Interfacial Phenomena and Heat Transfer, 5(3):215–222 (2017)

HEAT TRANSFER AND CRISIS PHENOMENA AT BOILING OF REFRIGERANT FILMS FALLING DOWN THE SURFACES OBTAINED BY DEFORMATIONAL CUTTING

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Original Manuscript Submitted: 1/24/2018; Final Draft Received: 4/17/2018

Determining the effective structures of heat-releasing surfaces that contribute to heat transfer enhancement and an increase in the critical heat flux values under various heat transfer conditions is of considerable scientific and practical interest. This paper presents the experimental results on heat transfer in the laminar-wave flow of a film with a mixture of R114/R21 refrigerants on three vertical cylinders with differently microstructured outer surfaces. It is shown that the heat transfer coefficients in the regime of boiling on surfaces with a microstructure of a smaller height and rib pitch exceed the values obtained for surfaces with larger characteristics. Surfaces with partially closed micropores (by knurling) in the regime of boiling have an advantage in heat transfer over microstructured surfaces without closed pores. All microstructured surfaces studied in this work demonstrated an increase in the values of the critical heat flux in comparison with a smooth surface.

KEY WORDS: *microstructured surface, falling films, heat transfer enhancement, nucleate boiling, boiling crisis, refrigerants*

1. INTRODUCTION

Falling liquid films are a widely known means of enhancing heat and mass transfer processes. Many theoretical and experimental papers have dealt with the study of hydrodynamics and heat transfer in falling films. Without examining them in detail, we should mention some classic works (Vorontsov and Tananayko, 1972; Kutateladze and Nakoryakov, 1984; Gimbutis, 1988; Alekseenko et al., 1992) and several new monographs (Shilyaev and Tolstykh, 2014; Pavlenko et al., 2016) devoted to this subject.

The most efficient process for intensive removal of heat from a heat-releasing wall is nucleate boiling of liquid. In film flows, this heat transfer regime has a lot common with pool boiling, but there are a number of different features. At small heat flux values, heat transfer in falling films is mainly determined by the irrigation density (evaporation and undeveloped nucleate boiling). At developed nucleate boiling, heat transfer depends on the evaporation rate (the number of active nucleation sites), which is directly related to the geometric characteristics of the surface. This is also true for pool boiling; however, the process of boiling in falling liquid films has a number of features associated with entrainment of vapor bubbles after their separation from the wall, additional heat removal due to drop entrainment at bubble collapse, etc. (Gogonin, 2010).

2169–2785/17/$35.00

In recent years, many studies on heat transfer during phase transitions have been devoted to intensifying heat transfer through structuring the heat-releasing surface. There are many publications on the study of heat transfer in the film flow of liquids on surfaces with different roughness (Drach et al., 1996), grooved surfaces (Fujita, 1998; Zaitsev et al., 2007; Helbig et al., 2009), and structured commercial surfaces of complex geometry: High Flux, Gewa-T, Thermoexcel-E, and Thermoexcel-EC (Fagerholm et al., 1987); and Turbo-B5 and Gewa-B5 (Christians and Thome, 2012). In these papers, it was noted that surface structuring leads to intensification of heat transfer at boiling (up to 12 times) and transition to nucleate boiling with a smaller temperature drop. However, the number of such works is limited and does not shed enough light on questions regarding the effect of the size and character of microstructuring on heat transfer.

To date, this approach continues to be successfully developed in connection with the growing need for cooling microelectronics and other systems with high heat flux densities (Kabov et al., 2014). There are new publications on heat transfer intensification at boiling using coatings made by the plasma deposition method that offer the possibility of creating a hierarchical porous structure (Surtaev et al., 2017, 2018). A block of research has been published on intensifying heat transfer at liquid boiling under conditions of free convection on microstructured surfaces made by the deformational cutting method (Shchelchkov et al., 2016). The possibility of enhancing heat transfer using nanomodified surfaces is being studied (Surtaev et al., 2016). However, most of these new studies have been carried out for pool boiling.

