Intensification of heat transfer in falling films on a bundle of horizontal tubes with microstructured surface

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Abstract. Experimental results on measuring heat transfer in falling films of R21 refrigerant on a bundle of horizontal tubes with structured surfaces are presented. The experiments were carried out in the range of Reynolds number of the saturated liquid film from 500 to 1500 at a pressure of 3 bar in the evaporator. To intensify heat transfer, copper tubes with an external surface treated by the method of deformational cutting (MDC) were used. Three types of structures were used: structure No. 1 with half-closed microcavities, structure No. 2 with a rhomboid shape, and structure No. 3 created on the basis of structure No. 2 with additional transverse ribbing. It was shown that the studied types of structures can significantly increase the heat transfer coefficient as compared to a smooth surface. The structure with half-closed microcavities was the most effective for heat transfer enhancement.

1. Introduction

The immersed and film heat exchangers are used in technological processes in a number of industries. The application of intensification methods based on already known principles can lead to a decrease in dimensions and mass of heat exchangers and corresponding operating costs due to an increase in the efficiency of apparatuses as compared to the produced models. Reducing the dimensions and metal consumption of devices (up to two or more times) can be achieved through the use of enhancing surfaces, and a decrease in the flow rate of the working fluid can be achieved by turning from immersed heat exchangers to the film ones [1]. The creation of new efficient heat exchangers is constrained both by the complexity of analytical description of the heat transfer process at boiling [2], and by the lack of knowledge about boiling of liquids on microstructured surfaces with different surface structures. Thus, there is a need for systematic studies of heat transfer at evaporation and boiling on potentially effective modified surfaces, such as, for example, microfinned surfaces with half-closed cavities [3].

One of highly effective and affordable methods of creating intensifying boiling surfaces is the method of deformational cutting (MDC), see patents [4, 5]. Intensification of heat transfer at pool water boiling on microstructured surfaces obtained by deformational cutting was studied by Schelekhkov et al. [6], Popov et al. [7], etc. The authors have developed and prepared a large number of experimental sections with two- and three-dimensional microtextures that differ in geometry. The maximal increase in heat transfer coefficients (4–6 times [6]) and critical heat fluxes (up to 6 times [6, 7]) was obtained...
on surfaces with three-dimensional microribbing and gaps of 120–180 μm with rib heights of 340–570 μm and longitudinal rib pitch of 240-400 μm.

Test results for a heat pump unit (HPU) with a bundle of tubes, processed by the DC technology mounted in its evaporator and condenser, are presented in the work of Antanenkova et al. [8]. The authors evaluated an increase in the efficiency of boiling and condensation of R22 freon in the devices under consideration in comparison with these processes on smooth tubes. It was shown that during the forced flow of freon in the intertubular space of the evaporator, the heat transfer coefficients at boiling increase 3-5 times, and at vapor condensation on a ribbed surface, they increase by 9-21 times as compared with smooth tubes. The reason for such a significant increase in the heat transfer efficiency of condensing freon may be a capillary effect on the tube bundle of the condenser due to peculiarities of the surface macrorelief.

Two types of structures of the heat-generating wall obtained by deforming cutting were studied in the aforementioned work [3]: microribbing with semi-closed subsurface pores (for boiling intensification) and micro-pin structures (surface development for intensification of evaporation). A mixture of freon R114/R21 was used as the working surface. The mixture film flowed over the outer surface of the vertical heated cylinders in the laminar-wave regime. The authors demonstrated that surfaces with half-closed cavities have an advantage in heat transfer enhancement at boiling (up to 4 times as compared to a smooth surface), while micro-pin structures contribute to an increase in heat transfer at evaporation (almost two times as compared to a smooth surface). A significant decrease in the temperature drop was demonstrated on both types of surfaces. The highest values for boiling intensification were obtained on a microstructured surface with a rib pitch of 100 μm, rib height of 220 μm and a longitudinal knurling pitch of 318 μm.

