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Heat transfer and crisis phenomena at pool boiling of liquid nitrogen on the surfaces with capillary-porous coatings

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ABSTRACT

The results of experimental study of heat transfer and crisis phenomena at pool boiling of liquid nitrogen with different heating conditions on the surface with capillary-porous coating are presented. Porous coatings with different thicknesses (400 and 1390 μm), morphology and high porosity (up to 80%) were obtained using the new plasma spraying technique. It was shown that at steady-state heat release the heat transfer at boiling essentially depends on the thickness and morphology of the coating. The maximum enhancement (~300%) compared to the smooth heater was detected to coated heater with a thickness of 1390 μm at low heat fluxes. The mechanism of heat transfer enhancement at pool boiling by using the capillary-porous coatings was proposed. Heat transfer hysteresis was detected for the heater with the coating of 400 μm. For the smooth heaters and the heater with 1390 μm coating, the heat transfer coefficients almost coincide with an increase in the heat flux and with its decrease. Data on the effect of coatings with different thicknesses on the critical heat flux (CHF) at boiling under steady-state heat release are presented. It is shown that for the smooth heaters the value of critical heat flux at rapid heating decreases in comparison with steady-state heat release. Capillary-porous coatings have a significant influence on development of the transition process and crisis phenomena at stepwise heat release. There is degeneration of boiling crisis development at rapid heating on the coated surfaces at the heat fluxes below the value of the CHF at steady state heat release. Fast transition to film boiling at stepwise heat release on the coated heaters with different thicknesses is observed at the heat fluxes 2 times higher than the critical heat fluxes, obtained at steady state heating.

1. Introduction

Boiling is the most effective way of removing heat from the heat transfer surface. However, increasing demands for reducing the weight and size of heat exchangers, improving the conditions of cooling and temperature control of high heat flux devices for various applications stimulate the development of techniques for heat transfer enhancement and increasing critical heat fluxes at boiling. To date, the most popular and effective methods are the methods associated with modification of heat-releasing surfaces. Modification is performed by microstructuring the original surface (the so-called ribbed surfaces) and creating the various micro- and nano-porous, nanoscale coatings on the heater [1–6]. There is a huge variety of different physical-chemical methods of microscale surface modification, such as sintering [7–9], electrodeposition [10–12], lithography [13–15], thermal (plasma) spraying [16–19], etc.

The highest heat transfer coefficients and critical heat fluxes can be obtained on the microporous coatings sintered of highly thermal-conductive powders (copper, bronze). One of the major advantages of these coatings is high porosity, which not only increases the effective area of heat transfer surface, but also facilitates the nucleation process, triggers generation of a new phase at less overheating, and increases the density of nucleation sites. In addition, using the sintering method it is possible to create the 2D and 3D cone-like and comb-like structures of different geometry; it was implemented in [20–22]. It was shown in these works that the heat transfer coefficient and critical heat flux at n-pentane boiling with the use of porous coatings can be more than 10 and 3 times higher, respectively, than the analogous values obtained on the uncoated surface. Based on the hydrodynamic theory of crisis development at boiling, the analytical relationship connecting the modulation wavelength of the porous coating and

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Nomenclature

A	area (m^2)
C	specific factor
c	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
D	diameter (m)
I	current (A)
Ja	Jacob number
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
l	length (m)
Nu	Nusselt number
p	pressure, Pa
q	heat flux ($W\,m^{-2}$)
R_a	mean roughness (μm)
r	enthalpy of vaporization ($J\,kg^{-1}$)
Ra	Rayleigh number
T	temperature (K)
U	voltage (V)
V	velocity ($m\,s^{-1}$)

Greek symbols

α	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
δ	thickness (m)
ε	porosity
λ_m	modulation wavelength (m)
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	surface tension ($N\,m^{-1}$)
τ	time (s)

Subscripts

CHF	critical heat flux
K-Z	Kutateladze – Zuber
$b.i$	boiling incipience
cr	critical
dep	departure
sat	saturation
th	threshold
h	heater

Superscripts

$'$	liquid phase
$''$	vapor phase

the CHF value was obtained; it described quantitatively the data of the authors.

