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Experimental study of heat transfer characteristics of high-velocity small slot jet impingement boiling on nanoscale modification surfaces

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ABSTRACT

Jet impingement boiling is one of the most efficient methods to increase the critical heat flux. Through controlling surface chemical properties and topography, plain nickel foil surface, three kinds of plain nickel-based chemical treatment surfaces and four kinds of nickel-based electrochemical treatment surfaces with nanocone array structure were used in the jet impingement boiling experiments to investigate the quantitative effects and the effect mechanism of the surface characteristic parameters, including nanoscale roughness (R_a): solid–liquid contact angle (CA) and effective heat transfer area ratio (r: the ratio of the actual heat transfer area to its projected area) on the heat transfer coefficient (HTC) and the critical heat flux (CHF). It is revealed that: similar to the heat transfer in pool boiling, changing nanoscale R_a has little effect on the heat transfer characteristics; decreasing solid–liquid CA can enhance the HTC while worsen the CHF obviously; increasing r can intensify both the HTC and the CHF. Predictive correlations of the HTC and the CHF of jet impingement boiling which include the effects of surface characteristics are presented. The predictive correlations presented can be widely used in various conditions with different working fluids and heating surfaces.

1. Introduction

With the rapid development of the modern industrial technology, extremely high heat dissipation has become the bottleneck in the fields of aviation and nuclear power. However, there is an ultimate value of critical heat flux in theory. According to Gambill and Lienhardthe's thermodynamics theoretical model [1], the theoretically ultimate heat flux at the atmospheric pressure with water as the working fluid is 2.23×10^8 W/m^2. So far, the biggest value of heat flux measured in experiment is at least an order of magnitude smaller than the ultimate value.

In steady heat transfer modes, cooling by jet impingement boiling has become one of the most promising methods to meet the extreme heat dissipation requirement in recent years. The jet flow with high subcooling and velocity is easier to break through the vapor layer and get better solid–liquid contact and much higher CHF when impinging the heat transfer surface. Similar to the heat transfer in pool boiling, surface topography and chemistry are two main factors that influence the HTC and the CHF of jet impingement boiling. Surface topography, which is usually represented by the surface roughness (R_a), mainly influences the active nucleation site density, surface capillary force and the effective heat transfer area. Surface chemistry, which is usually represented by solid–liquid CA, mainly affects the bubble departure frequency and the solid–liquid contact area.

Surface topography and chemistry can be changed by surface modification which includes surface chemical treatment, surface mechanical treatment, and attaching foreign materials to the surface and surface electrochemical treatment. When changing surface topography, the ratio of the actual heat transfer area to its projected area r, will be unit for plain surfaces and the heat transfer area will not increase. If there are capillary structures on surface, r will be larger than unit. And r will be much larger than unit for porous surface or nanometer array surface where the increase of effective heat transfer area should be considered.

There are many experimental studies about pool boiling on the modified heat transfer surfaces and abundant experimental data have been recorded. For the first two surface modification methods, several researches [2–5] have been done. The present authors also summarized a large number of pool boiling data on plain metal surfaces, metal plating surfaces and plain non-metal surfaces with high conductivity and presented the HTC predictive correlation which was suitable for all working media and solid–liquid CA conditions based on theoretical analysis [6]. For the last two surface modification methods, there are also many experimental

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Nomenclature

C	correlation factor (–)
c_p	specific heat (J/kg/K)
C'_L	heating surface length effect coefficient (–)
C'_s	comprehensive effect parameter of heating surface (–)
d	width of jet nozzle/heating surface (m)
h	heat transfer coefficient (W/m^2/K)
h_{lv}	latent heat of evaporation (J/kg)
I	current through the heat transfer surface (A)
L	length of nickel foil (m)
L'	non-dimensional length (–)
P	pressure (Pa)
k	thermal conductivity (W/m/K)
N_a	active nucleate site density (–)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
q_w	wall heat flux (W/m^2)
q_c	single phase convective heat flux (W/m^2)
q_b	nucleate boiling heat flux (W/m^2)
R	electric resistance (Ω)
Re	Reynolds number (–)
T	temperature (K)
$\bar{T}$	average temperature of the heating surface (K)
ΔT_{sat}	wall superheat; $T_{sat} = T_w - T_0$ (K)
ΔT_{sub}	subcooling of water; $T_{sub} = T_0 - T_l$ (K)
U	voltage between the two cuboid copper electrodes (V)
V	impact velocity exited from nozzle (m/s)
R_a	surface roughness (nm)
r	effective heat transfer area ratio (–)
S	nucleate boiling suppression factor (–)
h_{lv}, h_{fg}	latent heat of vaporization (J/kg)
g	gravitational acceleration (m/s^2)

