structure edges. The experimental results in Figure 5 show that in the evaporation regime at $q < 10^4 \text{ W/m}^2$, heat transfer intensification in comparison with a smooth surface reaches (70-80) %. A fragment of the video (Figure 3b) shows that liquid on the rhomb-shaped surface (upper tube) is distributed more evenly due to spreading over intersecting inclined grooves. At nucleate boiling, the heat transfer coefficients are approximately two times higher than the corresponding values on a plain tube.

Additional transverse ribbing of the tube surface with a rhomb-shaped structure with micro-ribs of 0.1-mm thickness and with a gap between them of 0.1 mm led to an increase in the heat transfer coefficients in the falling film at nucleate boiling by about 10%.

The Gogonin model was used to generalize the data on heat transfer during boiling of R21 falling films on various structured surfaces [15]. This model was developed to calculate heat transfer in falling films of one-component liquids over smooth vertical surfaces:

$$\text{Nu}^* = 0.01lbk \left( \text{Re}^* \right)^{0.8} \text{Pr}^{0.3} K^{-0.4} \frac{\lambda_c \rho_l}{\lambda_w \rho_w}. \quad (1)$$

The model takes into account heat transfer enhancement in boiling films due to liquid splashing and entrainment during the collapse of bubbles, as well as the thermophysical properties of liquid and the surface material. In this model, the Laplace constant $l_0$ is used as a characteristic length in the Nusselt and modified Reynolds number. The rate of vaporization $(q/rp_c)$ is used as a characteristic velocity. The results of data processing on heat transfer in a falling film of R21 on the array of horizontal tubes with the different surface structures are shown in Figure 6.
Figure 6. Generalization of data on heat transfer in a falling film:
1 – microstructure with semi-closed cavities; 2 – plain copper tube;
3 – MAO coating of 30 μm thick; 4 – plain tube made of alloy D16T;
5 – vertical copper cylinder with a microstructure, Re = 100 [12];
6 – vertical copper cylinder with a microstructure, Re = 300-360 [12];
I – calculation according to equation (1).

The dimensionless heat transfer coefficients for plain tubes made of copper and aluminum alloy D16T without coating agree with each other and with the calculation by equation (1) for the tube material D16T and modified Reynolds numbers Re’ < 70. The calculation for a copper tube gives higher values of the Nusselt number. Additional analysis will likely be required to assess the degree of the wall’s material influence on heat transfer in the falling film in the model [15].

A significant enhancement of heat transfer on the copper tube surface with semi-closed cavities created by the deformational cutting method is observed even at minimum heat fluxes during the transition from evaporation to nucleate boiling. In the regime of developed nucleate boiling, the dimensionless heat transfer coefficients on a microstructured surface with semi-closed cavities are almost three times higher than the corresponding values for the plain tube. At Re’ > 80, which corresponds to heat flux q > 4x10^4 W/m², the rate of an increase in the Nu’ number slows down with an increase in the modified Re’ number. The same is observed on plain tubes. There is no stratification of data on the liquid film Reynolds number for heat transfer on horizontal tubes.

The processing of data on heat transfer on a surface with a MAO coating demonstrates an almost linear increase in the heat transfer coefficients during the transition from the evaporation regime to nucleate boiling in the investigated range of heat fluxes. In the regime of developed nucleate boiling, the heat transfer coefficients on the surface of a tube with a MAO coating deposited in a silicate-alkaline electrolyte reach the same values as on the surface of a copper tube with a microstructure created by the DC method.

Data on heat transfer in falling films on a horizontal tube with a microstructured surface are compared in Figure 6 with previously obtained data on a similar surface of a vertical copper cylinder [12]. When analyzing the results, it should be borne in mind that experiments on an array of horizontal tubes were carried out at high Reynolds numbers of a falling film (Re = 400-1500), and experiments on a vertical cylinder were carried out at Reynolds numbers Re = 75-360.
In the range of heat fluxes \( q = (2-4) \times 10^4 \text{ W/m}^2 \) (Re \( \approx 30-80 \)), the dimensionless heat transfer coefficients on a horizontal tube and a vertical cylinder with the same surface structure agree satisfactorily. With an increase in the heat flux, the heat transfer coefficients on the vertical cylinder at the Reynolds numbers of the falling film Re \( \leq 100 \) begin decreasing. The deviation of data on heat transfer from the main data array takes place for those experiments in which the formation of dry spots and subsequent deterioration of heat transfer were observed. The value of heat flux causing dry spot formation, as a rule, decreased with decreasing flow rate of liquid in the film. With a higher irrigation density, the beginning of dry spot formation shifts towards higher heat fluxes; for Reynolds numbers Re \( = 300-360 \); no deterioration in heat transfer was observed. The first dry spots on the vertical cylinder appeared in the lower part of the heated surface, and as the heat flux increased, they spread upstream.

In the upper part of the heated zone on the surface, the regime of developed nucleate boiling remained, therefore, the average heat transfer coefficients, even in the presence of dry spots, remained high.