The obtained experimental data at pool boiling and in falling films were compared in [9] for modern intensifying tubes: Turbo-B5 (Wolverine Tube Inc.) and Gewa-B5 (Wieland Thermal Solution), using R-134a and R-236fa refrigerants. The experiments were carried out both on a single horizontal tube and on a tube bundle. The film Reynolds number varied in the range of 0-3000. An increase in the heat transfer coefficient in the falling films of about 1.5–2 times was shown in comparison with the conditions of a pool boiling for both a single tube and a tube bundle, depending on the type of refrigerant and used modified tubes.

The authors of [10, 11] studied heat transfer, using 4 types of structured copper tubes with external three-dimensional microtextured and internal ribbing, which differ in microcharacteristics of structuring. The authors used refrigerants R134a, R123, R32 and R410A as working fluids. The work demonstrated the effect of liquid flow rate on heat transfer in the film flow of freons along the horizontal bundles of various modified tubes. The results obtained on heat transfer for different refrigerants were compared. In particular, it was shown that R134a provides the heat transfer coefficient 2-3 times higher than R123 for all studied types of tubes.

The present work is aimed at the experimental study of heat transfer enhancement in the falling liquid films on a bundle of irrigated horizontal tubes with various three-dimensional surface microstructures: the structures that previously proved their efficiency for heat transfer intensification in the film flow of freons on a vertical tubes (structure No. 1, see [3]) and the new structures (No. 2, 3).

2. Experimental setup

An experimental evaporator for studying heat transfer at evaporation and boiling of the falling liquid films on a vertical single-row bundle of horizontal tubes is shown in Fig. 1. The setup is equipped with the windows for monitoring and video recording of the flow. Refrigerant R21 is used as a working fluid at an absolute pressure in the evaporator of ~ 3 bar. Irrigation is performed at the full length of the bundle through a slot distributor at a liquid inlet temperature approximately equal to the saturation temperature of R21. The range of irrigation density corresponds to the Reynolds number at the evaporator inlet of 400-1500. The flow rate of R21 refrigerant irrigating the bundle is measured by a turbine flowmeter. The bundle of experimental tubes is a vertical row of horizontal tubes with a diameter of 10 mm, arranged with a step of 12 mm. The heat flux is created by passing hot water inside the tubes (whose
temperature is higher than the saturation temperature of R21). Water for heating the experimental tubes comes from a constant level tank, which eliminates flow pulsations and provides a constant temperature drop between the wall of experimental tube and a liquid film.

Figure 1. Experimental evaporator, frontal view.

Figure 2. The sketch of structure No. 1 with half-closed microcavities (frontal view of a vertically oriented surface).
The tube bundle, which includes 40 tubes, consists of auxiliary irrigating brass tubes of 10×1.5 mm with screw knurling and experimental tubes alternating with irrigating ones at the bottom part of the bundle. The length of the structuring area is equal to the length of the irrigated part of tubes (625 mm), the tube wall thickness is 2 mm. To obtain the reference values of heat transfer coefficients, a copper tube of 10×2 mm with an untreated surface is installed in the bundle. The coolant (water) is pumped through the lower 16 tubes of the bundle. For structured tubes, the wall temperature is determined through the heat transfer coefficient $K$, which is inversely proportional to the sum of thermal resistances (see the description of the calculation method in [12]).

Working sections with structured surfaces are made of M1 copper, which has plasticity required to create a microstructure. The choice of the structure with half-closed microcavities (No. 1) is based on the results obtained previously by the authors when studying heat transfer in freon mixture films falling down a vertical cylinder [3]; the structure No. 1 is now rotated by 90° (because tubes are oriented horizontally) and has the following parameters: ribbing step of 100 μm, rib height of 220 μm, and knurling step of 318 μm, see Fig. 2. This structure is primarily intended to intensify the process of nucleate boiling.

Structure No. 2 is obtained by knurling with two helical rollers with a slope of corrugation angle of 10 and 30° and with corrugation steps of 0.8 and 1.2 mm. Such a rhomb-shaped structure, created with high accuracy by deformational cutting, should contribute to uniform distribution of the falling liquid film over the surface, as well as to boiling enhancement, by creating new active nucleation sites, fed by the fluid meniscus formed at intersections of microtexture faces.