Despite the efficiency of using the porous coatings obtained by sintering, this method has several disadvantages, which are as follows: complexity of coating deposition on the surfaces of different shapes, relative fragility of coatings, as well as complexity of manufacturing because of required high temperatures and pressures. In general, advantages and disadvantages of various microscale-modified surface techniques are discussed in detail in [1].

An alternative way of fabrication the microstructured porous coatings is plasma spraying. This method is known for a long time, and now there are several researches devoted to influence of plasma coating on heat transfer at liquid boiling [16–19]. However, the coatings produced by the traditional way of plasma spraying, have a significant disadvantage - low porosity. In [23], the method of plasma spraying with formation of a three-dimensional capillary-porous (TCP) structure by varying the inclination angle of the axis of the sprayed particle cone relative to the substrate surface was suggested. The advantage of this method over the conventional one is the fact that it allows to fabricate the coatings with maximal porosity $\varepsilon \sim 80\%$, high adhesion and uniformity. At the same time, the effect of coatings obtained by this method on heat transfer characteristics and crisis phenomena is currently unknown.

The effect of surface modification on the development of crisis phenomena at liquid boiling under the conditions of rapid heating is also unstudied. It is known that at a sharp increase in the heat load, the CHF value for a various types of fluids (ethanol, benzene, liquid nitrogen, freon, etc.) can be substantially less than the CHF, obtained in the steady state conditions [24–30]. The reason for reducing the value of CHF at rapid heating is as follows: at a stepped increase in the heat flux, there is no enough time to develop convective flows, and almost all heat is accumulated in a thin layer of superheated liquid near the heater surface. In this case, the vapor quality near the heater surface after abrupt boiling of liquid can be much higher than at stationary nucleate boiling at the same heat flux. Increased vapor quality near the heater provides the transition to film boiling at lower heat fluxes at rapid heating. The analysis of experimental and theoretical researches presented in literature shows that the transient critical heat flux $q_{cr}^{tr.min}$ complexly depend on the pressure, liquid subcooling, forced convection, the size and thermophysical properties of the heater, surface characteristics (roughness, wettability) and other factors. In particular, results of experiments [24] showed that increasing effective thickness and heat capacity of heated wall led to increasing the value $q_{cr}^{tr.min}$ up to the critical heat flux at steady-state heat release. The authors attribute this to the increase in the thermal inertia of the heated wall, preventing a rapid increase in temperature of its surface. Also, on the basis of the model of boiling crisis development at stepwise heat generation caused by merging vapor bubbles within the superheated layer near the heater, the authors [24] have obtained the calculation relationship with application of the heat balance, which satisfactorily describes experimental data for organic liquids at $p/p_{cr} \geqslant 0.02$. It was assumed in the framework of this consideration that liquid boiling-up occurs just after the beginning of the heat release. Therefore, the above relationship does not consider characteristics of liquid boiling-up at the heater surface, which determine the rate of vapor bubble growth as well as the effect of the unsteady thermal conductivity stage on $q_{cr}^{tr.min}$.

In [28–30], the theory of boiling crisis at stepwise heat generation with consideration of two stages of process development (the stage of unsteady thermal conductivity up to liquid boiling onset and the stage of vapor bubble growth before the transition to film boiling) was suggested. Calculation dependences presented in [28–30] for the minimal transient critical heat flux considering the parameters of liquid boiling onset, the boiling prehistory (nucleation site deactivation process on the heat-releasing surface), and curvature and thermal inertia of the heater describe a large data set for different types of fluids. At the same time, as it was mentioned above, in literature there is almost no information about the influence of microstructured surfaces and microporous coatings on dynamics of crisis phenomena development and the value of the critical heat flux at rapid heating.

The aim of this work is experimental study the effect of novel capillary-porous coatings fabricated by plasma spraying technique on heat transfer and crisis phenomena at pool boiling of liquid