Video filming of the film flow on an array of horizontal tubes shows that areas with a thin liquid film are located between the liquid rolls or boiling jets on the surface of horizontal tubes. The typical size of areas with a thin film on horizontal tubes is comparable to the tube diameter. Along with intense nucleate boiling in liquid rolls and boiling jets on a large surface area, heat removal is carried out by liquid evaporation with significantly lower values of heat transfer coefficients. Therefore, with an increase in heat fluxes the “effective” or length-average heat transfer coefficients on horizontal tubes can decrease in comparison with developed nucleate boiling. The experimental results shown in Figure 6 demonstrate that at Re \( \approx 300 \) there is a decrease in the dimensionless heat transfer coefficients on a horizontal tube as compared to a vertical cylinder. On a horizontal tube with a smooth surface in this region of heat fluxes, the heat transfer coefficients decrease also in comparison with the calculation by equation (1), which is consistent with the concept of the heat transfer mechanism on horizontal tubes described above. By analogy with a vertical surface, it can be assumed that with a further increase in heat fluxes on horizontal tubes, formation of stable dry spots in the areas with a thin liquid film will begin due to evaporation of the liquid residual layer, and this will lead to deterioration in heat transfer and development of crisis phenomena.

4. Conclusion
Experimental data on heat transfer enhancement in falling films of refrigerant R21 have been obtained on horizontal tubes with an enhanced surface in a vertical single-row array. In the studied range of liquid flow rates in the falling film, the effect of the Reynolds number on the heat transfer coefficients is not observed.

The intensification of heat transfer on horizontal tubes with coatings applied by micro-arc oxidation depends on the type of coating and the heat flux. The maximum values of the heat transfer coefficients in the falling film in the nucleate boiling regime were obtained on a tube made of D16T alloy with a MAO coating with a thickness of \( \approx 30 \mu m \), applied in an electrolyte solution (KOH + liquid glass). Heat transfer enhancement on this surface in the regime of developed nucleate boiling is comparable to the enhancement on a horizontal tube with micro-ribbing, applied by the deformational cutting method. The technology for applying MAO coatings can be very promising for the production of large-scale coil-wound heat exchangers.

On all surfaces of horizontal tubes modified by the deformational cutting method, a stable intensification of heat transfer in the falling film in the nucleate boiling regime is observed. On a surface with a rhomb-shaped structure, heat transfer enhancement in the regimes of evaporation and nucleate boiling is \( \approx (70-80) \% \), and on a microstructured surface with semi-closed pores, it is \( (2.5-2.8) \) times higher as compared to a smooth surface. Micro-ribbing of the rhomb-shaped surface leads to additional intensification of heat transfer in the nucleate boiling regime approximately by 10%.

5. References
[1] Fernandez-Seara J, Pardinas A A 2014 Applied Thermal Engineering 64 155–71
[2] Ribatski G, Jacobi A M 2005 Int. Journal of Refrigeration 28 635–53
[3] Christians M, Thome J R 2012 *Int. Journal of Refrigeration* **35**, 300–12
[4] Bock B D, Meyer J P, Thome J 2019 *Exp. Therm. and Fluid Sci.* **109** 109870
[5] Poniewski M E, Thome J R 2008 http://www.htri-net.com/ePubs/epubs.htm
[6] Kim D E, Yu D I, Jerng D W, Kim M H, and Ahn H S 2015 *Experimental Thermal and Fluid Science* **66** 173–96
[7] Suminov I V, Epel'fel'd A V, Lyudin V B, Krit B L, Borisov A M 2005 *Microdugovoe oksidirovanie: teoriya, tekhnologiya, oborudovanie [Microarc oxidation: theory, technology, equipment]* (Moskow, Ekomet Publ.) p 368 (in Russian)
[8] Alykrets R V, Ravodina D V, Trushkina T V, Vakhteev E V, Alekseeva E G 2014 http://trudymai.ru/eng/published.php?ID=49348 74 29–30
[9] Nikiforov A A, Nikiforova G L, Terleeva O P, Slonova A I, Eshchenko V N, Dong K Li 2005 *Patent* RU 2248416 C1 20.03.2005
[10] Pavlenko A N, Pecherkin N I, Volodin O A, Kataev A I, Mironova I B 2020 *Journal of Physics: Conference Series* **1677** 012091
[11] Thors P, Zoubkov N 2013 *US Patent* 8573022
[12] Volodin O, Pecherkin N, Pavlenko A, Zubkov N 2020 *Int. J. Heat and Mass Transfer* **155** 119722
[13] Volodin O A et al 2020 *Journal of Physics: Conference Series* **1677** 012099
[14] Liquefied Natural Gas Technology and Equipment http://www.airproducts.com/Industries/Energy/LNG.aspx
[15] Gogonin I I 2010 *J. Eng. Phys. and Thermophysics* **83** 876–81

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