Heat transfer at boiling of R114/R21 refrigerants mixture film on microstructured surfaces

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Abstract. The paper presents the results of experimental study of heat transfer in the film flow of R114/R21 refrigerant mixture on the vertical thin-wall copper cylinders with microstructured outer surfaces. Microstructuring is made by the method of deforming cutting with subsequent rolling by a straight knurl roller along the fin tops. The pitch of micro-finning was 100 or 200 μm and height was 220 or 440 μm, respectively. The knurling pitch in both cases was 318 μm. The film Reynolds number was varied in the range of 300-1500. The heat flux density was step-by-step increased from zero to the values corresponding to the boiling crisis. It is shown that the heat transfer coefficients at nucleate boiling on the studied surfaces with microstructuring exceed the corresponding values for a smooth surface more than by 3 times, the critical heat flux increases more than twice.

1. Introduction

The falling liquid films provide high intensity of heat and mass transfer processes, and they are widely used in the modern technological apparatuses. Despite the well-known advantages of using the film flows in various applications (distillation columns, evaporative equipment, cooling and thermostabilization systems, etc.), currently there are significantly less experimental data on boiling the flowing liquid films in comparison with data on pool boiling [1, 2]. This relates to both smooth and structured heat exchange surfaces of different scales.

The heat transfer coefficient at thin film boiling even in the case of a smooth heat exchange surface exceeds the heat transfer coefficient achieved at pool boiling at least at relatively low temperature drops [3, 4]. This is primarily caused by the contribution of evaporation, which remains significant even at developed boiling of falling films. Also they are able to cover a large area at low specific liquid flow rates.

Along with the above advantages, there is still considerable unrealized potential in the direction of increasing the heat transfer coefficient in the nucleate boiling regime [5]. According to the modern ideas about the mechanisms of boiling and experimental data with observation of a multiple increase in the heat transfer coefficient obtained under the conditions of pool boiling (by the factor of 4-5) [6] and in some experiments with falling films (more than 10 times) [7], one of the promising methods of heat transfer intensification is the arrangement of microstructures with chaotic or ordered spacing of microcavities, which increase the nucleation site density and reduce the temperature drop.
For the film flows, this direction has not been sufficiently developed and investigated. In literature, there are separate studies of heat transfer at the film flow of liquid on the surfaces with artificial pores and varying roughness degree (e.g., [8]) as well as on the known industrial structured surfaces: Turbo-B5, Gewa-B5 [9]. In particular, in [9], it is reported that the heat transfer coefficients increase in the films flowing along the horizontal modified tubes in comparison with the pool boiling by the factor of 1.5-2.5.

The above-mentioned work [7] is one of the few that systematically investigate heat transfer in the film flow of R114 refrigerant on various porous surfaces (in this case industrial ones): High Flux, Gewa-T, Thermoexcel-E and -EC. The length of microstructured tubes in experiments was 2 m, subcooling temperature was 1K, and variation range of the Reynolds film number of 3000-5000 was in the region of turbulent regime. These studies showed high efficiency of these types of surface structuring for the film flow conditions. An increase in the heat transfer coefficient at nucleate boiling of the R114 film in comparison with the smooth tube was 5-12.

This work is the initial part of research for obtaining the systematic data on intensification of heat transfer at nucleate boiling of films of low-viscous highly-wetting liquids (refrigerants and their mixtures, cryogenic liquids) that flow along the microstructured surfaces of complex geometry.

2. Experimental methods
A schematic diagram of experimental setup for studying heat transfer in the film flow of binary mixtures of refrigerants is shown in Fig. 1. The detailed description of experimental setup is given in [2, 3, 10, 11].

The film of R114/R21 binary mixture flows down along the vertically oriented cylinders of 50-mm diameter. The thickness of the cylinder wall was 1.5 mm. The length of the microstructured area was 80 mm. The experiments were carried out on a smooth standard section with surface roughness Ra = 2.5 μm [2, 3] and sections with microstructures (see Fig. 2, 3).

