Experimental study of the effect of structured capillary-porous coating on rewetting dynamics and heat transfer at film cooling by liquid nitrogen

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Abstract. The results of an experimental study of the dynamics of rewetting and heat transfer on a copper plate with a structured capillary-porous coating, obtained by directional plasma spraying at film flow of liquid nitrogen are presented. The experiments were carried out at different orientations of the coating relative to the flow of the liquid. A comparison with the experimental data obtained on a smooth heater is made. It is shown that the presence of a coating has a significant effect on the character of the temperature curves and reduces the total cooling time of the plate during rewetting by more than three times as compared to the uncoated plate, but it does not significantly affect the heat transfer under conditions of stationary heat release. Data of high-speed video recording of processes are presented.

1. Introduction

As known, film flows of liquid, 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 a sufficiently large number of papers devoted to the theoretical and experimental study of the hydrodynamics of the wave flow, the heat transfer of evaporating and boiling liquid films under conditions of stationary heat release. Recently, the increased interest of researchers is directed to ways of intensifying heat transfer and increasing critical heat fluxes. Among the most effective methods with respect to these problems, there are the methods devoted to creating modified heat transfer surfaces: various micro and nano coatings, porous and structured surfaces, etc. [1]. For example, the results of an experimental study of heat transfer in the film flow of a binary mixture of Freon R114 / R21 on a vertical cylinder with a microstructure created by methods of deforming cutting are given in [2]. It was shown by the authors that the heat transfer coefficient in boiling regime on a structured surface is three times higher than the corresponding values for a smooth heater. Also these authors carried out a study on the effect of mesh coatings on heat transfer in a flowing liquid film [3]. It is shown that the coefficient of heat transfer on a surface with a coarse grid is twice as large as the corresponding values for a smooth surface in the evaporation regime of a film and practically does not change in the boiling regime.

In addition to studying the boiling and evaporation regimes of liquid films, an important task is to study rewetting regimes that have a significant effect on the dynamics of cooling of superheated surfaces in metallurgy and the food industry, as well as on non-stationary heat transfer in power equipment. An experimental study and numerical modeling of the features of the dynamics of...
rewetting a superheated smooth plate with a liquid film, such as the shape and velocity of the front, the time of total cooling are presented in [4,5]. The authors of [6] showed that the presence of a layer of low-conductivity coating on the surface of the heater reduces the time of total cooling of the plate by a liquid nitrogen film approximately four-fold as compared to the case without coating.

As can be seen from the above studies, various methods of modifying heat exchange surfaces greatly affect the heat transfer processes at film flow of liquids. In [7] a method of directed plasma spraying was proposed to produce modified surfaces that simultaneously combine high-porosity coating and surface structuring in the form of quasi-ordered ridges and channels. The aim of this work is an experimental study of the dynamics of rewetting and heat transfer on a vertical copper plate with a structured capillary-porous coating obtained by directional plasma spraying at film cooling by liquid nitrogen.

2. Experimental methods
To carry out the experiments on rewetting and heat transfer at liquid film cooling, the cryogenic circuit was used, the detailed description of the elements of which is presented in [4]. Figure 1 shows the scheme of the working area. The liquid nitrogen on the saturation line at atmospheric pressure was used in experiments. Nitrogen from the constant level tank flows through the slit distributor along a vertical plate of duralumin with a width of 75 and height of 160 mm, then it enters the working zone – the heated vertical copper plate – and then flows into the measuring vessel. The flow rate for the liquid film is determined by the volumetric method using a measuring vessel located under the experimental section. The film Reynolds number Re = 4Γ / ν in the experiments varied from 250 to 1500 (here, Γ is the volumetric liquid flow rate per unit length, and ν is the kinematic viscosity of the liquid) by regulating the amount of liquid in the constant level tank. Video recording of the proceeding processes was carried out through optical windows using a digital video camera Phantom v.7.0.