This work continues a series of research on enhancing heat transfer in falling films of binary mixtures of refrigerants at evaporation and boiling (Pecherkin et al., 2011, 2015; Pavlenko et al., 2012, 2016). In particular, some studies have used microstructured surfaces (Volodin et al., 2017) made by the method of deformational cutting (MDC). This method allows creating highly efficient heat-exchanging surfaces with the possibility of increasing the surface area up to 12 times (Zoubkov and Ovtchinnikov, 1998; Thors and Zoubkov, 2013).

The results of investigations on heat transfer in the film flow of liquids on surfaces with different ordered microrelief arrangements can be useful in selecting optimal microstructures when commissioning structured pipes and other surfaces intended to intensify heat transfer at boiling in falling liquid films. The array of obtained experimental data concerning refrigerant boiling on microstructured surfaces will provide a basis for numerical simulation of such processes and testing the analytical models of boiling.

2. SETUP AND EXPERIMENTAL METHODS

A schematic diagram of the experimental setup for studying heat transfer in the film flow of refrigerants is given in Fig. 1, which shows the film of a mixture of R114/R21 refrigerants falling down vertically oriented replaceable copper cylinders with an outer diameter of 50 mm. The thickness of the cylinder wall was 1.5 mm. The length of the heat-releasing zone along the flow was 50 or 70 mm. The experiments were carried out on a smooth test section with surface roughness $R_a = 2.5$ μm and test sections with different microstructures.

To measure the local surface temperature, four copper-constant thermocouples with a diameter of 0.18 mm were fixed flush with the surface along the height of the heat-releasing zone. The distance between the thermocouples was 14 mm, and the distance between the beginning of the heat-releasing zone and the upper thermocouple was 4 mm. Cold junctions of thermocouples immersed into the liquid layer at the column bottom were kept at the same temperature, measured by the HEL-700 series thermistor (Honeywell International Inc., Morristown, NJ, USA) (Pecherkin et al., 2015).

The absolute pressure in the column was measured by the Metran-100 manometer (CJSC Industrial Group "Metran", Chelyabinsk, Russia), and the liquid flow rate was measured by the CORI-FLOW flowmeter (Bronkhorst Inc., Ruurlo, Netherlands), which measures the mass flow rate of liquid in the range of 0–100 kg/h. The molar concentration of the components of the binary refrigerant mixture was measured by gas chromatography. The mixture composition was measured before and after the test section. The effect of a change in mixture composition at evaporation of the boiling component on heat transfer is discussed in Pecherkin et al. (2015); in the current work, this issue is not considered.

The dynamic processes in liquid film were visualized and registered by a high-speed digital video camera (Phantom 7.0, Vision Research, Wayne, NJ, USA) at a frequency of 1000 frames per second. During the experiment, the

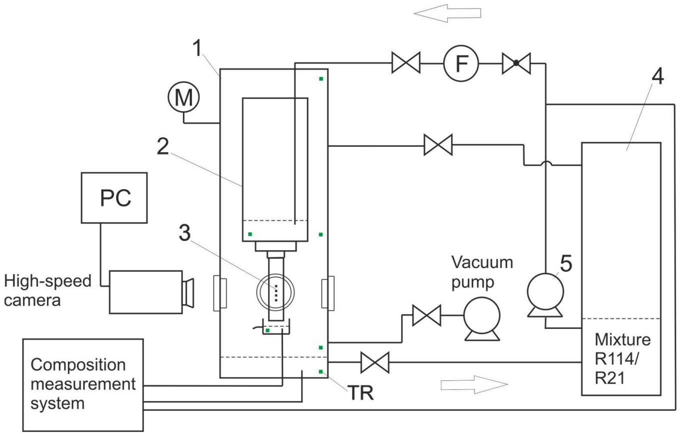


FIG. 1: Schematic diagram of the experimental setup for studying heat transfer in the film flow of refrigerants (1, column body; 2, constant header tank; 3, test section; 4, refrigerant mixture tank; 5, pump; M, manometer; F, flow meter; TR, thermistors)

