The influence of the surface structuring type on heat transfer in falling films of the refrigerant mixture

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Abstract. The paper considers the influence of enhanced surfaces on heat transfer during evaporation and boiling of a falling laminar-wave liquid film. A mixture of R114/R21 refrigerants was used as a test fluid. The liquid film flowed on the outer surface of vertically-oriented cylinders. To intensify the evaporation process, the authors used the mesh coatings with variable mesh sizes, whereas the surfaces with variable characteristics of microstructure obtained by deformational cutting were used to enhance boiling. The report makes a conclusion about the studied types of structured surfaces, most effective for enhancement of heat transfer in different regimes. It is shown that the mesh coatings intensify heat transfer at evaporation twice as compared to a smooth surface; the microstructured coatings with partly-closed micropores obtained by deformational cutting allow fourfold heat transfer intensification at boiling.

1. Introduction

In connection with the development of processing techniques and ever-increasing technological requirements for the amount of heat flux taken away (for example, there is already a need to remove up to 100 W/cm² from the surface of computing modules), it is necessary to continue research on the development and improvement of enhanced surfaces, efficient under different conditions, and expand fundamental knowledge about the processes of boiling and evaporation.

The first experiments on intensifying the process of water boiling were carried out back in 1931 by Jakob and Fritz, allowing an increase in the heat transfer coefficient up to three times in comparison with a smooth surface (the structured surface has a square mesh of machine grooves), however, it turned out that for the "aging effect", resulting intensification disappeared after a few days [1]. So the result was considered useless for practical application.

Interest in the research of intensification with the help of developed surfaces returned in the 50s of the last century. Already in the first such works [2], it was shown that boiling enhancement occurs with an increase in the density of active nucleation sites due to the artificially created stable (and long-living) centers. It was also shown that the creation of artificial nucleation sites leads to a decrease in the temperature drop.

In the 1970s, researchers developed and registered patents for a number of boiling surfaces, such as Thermoexcel-E [3], GEWA-T [4], etc. (see [5]). Processing methods and the enhanced surfaces obtained with their help continue to be improved.
In 1997, Thors et al. registered a patent for the Turbo-BIII surface, which turns out to be 70% more efficient than the earlier version of this type of surface, Turbo-B [6]. Approximately at the same time (in 1996), the first patent of Zubkov and Ovchinnikov [7] appeared, and in 2007 and 2013, there were the joint patents of Thors and Zubkov [8, 9], which described the technology of surface microprocessing using the so-called deformational cutting method (MDC). Boiling surfaces used in this work were created using this method.

Starting from [10, 11], attempts have been made to create the models that describe boiling of liquid on artificial sites of structured coatings, but at the moment, this area is still being developed. Despite a large number of thematic works, there is still a need for further research on boiling enhancement using microstructured surfaces, especially for falling liquid films.

This paper presents also the data obtained during the study of intensification of falling film evaporation with the help of mesh coatings. Such a fairly simple method of surface development can also give positive results and help to shed light on the physical mechanisms of intensification. Not many works are devoted to the study of heat transfer intensification using mesh coverings. In [12], the possibility of intensifying the process of heat and mass transfer during the evaporation of falling films of water was shown. The results of test apparatus performance indicated evaporation rates up to 3-fold higher using the mesh promoter than without it (at water inflow rates of 0.72-1.00 g/s and fixed carrier gas inflow rate of 2.44·10^{-3} m^3/s).

In [13], the dielectric fluorocarbon PF 5060 was used. The experiments were carried out at pool boiling, as well as under geometrically limited conditions when the mesh was covered with a plate of glass or polycarbonate. The largest increase in heat transfer coefficient at boiling reached 4 times as compared with a smooth surface for a mesh containing 20 wires/cm.

In [14], heat transfer intensification was investigated using the thin metal meshes with different numbers of layers (from 1 to 4) at pool boiling. Alcohol was used as a working fluid. The authors achieved a significant enhancement of boiling heat transfer (about 8 times) and a significant decrease in the temperature drop. It is shown that the use of the 4th layer of the mesh affects heat transfer. Some models presented in the paper do not describe adequately the experimental data obtained by the authors.