The studied types of microstructuring are obtained by deforming cutting [12] with subsequent rolling by a straight knurl roller along the fin tops (Fig. 2, 3). Parameters of microstructure No. 1: fin pitch is 100 μm, fin height is 220 μm. The knurling pitch is 318 μm. Parameters of microstructure No. 2: fin pitch is 200 μm, fin height is 440 μm. The knurling pitch is 318 μm. The coefficient of surface area increase was calculated as the ratio of the fin perimeter on the length of the finning pitch to the finning pitch and for both microstructures it was: $k = 5.4$.

To heat the test section, a heating cartridge with the length of 50 or 70 mm along the flow was used. The upper boundary of the heat-generating zone was at the distance of ~ 100 mm from the slot liquid distributor, and this provided the liquid film flow along the heat-generating surface in the regime of hydrodynamic stabilization.

To measure the local temperature, four copper-constantan thermocouples with the diameter of 0.18 mm were fixed flush with the surface along the height of the heat-generating zone of the tube. The step between the thermocouples was 14 mm, distance between the beginning of the heat-generating zone and upper thermocouple was 4 mm (or 17 mm in the case of a long heater). Cold junctions of thermocouples immersed into the liquid layer at the bottom of the column were at the same temperature, which was measured by the HEL-700 thermistor. To achieve thermal insulation from the column bottom, the cold junctions of thermocouples and thermistor were fixed on a fluoroplastic substrate.
**Figure 1.** Scheme of setup for studying heat transfer in the films of refrigerant mixtures: 1 – thermally insulated column; 2 – supply tank; 3 – test section; 4 – heated zone of test section; 5 – receiving collector, 6 – thermocouples, 7 – points of measuring the liquid phase temperature; 8 – points of measuring the vapor phase temperature.

The temperature in various sections of the working volume of experimental column was controlled by platinum thermistors. The liquid temperature was measured in a vessel in front of the working section, in the collecting cup immediately after the test section, and at the bottom of the column. The vapor phase temperature was measured in the upper, middle and lower parts of the column. The absolute pressure in the column was measured by the Metran-100 manometer, and the flow rate was measured by the CORI-FLOW flowmeter of Bronkhorst production, which measures the mass flow rate in the range of 0-100 kg/h. Molar concentration of binary mixture components was measured by gas chromatography. The mixture composition was measured before and after the test section.

The process of liquid film boiling was visualized and recorded using a high-speed digital video camera Phantom 7.0 with the frequency of 1000 frames per second. The experiments were carried out under the stationary conditions. The binary mixture of R114/R21 refrigerants circulating in a closed loop during the experiment was under the saturation conditions. Initial concentration of the volatile component R114 was 15%. The experiments were carried out under the pressure of 2 bars. The film Reynolds number was varied in the range of 300-1500 and it was defined as \( \text{Re}=4Q/(\pi d \cdot \nu) \), where \( Q \) is the volumetric flow rate of liquid, m\(^3\)/s; \( d \) is the tube diameter, m; \( \nu \) is kinematic viscosity of liquid, m\(^2\)/s. Heat flux density \( q \) during the experiments was varied from 0 to \( 13 \cdot 10^4 \) W/m\(^2\). The heat losses from the ends of the heated section, according to calculation, was not higher than 10%. 
3. Results and discussion

The video shots of the boiling process of refrigerant mixture film on the smooth surface and microstructured surface No. 1 are shown in Fig. 4. Visual observations showed that for the approximately equal liquid flow rates and heat flux densities \( q = 3.5 \text{ W/cm}^2 \), the washed dry spots can appear in the lower part of the heating zone on a smooth surface, while on the microstructured surface, there is stable nucleate boiling with high density of nucleation centers. The observed delay in boiling crisis development on the studied microstructured surfaces is confirmed below by experimental data on the critical heat flux.
Dependence of the heat transfer coefficient averaged over the length on the heat flux density obtained for the microstructured surface No. 1 using the 70-mm heater is shown in Fig. 5. It can be seen that the heat transfer coefficient increases slightly with increasing heat flux in the evaporation regime ($q < 1 \text{ W/cm}^2$). The influence of the liquid flow rate is not observed. At nucleate boiling, the heat transfer coefficient increases with the Reynolds number; the discrepancy of values is more pronounced for the high heat fluxes. The decrease in HTC for small Re numbers at high heat fluxes is associated with the appearance of washed dry spots in the lower part of the heated surface.