binary R114/R21 mixture circulating in a closed circuit was under the conditions of saturation. The initial concentration of the low-boiling component R114 was 15%. The experiments were carried out at a pressure of 2 bar. The film Reynolds number was varied in the range of 300–1500 and was defined as $\mathrm{Re} = 4Q/(\pi \cdot d \cdot \nu)$, where Q is the volumetric flow rate of liquid (m^3/s); d is the tube diameter (m); and ν is kinematic viscosity of liquid (m^2/s). The value of heat flux density q during the experiments was varied from zero up to the critical values. Heat losses from the ends of the heated area were estimated to be lower than 10%.

The microstructures of studied surfaces Nos. 1 and 2 present microfinning obtained by the MDC, followed by knurling with a straight knurl roller along the fin crests. The roller movement is directed along the fins, thus corrugations of the knurl roller are normal to the fins. The tooth pitch of the knurl roller was 318 μm. The angle at the top of roller tooth was 90°. At knurling, the fin tops were deformed, closing the interfin gap. As a result, a porous surface structure with semi-closed subsurface cavities, serving as ready evaporation sites, was formed.

Figure 2 shows surface No. 1 with the following structuring parameters: fin pitch of 100 μm, fin height of 220 μm, and knurling pitch of 318 μm. The coefficient of the increase in the surface area was calculated as the ratio of

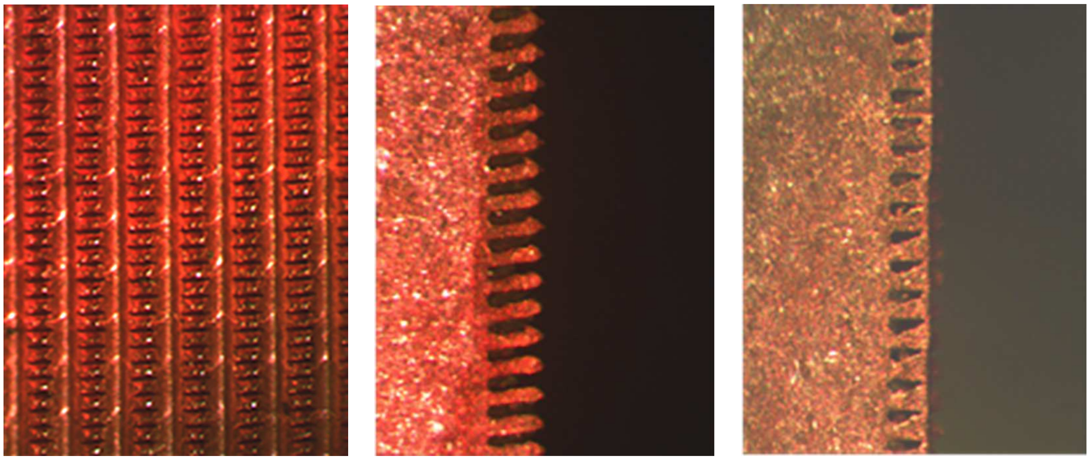

(a) (b) (c)

