Heat transfer and dynamics of transient processes at liquid film flowing on smooth and modified surfaces

A N Pavlenko¹, D V Kuznetsov¹, O A Volodin¹ and N N Zubkov²

¹ Kutateladze Institute of Thermophysics, Acad. Lavrentiev ave., 1, Novosibirsk, Russia
² Bauman Moscow State Technical University, Baumanskaya 2-ya, 5, Moscow, Russia

E-mail: kuznetsov_9308@mail.ru

Abstract. The paper presents the results of an experimental study on propagation dynamics and structure of the wetting front under adiabatic conditions and on a preheated surfaces with a needle-like microstructure, as well as heat transfer and critical heat fluxes at a film flow of liquid nitrogen. The surface was structured by the method of deforming cutting (MDC). A comparison with the data obtained on a smooth plate was performed. Data of high-speed video of the processes are presented.

1. Introduction

As it is known, the film flows, being an effective method of heat and mass transfer, are widely used in various technological processes such as absorption, rectification, evaporation, cooling, etc. To date, there are quite a large number of works devoted to the theoretical and experimental study of wave flow hydrodynamics, heat transfer of evaporating and boiling liquid films under the conditions of stationary heat release. Recently, the increased interest of researchers is focused on the ways to intensify heat transfer and increase critical heat fluxes. The most effective methods for these tasks are the methods for creating modified heat transfer surfaces: various micro and nano-coatings, porous and structured surfaces, etc. [1].

The authors of this paper have carried out a series of research to study the effect of various coatings on rewetting dynamics of strongly overheated plates, as well as heat transfer under stationary heat release during film cooling by liquid nitrogen. Thus, it was shown in [2] that the presence of a low-heat-conductive coating with a thickness of 250 μm has a significant effect on the character of temperature curves and reduces the total time of plate cooling from the maximum temperature to the saturation temperature of liquid nitrogen by more than four times as compared to an uncoated heater. Based on a comparison of experimental data, it has been found that the presence of a low-heat-conductive coating leads to the formation of a cellular front structure with a regular boiling jet, typical of rewetting of superheated thin-walled plates. The results of an experimental study of the effect of a structured capillary-porous coating obtained by the method of directional plasma spraying on heat transfer at a film flow of liquid nitrogen are presented in [3, 4]. It was shown that the presence of such coating also leads to a decrease in time of complete cooling of the overheated working section by more than three times; however, it slightly affects heat transfer under the conditions of stationary heat release in the studied range of irrigation. Based on the analysis of synchronized measurements of the plate temperature and high-speed video recording of transient processes, the authors of [3, 4] showed
that a higher cooling rate in the presence of coatings is associated with the development of intense boiling in the rewetting front at a significantly higher plate temperature.

Another method for making the modified surfaces that has proven itself in relation to the tasks of heat transfer enhancement and increasing critical heat fluxes under the conditions of film flow of liquids is the method of deforming cutting (MDC). For example, experimental results on heat transfer in a film flow of a binary mixture of R114/R21 freons on vertical cylinders with microstructures, obtained using the above method, are presented in [5, 6]. The authors have shown that the heat transfer coefficients at nucleate boiling on such surfaces depend on the characteristic parameters of the structure and can exceed the corresponding values for a smooth heater up to three times. In addition, a significant increase (up to 2 times) in the critical heat fluxes under the conditions of stationary heat release was revealed for the modified samples.

Based on the analysis of these works, it is of direct interest to study the effect of structured surfaces, obtained by the MDC, on wetting transients, as well as the effect of characteristic parameters of these coatings on heat transfer in flowing liquid films. Thus, the goal of this work is an experimental study of propagation dynamics and structure of the wetting front under the adiabatic conditions and a preheated surfaces with a needle MDC-microstructure, as well as heat transfer and critical heat fluxes at film flow of liquid nitrogen.

2. Experimental setup and techniques

To perform the experiments with film flow of liquid nitrogen on the saturation line under the atmospheric pressure, an experimental setup was used: a cryogenic circuit, whose detailed description is presented in [3, 7]. The film Reynolds number \( \text{Re} = 4I/v \) in experiments varied in the range from 200 to 1500 (here: \( I \) is irrigation density, \( v \) is kinematic viscosity of liquid). The processes were recorded through the optical windows of cryostat using a high-speed digital video camera Phantom v.7.0.

A smooth copper plate and a plate with micro-needle fins, obtained using MDC, were used as the working sections in experiments. This method of mechanical processing is based on cutting the surface layer of the workpiece material and subsequent deformation of the cut layer with the formation of macro- and micro-relief in the form of edges, spikes, and cells. The description of this technology of micro-surface treatment is presented in [8–10]. The thickness of the heated copper plate was 2.5 mm, the height and width were 50 and 75 mm, respectively. The characteristic parameters of the investigated coating are as follows: the needle microstructure height is 500 \( \mu \)m; the step of the micro-pins alternation is 70 \( \mu \)m; the characteristic transverse size of micro-pins is 70 \( \mu \)m.