![Figure 4](image1.png)

**Figure 4.** Boiling on smooth surface, $Re = 318$, $q=3.5 \text{ W/cm}^2$ (a) and surface with microstructure No. 1, $Re = 370$, $q=3.5 \text{ W/cm}^2$ (b).

![Figure 5](image2.png)

**Figure 5.** Heat transfer coefficient vs. heat flux density for different Re numbers. Data for microstructure No. 1.

Data on the HTC obtained for microstructured surfaces No. 1, 2 and smooth surface are compared in Fig. 6. In experimental series 2 with microstructured surface No. 1, the heater of 70-mm length was
used (in all other cases, the length of the heater was 50 mm). The data presented allow us to conclude that the heat transfer coefficient at boiling on microstructured surfaces No. 1, 2 increases up to 3 times in comparison with a smooth surface. At that, the HTC for microstructured surface No. 1 exceeds the heat transfer coefficient for structure No. 2 with larger characteristic dimensions of microstructuring, approximately by 25% (in the region of developed boiling). At evaporation ($q < 1 \text{ W/cm}^2$), there is no appreciable heat transfer intensification, stably obtained from one experimental series to another, in comparison with a smooth surface.

**Figure 6.** Comparison of experimental data on heat transfer coefficient for different surfaces.

Experimental data on the critical heat flux value obtained for microstructure No. 1 and their comparison with the data obtained for a smooth surface, experimental data of [9] and known calculated dependences are presented in Fig. 7. According to this figure, the data on CHF for microstructure No. 1 (points 1) are more than twice as high as the values for a smooth surface (points 2), described by dependence [13] (line 3). According to the basic model of dependence [13], crisis development requires evaporation of liquid in the residual layer between the wave crests and liquid that periodically nourishes the residual layer, when the large three-dimensional waves propagate along the film.

It can be also seen from Fig. 7 that the CHF values obtained in the region of high flow rates are significantly higher than the data of [9] (points 4, 5) for the Gewa-B5 surface. Line 6 in Fig. 7 corresponds to the semi-empirical model [14], describing the data obtained on a vertical cylinder for water and refrigerants R11 and R113. The low CHF values obtained by the authors of [14] can be related to the different geometry of the heated tube, more extended and smaller in diameter than in the present study (tube length of 180 mm and outer diameter of 8.0 mm). Model [15] (line 7) was tested for the turbulent Reynolds numbers, the crisis development in this model is associated with complete evaporation of a thin sublayer of liquid, while the bulk of liquid film is separated from the heater by a vapor layer. Apparently, this model, poorly describes the data corresponding to the laminar-wave and transition to turbulent regimes of the film flow. Line 8 corresponds to calculation of complete liquid evaporation at the test section outlet.
Figure 7. Dependence of critical heat flux density on film Re number.  
1 – microstructure No. 1 (R114/R21); 2 – smooth surface (R114/R21); 3 – dependence [13];  
4, 5 – data of [9] for Gewa-B5 (Freons R236fa and R134a). 6 – dependence [14];  
7 – dependence [15]; 8 – heat flux corresponding to complete film evaporation.

Experimental data obtained in the present study on heat transfer with the use of surfaces created by the method of deforming cutting [12] are planned to be supplemented with new data on heat transfer using a micro-pinned surface, well proven previously under the conditions of a pool boiling [6]. The parameters chosen for the ongoing experimental series with this microstructured surface are close to the parameters of microstructure No. 1. The pitch along the axis is 100 μm, the height of the pins is 150 μm (the thickness of the pin is approximately 0.5 of the pitch along the axis), and the circumferential pitch is 300 μm.

The final systematized data on heat transfer study with a change in geometry of microstructure of the heat-generating surface and variation of characteristic geometric parameters will be useful for choosing the optimal types of microstructures at adoption the structured tubes and other surfaces intended for heat transfer intensification at boiling the low-viscous high-wetting liquid films.

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