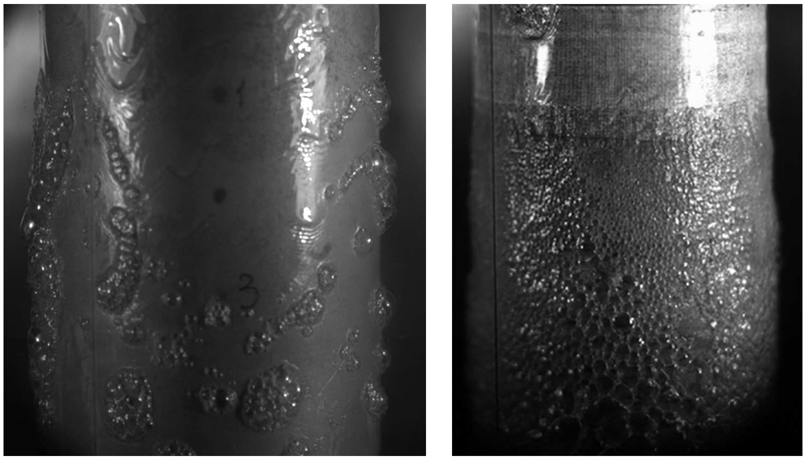
FIG. 2: Surface No. 1: (a) frontal view (longitudinal lines, knurling zones); (b) cross section along the fins; (c) cross section along the knurling zone (zone with closed pores)

the fin perimeter along the fin pitch length to the fin pitch, which was $k = 5.4$. The Geometry of surface No. 2 was similar, but it differed by the value of the characteristic parameters: the fin pitch was 200 μm, the fin height was 440 μm, the knurling pitch was 318 μm, and $k = 5.4$. Thus, the effect of the scale factor of the microstructure at liquid boiling in the falling films was estimated. Surface No. 3 (Fig. 3), unlike the previous surfaces, did not have semi-closed subsurface pores. The vertical micropins of this surface were made by preliminary knurling with a roller before deformational cutting, and this led to fin rupture with the formation of micropins. The fin pitch was 150 μm, the pin height was 250 μm, and the knurling pitch was 318 μm. The coefficient of the increase in the surface area for surface No. 3 was $k = 3.6$.

3. RESULTS AND DISCUSSION

The patterns of nucleate boiling of a film of the refrigerant mixture on microstructured surface No. 1 and a smooth surface are compared in Fig. 4. According to visual observations, while there is stable nucleate boiling with high density of nucleation centers on microstructured surface No. 1 at approximately equal Reynolds numbers and heat

FIG. 3: Surface No. 3 with micropins (frontal view)



(a) (b)

FIG. 4: Boiling on a smooth surface (Re $= 318$, $q = 3.5 \times 10^4$ W/m^2) (a) and microstructured surface No. 1 (Re $= 370$, $q = 3.5 \times 10^4$ W/m^2) (b)

fluxes, nucleate boiling on the smooth surface is less pronounced, and a washed-out dry spot is observed in the lower part of the heated surface. The observed delay in the development of a boiling crisis on the studied microstructured surfaces will be further illustrated by the experimental data on the critical heat flux (CHF).

Data on the heat transfer coefficient versus the heat flux density obtained on microstructured surface No. 1 in the range of film Reynolds numbers 300–1500 are shown in Fig. 5. The heat transfer coefficient increases slightly with increasing q at evaporation ($q < 1 \times 10^4$ W/m^2). The flow rate effect is not observed. In the regime of nucleate boiling, the heat transfer coefficient increases with an increase in the Re number, and divergence of the heat transfer coefficients becomes noticeable at high heat fluxes: under near-crisis conditions, the appearance of washed-out dry spots on the surface reduces the heat transfer coefficient (primarily for low liquid flow rates).

Figure 6 illustrates the effect of different types of surface microstructuring on heat transfer. According to Fig. 6, the heat transfer coefficient at boiling on microstructured surfaces Nos. 1 and 2 is three times higher compared to a smooth surface. The heat transfer coefficient for microstructured surface No. 1 exceeds that for structure No. 2 by about 25% (in the region of developed boiling). For the surface with micropins (surface No. 3), in comparison with the smooth surface, augmentation of the heat transfer coefficient in the boiling regime is not observed, and this can be related to the absence of closed micropores, which contribute to an increase in the density of nucleation sites.