The working sections were heated by passing an electric current through a constantan foil pressed to the backside of the copper plate without structuring, insulated by a thin dielectric gasket using a controlled power source. The plate temperature was measured by four copper-constantan thermocouples. The control of current sources, measurement of signals of thermocouples and liquid level gauges that determine the flow rate were carried out using two ADC/DAC boards and the LGraph program of experiment control. For experiments under the conditions of stationary heat release, the heat flux density was determined by the values of current passed through a constantan foil and potential difference between the terminals located at its ends.

To perform the experiments on the study of rewetting dynamics after the supply of liquid nitrogen with a given flow rate, the flow lock was turned, and the flow of nitrogen along the working section was stopped. While, the flow rate of liquid nitrogen, output by the lock, was maintained. Then, the plate was heated by a constantan foil to a predetermined maximum (initial) temperature \( T_{\text{max}} \). For each \( \text{Re} \) number, the experiments were carried out at different maximum temperatures (105, 150, 215, and 300 K). At the next stage, the heater was turned off and simultaneously the lock went to its original position. After that, the uniform film flow of liquid nitrogen was renewed and the process of working section rewetting was carried out. The experiments under adiabatic conditions (without plate heating) also were carried out synchronizing video recording and restoration patterns of the liquid flow.
3. Experimental results and discussion
The frames of high-speed video recording of the wetting of the microstructured working section with a liquid nitrogen film under adiabatic conditions at $\text{Re} = 1250$ are presented in figure 1. Dashed lines indicate the boundaries of the wetted surface. As it can be seen, the wetting front is not flat, but it is formed by the separate liquid jets and inter-jet zones. Such a dynamics of wetting front formation under the adiabatic conditions is associated with the development of instability when the large waves in a liquid nitrogen film surge towards the surface of the studied plate. According to the analysis of experimental data, the number of individual rivulets (jets) increases with increasing degree of irrigation. A similar picture of the process development was observed for a smooth working section. At the same time, the structure, formed on the heater surface, leads to additional distribution of liquid due to the capillary forces in the transverse direction relative to the nitrogen flow and, as a result, to transverse expansion of the individual rivulets. This effect is most pronounced for high values of the film Reynolds number.

![Figure 1. The rewetting front under the adiabatic conditions. Re = 1250.](image)

Based on the processing of experimental data of high-speed video recording, the propagation velocities of individual rivulets, inter-rivulet zones, as well as the propagation velocity of large waves in a liquid nitrogen film after full wetting of the working section at various Reynolds numbers were obtained. As it follows from the analysis (figure 2), the average propagation velocities of liquid rivulets and inter-rivulet zones over the unwetted surface with a fixed $\text{Re}$ number almost coincide and they are significantly below the values of velocity of large wave propagation, which is caused by the influence of a dynamic wetting angle between the oncoming film of liquid nitrogen and plate surface. It is also worth noting that for a modified working section the velocity of jets propagation is less than the similar values for a smooth heater at high $\text{Re}$ numbers. The above-described expansion of the transverse size of rivulets on the surface of a structured heater leads to a decrease in local liquid flow and, as a consequence, to a decrease in the velocity of the wetting front in the zone of rivulet propagation.

The time dependences of the smooth plate temperature and temperature of a plate with microstructure in the process of rewetting by a flowing nitrogen film at different Reynolds numbers and fixed maximal initial temperature $T_{\text{max}}$ are compared in figure 3. As one can see, there are two main characteristic stages of cooling the highly overheated plate: the first stage with slow cooling of the working section and the second stage with a fast rate of cooling, the beginning of which is accompanied by a bend in the temperature curve, reflecting a change in the heat transfer regime during rewetting front propagation. The characteristic temperatures at the bend points correspond to the plate threshold temperatures when the transition from low-intensity heat transfer on the dried surface to its rewetting and development of heat transfer in a boiling regime in the process of front propagation with liquid film fall begins. While turning to the second fast stage, the heater temperature, when the front begins to spread rapidly across the plate, depends weakly on both the degree of irrigation throughout the entire range of Reynolds numbers and initial temperature. In addition, there is a decrease in time of complete heater cooling with increasing degree of film irrigation for all studied plate overheating. This structure on the surface of the working section has a little effect (as compared with the results obtained in [3, 4] when using capillary-porous coatings) on the time of complete plate cooling. However, for a
fixed degree of irrigation, the curve zone corresponding to the second stage of cooling for a smooth heater has a steeper slope than for a modified sample, indicating a decrease in the velocity of rewetting front propagation in the presence of a microstructure. This effect can be explained by partial steaming of the lower layers of the micro-needles structure (micro-needles zones adjacent to the plate) in the process of rewetting and by an increase in thermal resistance.