Greek symbol

σ	surface tension (N/m)
ρ	density (kg/m)
θ	solid–liquid CA (°)
ξ_{loss}	ratio of the heat loss to the total heat (–)
Φ	heat source density (W/m^3)
α	temperature coefficient of resistance (K^{-1})
δ	thickness of the heating surface (m)
γ	influence parameter of heating surface material (–)
$\emptyset_s$	solid fraction

Subscripts

0	saturation state
b	nucleate boiling
l	liquid
w	wall
v	vapor
s	solid surface
sat	saturation state
sub	subcooling state
lv	liquid–vapor

Abbreviations

CHF	critical heat flux
HTC	heat transfer coefficient
ONB	onset of nucleate boiling
CA	contact angle

studies of pool boiling on microscale and nanoscale modified surfaces [7–10].

However, there are very few studies about jet impingement boiling on modified surfaces were discussed [11,12]. It was presented that using nanoscale modified heat transfer surface to decrease solid–liquid CA and increase efficient heat transfer area was also a key method to increase the CHF apart from higher jet velocity and smaller jet dimension. Besides, the present authors carried out an experimental research on the CHF of jet impingement boiling on the plain heat transfer surfaces with different solid–liquid CA which were prepared by nano coating [12]. Then a semi-theoretical and semi-experimental predictive correlation for the CHF was obtained. The conclusion that decreasing CA will worsen the HTC and enhance the CHF was got. On the condition of constant width of heat transfer surface, extremely high heat flux, bigger than 10^8 W/m^2, was measured by changing the length of the smooth heat transfer surface in reference [13]. Then a CHF predictive correlation with the length of heat transfer surface was obtained by amending the previous proposed correlation with the experimental data measured. Besides, it was concluded that decreasing the length of heat transfer surface has little influence on the HTC and will enhance the CHF.

Two kinds of nanoscale modification surfaces (chemical treated plain surfaces and nanocone array surfaces) are prepared in this study to change surface chemical properties and topography for high-velocity jet impingement boiling experiments. The influences of parameters of nanoscale modification surfaces on the HTC and the CHF of jet impingement boiling are the emphasis in this study. The quantitative effects and mechanism of nanoscale roughness, R_a, solid–liquid CA and r on the heat transfer coefficient (HTC) and the critical heat flux (CHF) of high-velocity jet impingement boiling on both the modification plain surfaces and nanocone array surfaces were studied and summarized. Meanwhile, by connecting high-velocity jet impingement and micro heat transfer surfaces technology, the biggest experimental value of CHF, 1.62×10^8 W/m^2, which is close to the theoretical limit, is measured in the experiments. The jet CHF predictive correlation presented by the authors before, which included the influence of solid–liquid CA only, gets improved by adding the influences of wall capillary force and solid fraction which represent nano structure's characteristics. Then an improved CHF predictive correlation which is suitable for both normal plain surfaces and nanoscale modification surfaces is presented.

2. Experimental facilities and methods

2.1. Experimental facilities

The experimental system is basically the same as that of the previous jet impingement boiling study on the smooth surface [13]. The experimental facilities of jet impingement boiling are composed of experiment box, water circulation system, measuring system and power system. Deionized water with conductivity of 3×10^{-4} S was used as the working fluid. The experiments were carried under atmospheric pressure. The working fluid was maintained at a given temperature by thermostat in water storage tank, then accelerated by multistage centrifugal pump and exited from the vertical nozzle at last. The flow rate of working fluid, which was shown in the turbine meter in the main flow pass, was controlled by adjusting the branch regulating valve. There was a thermocouple in the front of nozzle to measure the outlet temperature