Thus, it can be noted that at present there are not so many results on the study of the mesh coating effect on heat transfer, and available research is mainly devoted to pool boiling. That is also true for the studies of the effectiveness of microstructured boiling surfaces. At the same time, such studies are necessary, since the falling films have a number of well-known advantages in comparison with heat transfer at pool boiling, as well as specific features (bubbles driftage, drop entrainment, influence of film velocity, and contribution of evaporation from the free surface even in the boiling regime) that distinguish them from pool boiling.

The purpose of this work was an experimental study of the effect of different types of coatings on heat transfer enhancement at evaporation and boiling. For each of the coating types (MDC-microstructures, mesh coatings), characteristic parameters were varied. It is shown that external mini-scaled mesh structures with respect to a smooth heat releasing surface contribute to the heat transfer enhancement in evaporation regime, while microstructures with partially covered micropores (being rather subsurface) obtained by MDC, enhance boiling greatly.

The results will be useful for the further study of heat transfer enhancement during evaporation and nucleate boiling of liquids (primarily for the case of falling films) using surfaces structured on different scales, for developing an understanding of the physical mechanisms of intensification, as well as for designing new high-performance types of enhanced surfaces.

2. Experimental setup and techniques
The scheme and description of setup for studying heat transfer at film flow of refrigerant binary mixtures are given in [15, 16]. The R114/R21 refrigerant mixture film flowed on vertically oriented cylinders with a diameter of 50 mm. The concentration of volatile component (R114) of the mixture at the inlet of the test section was 15% and it did not change. For the mixture used, the effect of a change
in its concentration during evaporation on the heat transfer coefficient was not noticeable (this issue is discussed in [15]). The cylinder wall thickness was 1.5 mm. The length of the structuring area was 80 mm, and the length of the heat releasing zone was 70 mm. The experiments were carried out as on a smooth cylindrical surface with roughness $R_a = 2.5 \, \mu m$, so on the MDC-structured surfaces and the sections with mesh coatings. When calculating the heat flux density, an increase in the area of the structured heat transfer surface due to the formation of (micro-) relief was not taken into account.

The surfaces obtained by the method of deformational cutting were used as boiling surfaces. Photographs of one of the surfaces, microstructured by MDC, in various sections are shown in figure 1. Table 1 shows the characteristic parameters of the studied MDC-surfaces.

![Images of microstructured surfaces](a), (b), (c)

**Figure 1.** Surface No. 1: a – frontal view; b – section along the fins; c – section along with the knurling.

| No. | Fin pitch, μm | Fin height, μm | Knurling pitch, μm |
|-----|---------------|----------------|-------------------|
| 1   | 100           | 220            | 318               |
| 2   | 200           | 440            | 318               |
| 3   | 60            | 120            | 318               |

*Table 1. Parameters of microstructured boiling surfaces.*

Figure 2 (a-d) shows the used test sections with the wire mesh coatings, the parameters of meshes are given in Table 2.


**Figure 2.** Test sections with mesh coatings Nos. 1-4 (a-d).

**Table 2.** Parameters of the studied mesh coatings.

| No. | Material       | Cell size, mm | Wire diameter, mm | Mesh disposition |
|-----|----------------|---------------|-------------------|------------------|
| 1   | Brass          | 1.6×1.6       | 0.4               | Vertical         |
| 2   | Brass          | 1.6×1.6       | 0.4               | Diagonal         |
| 3   | Stainless steel| 3.0×3.3       | 0.5               | Vertical         |
| 4   | Stainless steel| 6.0×6.0       | 0.7               | Vertical         |

3. **Experimental results and discussion**

Figure 3 in $q$-$dT$ coordinates shows a comparison of the data obtained by authors for microstructured surfaces Nos. 1-3 (from Table 1) and sample smooth surface [16] with experimental data of [17] for R113. The data of [17] were obtained for the smooth and structured surfaces (Gewa-K19, Gewa-T19D) at pool boiling of R113 and water. The surface structure of Gewa-K19 is the plain transverse finning of the tube, while the tops of the fins of the Gewa-T19D have the flattened T-shaped form, close to the form of the flattened fins of microstructures Nos. 1-3 (see figure 1c).