The smooth copper plate and the plate with a structured capillary-porous coating were used in the experiments as the working areas. The thickness of the heated copper plate is 2.5 mm, the height and width are 50 and 75 mm, respectively. The coating on the initial surface was deposited by the method of directional plasma spraying [7]. As can be seen from figure 2, in addition to the porous structure, the coating is, in fact, uniformly distributed and oriented over the heater surface, predominantly in one direction, ridges and channels. However, large ridges in the transverse direction have a flat surface on one side and a steeper one with a negative inclination angle on the other side. The experiments were carried out both with a direct orientation of the coating relative to the flow of liquid (the liquid flows on the flat part of the ridges) and with the reverse orientation. For spraying, a bronze powder

![Figure 1. Working section layout: 1 – constant liquid level tank; 2 – slit dispenser; 3 – duralumin plate; 4, 5 – control module of the flow cutter; 6 – cooper plate; 7 – coating; 8 – dielectric gasket made of oxidized duralumin; 9 – constantan foil; 10 – screw clamping device; 11 – textolite case; 12 – clamping plate; 13 – thermocouples; 14 – clamping screws; 15 – silicon rubber; 16, 21 – liquid nitrogen; 17, 20 – liquid level gauges; 18 – measuring vessel; 19 – exemplary thermometer.](image-url)
containing 9% aluminum and 2% manganese was used. The coating with an average thickness of 0.57 mm and porosity of 53% was used.

Heating of the working areas was made by a foil of constantan (25 μm) pressed to the underside of the copper plate without coating through which a direct current with controlled parameters was passed using a controlled power source. A dielectric gasket made of microarc oxidized duralumin with a thickness of 0.5 mm was installed between the copper plate and the foil. To reduce the heat leaks from the back of the constantan foil, a layer of silicone rubber 2 mm thick was installed. The surface temperature of the plate was measured by four copper-constantan thermocouples sealed from the coating side. The second alloys of thermocouples were placed in liquid nitrogen in a measuring vessel. The temperature of nitrogen in it was controlled by a resistance thermometer with an accuracy of ± 0.2 K. The thermoelectric power was measured at a frequency of 20 Hz, and the temperature values were recalculated in accordance with standard tables with correction of calibration at 77.6 K (liquid nitrogen boiling at atmospheric pressure 0.102 MPa), which allowed recording of the temperature in non-stationary cooling modes with an accuracy of ± 0.5 K. The control of the current source, measurement of the signals of thermocouples and liquid level gauges, determining the flow, was carried out using two ADC / DAC boards and the experiment control program LGraph. For experiments under steady-state heat generation, the heat flow density was determined from the indications of the current passing through the constantan foil and the potential difference between the terminals located at its ends. The error in measuring the density of the heat flux under conditions of stationary heat release, taking into account the resolution capabilities of the boards, did not exceed 4%.

In order to conduct experiments on the rewetting dynamics after delivering the liquid nitrogen (with a preset flow rate), the flow cutter was turned and the nitrogen flow over the working area was stopped. At the same time the flow rate of liquid nitrogen removed by the cutter remained constant. Then the plate was heated by a constantan foil to a preset maximum (initial) temperature. For each Re number, the experiments were carried out at three different maximum temperatures (T_{int} = 185, 200 and 215 K). At the next stage the heating was switched off and at the same time the cutter was shifted to the starting position. After that the uniform film flow of liquid nitrogen was resumed and the process of rewetting the working section was started.

3. Experimental results
The comparison between the temperature dependences of the uncoated plate and the coated plate (both direct and reverse orientation relative to the liquid flow) versus time during rewetting by the flowing nitrogen film is shown in figure 3. As it can be seen, the character and rate of the plate temperature decrease differ significantly for the heater with and without the coating. The presence of the coating leads to a significant decrease in the time of total cooling of the heater (more than 3 times) from the preset temperature T_0 = 190 K to the saturation temperature of liquid nitrogen. In addition, the
minimum cooling time is observed for the orientation of the surface, at which the liquid flows on the steeper part of the ridges (reverse orientation). The analysis of the obtained data shows that the maximum overheating of the coated plate has little effect on the cooling time from the selected fixed temperature $T = 180$ K. At the same time, a direct proportionality is observed in the cooling time of the smooth heater from the preset temperature, depending on the initial (maximum) superheat for all Re. The difference in cooling time from 180 K to the saturation temperature of nitrogen is of the order of 50 s with a maximum heating of 215 K and 185 K, respectively, and a fixed flow rate of the liquid. An increase in the degree of irrigation when using both a smooth heater and a heater with a structured capillary-porous coating results in an insignificant decrease in the total cooling time in the studied range of Reynolds number. The significant decrease in the overall cooling time of a plate with a structured capillary-porous coating observed in these experiments is due to the development of high-intensity heat transfer in the transition and boiling regimes (at the stage of the beginning of the rewetting front propagation) at much higher plate temperatures. This effect can be explained by the penetration of liquid by capillary forces into the pores, and as a result, by a sharp decrease in the temperature of the upper layers of the coating. Moreover, for such highly porous structure, the heat delivery from the copper plate to the upper layers of the coating is limited by the loose packing of the deposited particles.