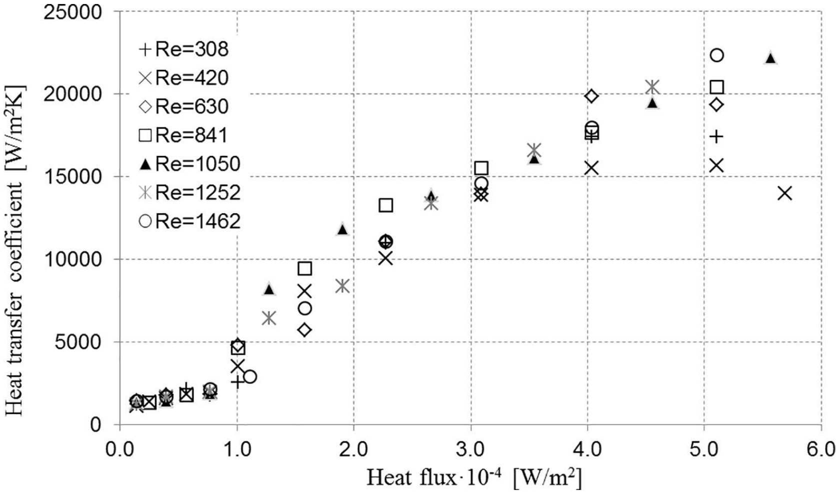


FIG. 5: Heat transfer coefficient versus heat flux density for different Reynolds numbers

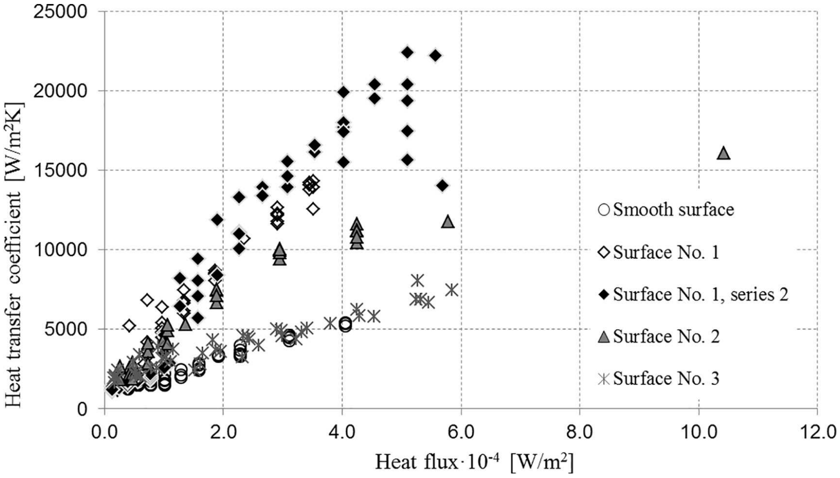


FIG. 6: Heat transfer coefficient versus heat flux density for surfaces Nos. 1–3

However, the more developed area of this surface leads to an increase in the heat transfer coefficient at evaporation of the liquid film (almost twice as much compared to the smooth surface).

It should be noted that according to the data from Fagerholm et al. (1987), who dealt with the study of heat transfer in films falling over structured tubes, commercial tubes with developed surfaces (High Flux, Gewa-T, Thermoexcel-E, and Thermoexcel-EC) can intensify the heat transfer coefficient more than was done in the current study. At nucleate boiling of the film of refrigerant R114 at the turbulent flow regime (Re = 3000 to 5000), Fagerholm et al. (1987) reported an increase in the heat transfer coefficient by a factor of 5–12 in comparison with a smooth tube. Thus, the potential of microstructured surfaces is not confined by the threefold intensification of the heat transfer coefficient obtained in this study.