Structure No. 3 is created on the basis of structure No. 2, but with additional transverse microribbing with a pitch of 0.2 mm, inter-rib gap of 0.1 mm, and rib height of 0.4 mm. Additional microribbing can increase critical heat fluxes due to even better fluid retention in the texture grooves by capillary forces.

The studied tubes were usually mounted in the tube bundle in duplicate, to verify the results obtained.

3. Results and discussion

The pattern of the boiling film of R21 refrigerant flow along experimental tubes at the lower part of the bundle with characteristic types of structures under study is shown in Fig. 3. The upper tube has a rhomb-shaped structure, the third tube from the top has a microstructure with half-closed cavities, and the lower tube in the photo is smooth. Auxiliary irrigation brass tubes with transverse ribbing (darker in the photo) are between the above tubes.

![Figure 3. The flow of refrigerant R21 film over experimental tubes of the bundle (boiling regime). Re = 600.](image)
The experimental data on the dependence of heat transfer coefficient $K$ on heat flux density for the studied structured tubes (No. 1-3) and the reference smooth copper tube are shown in Fig. 4. It can be seen that the structure with half-closed cavities (structure No. 1) is the most effective. It can be also noted that the heat transfer coefficients for the modified tubes consistently exceed the values for a smooth surface in the entire range of heat fluxes. The rhomb-shaped structures as well as the rhomb-shaped structures with transverse ribbing (structures No. 2 and 3, respectively) give heat transfer values that are close in magnitude, which indicates the absence of the effect of transverse micro-ribbing with selected parameters on heat transfer enhancement; these values also exceed significantly the $K$ values, obtained for a smooth surface.

![Figure 4](image.png)

**Figure 4.** Dependence of heat transfer coefficient $K$ on heat flux density for modified and smooth tubes, $Re = 600$.

The results obtained for modified and smooth tubes are presented in Figs. 5a, b in the form of the ratio of the amount of heat removed from the selected modified and smooth tubes $Q_{\text{struc}}/Q_{\text{smooth}}$ to the coolant temperature (at the inlet) for two Reynolds numbers. According to Fig. 5a, the modified tubes with half-closed microcavities allow the removal of thermal capacity of up to 1.8 times higher than the corresponding values for a smooth surface. Rhomb-shaped tubes produce a 1.4-fold increase in the amount of heat removed as compared to a smooth surface. The heat transfer maximum observed for all tubes under study at a coolant temperature of about 46°C is associated with the transition from liquid film evaporation to boiling.
Figure 5. Dependence of $Q_{\text{struc}}/Q_{\text{smooth}}$ on coolant temperature at the inlet for $\text{Re} = 600$ (a) and $\text{Re} = 1000$ (b).

The effect of inlet Reynolds number on heat transfer enhancement for the studied modified tubes is shown in Fig. 6 a-c in similar coordinates. It can be seen that for the lowest of the studied Reynolds numbers (600), the highest values of $Q_{\text{struc}}/Q_{\text{smooth}}$ are obtained; with an increase in the Reynolds number
(see experimental data for Re = 1000 and Re = 1500), the flow rate almost ceases to have a noticeable effect on heat transfer.
Figure 6. Dependence of $\frac{Q_{\text{struc}}}{Q_{\text{smooth}}}$ on Reynolds number.
(a) – structure with semi-closed cavities No. 1 (sample 2); (b) – rhomb-shaped structure No. 2 (sample 2); (c) – rhomb-shaped structure with transverse microribbing No. 3.

Conclusions
The paper presents investigation results on heat transfer in the refrigerant films flowing over a bundle of horizontal tubes with various structures of the outer surface.

To study the heat transfer enhancement, the authors used a previously developed microstructure with half-closed microcavities; this microstructure proved itself well at intensification of nucleate boiling in falling liquid films. A new rhomb-shaped structure, made with high accuracy by the deformational cutting method, and its version with additional transverse microribbing were used as well.

The experimental results have shown that the structure with half-closed microcavities gives the largest increase in the heat transfer coefficient as compared to a smooth surface (up to 1.8 times), while the rhomb-shaped structure and that with transverse microribbing are less effective. The values of heat transfer intensification achieved on the studied modified tubes are consistently observed in the entire range of heat flux changes.

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