Analysis of the results of high-speed video recording showed insignificant differences in the structure and shape of the rewetting front for a smooth heater and a capillary-porous coating heater with a direct and reverse orientation. In the case of small values of Re (figure 4 (a)) on the uncoated plate, the front is distorted during the entire rewetting process due to the periodic separation of droplets and liquid jets in the rewetting zone. For both the smooth heater and the heater with the structured capillary-porous coating, the front is quasi-flat.

As can be seen from figure 4 (b), with a high degree of irrigation, the formation of regular boiling jets is not so pronounced and is observed only at the initial stage of the rewetting front propagation. The average (over the plate height) local front velocities along its boundary, defined as the ratio of the difference in coordinates of the points of the front in the vertical direction to the time of passage of the indicated distance, differ significantly and lie in the ranges of $(7 – 10)$ cm / s for a smooth heater, $(1 – 3)$ cm / s for a heater with a direct coating orientation and $(0.5 – 1)$ cm / s for a reverse heater orientation. At the same time, there is a tendency to increase the propagation velocity of the front at a given stage of the transition process as the degree of irrigation increases. Lower front velocities for the coated plate are associated with a higher temperature of the initial rewetting process as compared to that for the smooth heater.

Figure 3. Dependence of the heater temperature on time in the cooling process at $T_{\text{init}} = 215$ K: (a) – Re = 250 for heater with coating, Re = 350 for smooth heater, (b) – Re = 1010; 1 – smooth heater, 2 – with coating (direct orientation), 3 – with coating (reverse orientation).
Experimental data on the intensity of heat transfer for a smooth plate heater and a heater with a structured capillary-porous coating (reverse orientation) for various degrees of irrigation under conditions of stationary heat release are presented in figure 5. The presence of the capillary-porous coating on the surface of the heater does not lead to a significant change in the heat transfer coefficients as compared to the smooth plate at heat fluxes $q > 3 \text{ W} / \text{cm}^2$ in the entire investigated range of irrigation degree. In the region of smaller heat fluxes, the coating has an ambiguous effect on the heat transfer coefficients for various $Re$.

The analysis of high-speed video data (figure 6) showed that the transition from the heat transfer regime during evaporation to boiling of nitrogen begins in the zone at the upper boundary of the smooth heater and gradually spreads down the entire heat releasing surface as the heat flux density increases. In the pre-crisis boiling regimes, the formation of dry spots with their subsequent propagation along the entire heat transfer surface accompanied by a sharp increase in temperature is
observed when the critical heat flux is reached. The value of the critical heat flux for a smooth sample increases with an increase in the degree of irrigation and is \( q_{cr} = 3.7; 5.4; 6.7 \) and \( 7.5 \) W / cm\(^2\) for the values of the number Re = 350, 500, 750, 1010, respectively. The nucleation of the vapor phase on the capillary-porous coating with an increase in the heat flux density occurs predominantly at the upper boundary of the heater. At the same time, there is a difference in the character of initiation of bubble boiling as compared to a smooth heater: the nucleation sites develop more actively along the entire surface of the porous coating. A characteristic feature of the boiling process on a coated heater is the formation and stable existence of zones of a dried surface over a long period of time without sudden temperature rise at high heat fluxes (figure 6), which makes it difficult to determine accurately the critical heat flux. Nevertheless, the appearance of dry spots on the coated surface is observed at heat fluxes approximately equal to \( q_{cr} \) for a smooth heater at similar values of the Reynolds number.

4. Conclusion
The results of an experimental study of the rewetting dynamics and heat transfer on a copper plate with a structured capillary-porous coating obtained by directional plasma spraying method in the film flow of liquid nitrogen are presented. It is shown that the presence of such coating has a significant effect on the character of the temperature curves and reduces the total cooling time of the plate during rewetting by more than three times as compared with the uncoated plate. The maximum decrease in the cooling time is observed for the reverse orientation of the coating relative to the flow of the liquid. It is shown that an increase in the degree of irrigation with a change in the Re number from 250 to 1500 slightly reduces the total cooling time of both the smooth and coated plates. Experiments under steady-state heat generation showed insignificant effect of the coating on the heat transfer during film flow of liquid at heat fluxes \( q > 3 \) W/ cm\(^2\) in the investigated range of variation of the degree of irrigation. From the analysis of high-speed video data, it was found that the formation of stable zones of a drained surface on a coated plate is observed at heat fluxes approximately equal to the critical heat flux values for the smooth heater.

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