Figure 2. The average propagation velocities of characteristic zones of wetting front. Structured heater: 1 – rivulets, 2 – inter-rivulet zones, 3 – waves on a wetted surface. Smooth heater: 4 – rivulets, 5 – inter-rivulet zones, 6 – waves on the wetted surface.

According to the analysis of high-speed video data (figure 4), the rewetting front for both a smooth and structured heater is quasi-flat and differs little in the form and structure over the entire range of the studied Reynolds numbers. The velocity of the rewetting front propagation, average over the plate height, at the second stage of the process increases with an increase in the degree of irrigation and does not depend on the initial maximal temperature (see table). It can be seen that for a smooth heater the velocity is almost twice as high as the similar values for the modified working section at a fixed Re number.

Figure 3. Dependence of plate temperature on time for different Reynolds numbers at initial temperature: (a) – 300, (b) – $T_{\text{max}} = 105$ K. Structured heater: 1 – 200, 2 – 500, 3 – 750, 4 – Re = 1250; smooth heater: 5 – 200, 6 – 500, 7 – 750, 8 – Re = 1100.
Figure 4. The process of rewetting of the structured plate at Re = 1250 and initial temperature $T_{\text{max}} = 300 \text{K}$.

Table. Average velocities of the rewetting front (mm/s).

| Re   | Structured heater | Smooth heater |
|------|------------------|---------------|
| 200  | 5                | 8             |
| 500  | 8                | 14            |
| 750  | 9                | 16            |
| 1250 | 11 (1100)        | 25            |
| 1500 | -                | 35            |

Figure 5. Heat transfer curves at stationary heat release. Structured heater: 1 – 200, 2 – 500, 3 – 750, 4 – Re = 1250; smooth heater: 5 – 200, 6 – 500, 7 – 750, 8 – Re = 1100.

The results of an experimental study of heat transfer intensity and critical heat fluxes for a smooth plate heater and heater with micro-needle finning are presented in figure 5 depending on the degree of irrigation with a liquid nitrogen film under the conditions of stationary heat release. This structure on the copper plate surface does not lead to a significant change in the heat transfer coefficients as compared to a smooth plate in the entire range of irrigation levels. An exception is Re = 200 when the heat transfer coefficients for the modified sample are significantly reduced in comparison with a smooth plate in the pre-crisis boiling regimes. Also, a decrease in the critical heat flux is observed at Re = 750 and 1250 with respect to a smooth heater.

4. Conclusions
The experimental results on propagation dynamics and structure of the wetting front under adiabatic conditions and on a preheated surface with a needle MDC-microstructure, as well as heat transfer and critical heat fluxes in the film flow of liquid nitrogen are presented. It is shown that the presence of a MDC structure on the heater surface leads to a change in the character of the wetting front propagation
of an unheated plate for high Reynolds numbers, reducing the velocity of liquid jets due to a decrease in the local flow of the film. In the rewetting regimes, the average propagation velocity of the front along the heater height is halved for a modified sample as compared to a smooth heater. However, the time for complete cooling of a coated plate does not change significantly over the entire range of studied Re numbers. Experiments under the conditions of stationary heat release showed the absence of a significant effect of micro-needle finning on heat transfer in a film flow of liquid under the boiling regime. At the same time, a certain decrease in the critical heat flux at boiling on a heater with micro-needle finning is shown.

Acknowledgements
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) and Russian Foundation for Basic Research (RFBR) (project no. 18-08-00402-a).

References
[1] Surtaev A S, Serdyukov V S and Pavlenko A N 2016 Nanotech. In Russia 11 (11-12) 696
[2] Pavlenko A N, Tsoi A N, Surtaev A S, Kuznetsov D V and Serdyukov V S 2016 High Temp. 54 (3) 370
[3] Pavlenko A N, Tsoi A N, Surtaev A S, Kuznetsov D V, Kalita V I, Komlev D I, Ivannikov A Yu, Radyak A A 2018 High Temp. 56 (3) 404
[4] Pavlenko A N and Kuznetsov D V 2018 J. Phys.: Conf. Ser. 1105 (1) 012053
[5] Volodin O A, Pecherkin N I, Pavlenko A N and Zubkov N N 2017 Interf. Phenomena and Heat Transf. 5 215
[6] Volodin O A, Pecherkin N I, Pavlenko A N, Zubkov N I and Bityutskaya Yu L 2017 J. Phys.: Conf. Ser. 891 012035
[7] Pavlenko A N, Surtaev A S, Tsoi A N, Starodubtseva I P and Serdyukov V S 2014 High Temp. 56 (6) 861
[8] Zubkov N N, Ovchinnikov A I 1996 European Patent EP 0727269
[9] Thors P and Zoubkov N 2007 U.S. Patent 7311137
[10] Thors P and Zoubkov N 2013 U.S. Patent 8573022