It can be seen in figure 3 that the values of heat flux for microstructures Nos. 1 and 2 in the boiling region lie above the values obtained for Gewa-T19D, and the boiling curves have the sharper growth than the dependences shown in the figure for all other surfaces. The heat flux values for surface No. 3, which does not give intensification as compared to a smooth surface at film flow [16], nevertheless, lie above the heat flux values corresponding to pool boiling on a smooth surface [17] (this is due to the characteristic features of evaporation and boiling in thin films of liquid that intensify heat transfer in comparison with pool boiling) and practically coincide with the data for Gewa-K19. The absence of
enhancement for surface No. 3 can be related to the absence of notable effect of small micropores on "suction and evaporation" process (in terms of Nakayama [10]), so characteristics of this structure could be considered as limiting (the structure dimensions) from below.

The observed enhancement of heat transfer for microstructured surfaces Nos. 1, 2 in comparison with Gewa-T19D and Gewa-K19 (in the boiling region), besides the differences caused by the specificity of heat transfer in falling films, apparently, is directly related to the smaller characteristic sizes of microtextures Nos. 1, 2 and, as a result, a large number of nucleate sites per unit area. The finning pitch for surfaces 1, 2 was 100 and 200 μm, respectively (see Table 1), while the pitch for Gewa-K19 and Gewa-T19D surfaces was 1.35 mm [17].

**Figure 3.** Comparison of boiling data for MDC-surfaces and Gewa-series surfaces [17].

**Figure 4.** The dependence of the heat transfer coefficient on the heat flux density for a smooth surface and mesh coated surfaces (Nos. 1, 3, 4 from Table 2): a – Re = 640, b – Re = 1040.

Dependences of the length-averaged heat transfer coefficient on the heat flux density for different mesh coatings is shown in figure 4a, b in comparison with the results for a smooth surface for two different film Reynolds numbers (see definition of film Re number in [15, 16]).

Experiments showed that the data for the evaporation heat transfer coefficient for a large mesh No. 4 (Table 2), slightly exceeding the values for other meshes in the case of Reynolds number 640, are
close in magnitude to the heat transfer values for meshes with a smaller cell size for other Reynolds numbers (208-1040) and they are approximately two times higher than the heat transfer values obtained for a smooth surface (see figure 4).

The increase in the heat transfer coefficient in evaporation regime on the meshed structures, apparently, is due to the change in hydrodynamics of the wave flow of the film caused by capillary forces. It was shown in [18] that intensification of heat transfer using wire coatings occurs due to the appearance of recirculation zones arising because of the pressure gradient behind the transverse rings of the wire.

In the regime of nucleate boiling \( (q > 1 \cdot 10^4 \text{ W/m}^2) \), a noticeable increase in heat transfer coefficients in comparison with a smooth surface is not observed for the studied mesh coatings (see figure 4a, b).

4. Conclusions

The presented results demonstrate the effect on heat transfer in falling films with the formation of external or internal (with respect to a smooth surface) ordered structural disturbances.

At the time of the research, the minimum knurling pitch was limited by 318 \( \mu \text{m} \), and the knurling roller had the sharpened teeth, which made it impossible to create full-fledged semi-closed pores during knurling. These factors could limit the magnitude of intensification obtained for the MDC-surfaces.

Sufficiently high enhancement results obtained with the use of MDC-structures [19] for pool boiling demonstrate also that the possibilities of heat transfer intensification at nucleate boiling using deformational cutting are not exhausted yet and require additional studies.

Acknowledgments

The study was performed at Kutateladze Institute of Thermophysics (IT SB RAS) with the support of the BSI SAS Program for 2017-2020 (project III.18.2.3, reg. no. AAAA-17-117030310025-3)

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