Together with the heat transfer coefficient, another essential value in thermal engineering is the CHF limiting the value of maximal heat transfer. Figure 7 presents data on the CHF versus the Reynolds number for microstructured surfaces Nos. 1 and 3 (in which the length of the heated zone is 70 mm), a comparison with the calculated dependencies and previously obtained experimental data for structured surfaces with a larger scale of structure (Pecherkin et al., 2015), and experimental data from Christians and Thome (2012). According to Fig. 7, the values of the CHF for microstructured surfaces Nos. 1 and 3 are more than twice as high as the CHF values for the smooth surface; the latter is well described by the correlation in Pavlenko and Lel (1997). The obtained CHF values are significantly higher than the CHFs obtained for previously studied structured surfaces with larger characteristic structure parameters (Pecherkin et al., 2015), and CHFs for Gewa-B5 (Christians and Thome, 2012).

The experimental data obtained on the heat transfer coefficient and CHF confirm the prospects of further studies using the MDC for making surface microstructures that contribute to heat transfer intensification of falling films for various technical applications.

4. CONCLUSIONS

In this work, it is shown experimentally that an increase in the heat transfer surface area as well as the presence of subsurface semi-closed pores have significant importance in the intensification of boiling processes, including those in falling films. From the results obtained in this study, the following conclusions can be drawn:

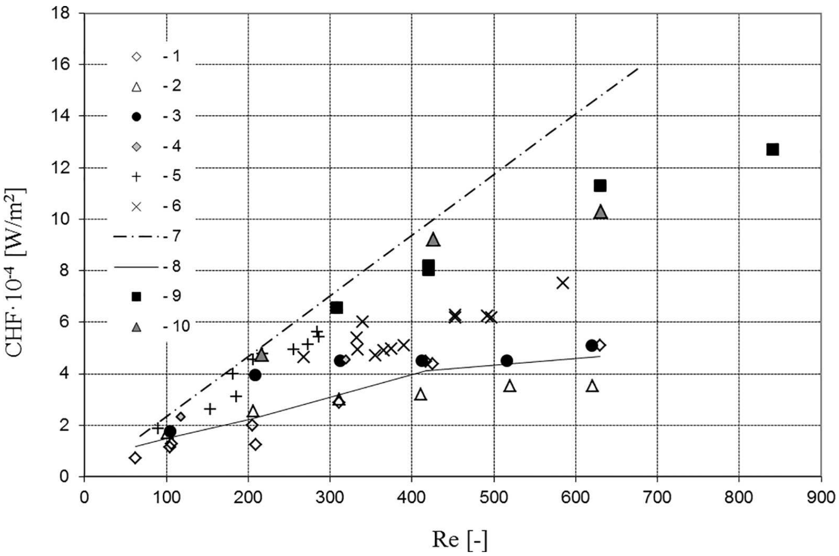


FIG. 7: CHF vs. Re number. Data for R114/R21 mixtures (Pecherkin et al., 2015): 1, smooth surface; 2, transverse finning; 3, rhomb-shaped texture; 4, mesh coating; 5 and 6, data for refrigerants R236fa and R134a (Gewa-B5) from Christians and Thome (2012). Correlations: 7, heat flux corresponding to complete evaporation at the outlet (70 mm section); 8, data from Pavlenko and Lel (1997); 9, surface No. 1; 10, surface No. 3

- The heat transfer coefficient at boiling for the studied surfaces Nos. 1 and 2 was about three times higher than that for the reference smooth surface (surface No. 1 with a fin height of 220 µm and fin pitch of 100 µm was more efficient).
- On surface No. 3 with micropins and without closed pores, augmentation was observed in the evaporation regime, but there was no significant increase in the heat transfer coefficient at boiling.
- The values of the CHF for microstructured surfaces Nos. 1 and 3 more than twice exceeded the values of the heat transfer coefficient for the smooth surface and significantly exceeded these values for previously studied structured surfaces.

ACKNOWLEDGMENTS

The study was performed at the Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences, under grants from the Russian Foundation for Basic Research (Project No. 16-08-00489) and the Russian Science Foundation (Project No. 14-49-00010, section on the study of heat transfer enhancement using micro-pin structures), and with support from the Russian Ministry of Education and Science.

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