International Journal of Heat and Mass Transfer 91 (2015) 584–593

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Effect of conjugation on jet impingement boiling heat transfer

Lu Qiu [a,b], Swapnil Dubey [a], Fook Hoong Choo [a], Fei Duan [b,*]

[a] Energy Research Institute @ NTU, Nanyang Technological University, 1 Cleantech Loop, 06-04 Cleantech One, Singapore 637141, Singapore
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 8 March 2015
Received in revised form 16 May 2015
Accepted 28 July 2015

Keywords:
Jet impingement
Boiling
Conjugation
Heat transfer

ABSTRACT

Boiling involves significant bubble induced flow mixing and phase change which give rise to a phenomenal heat transfer rate. The jet impingement produces a strong convection and influences the nucleate boiling heat transfer and burn-out characteristics. Experimental studies on jet impingement boiling heat transfer have been conducted, whereas only limited numerical simulations have been reported. In the current study, three jet impingement configurations are studied with a numerical approach in which the Rensselaer Polytechnic Institute (RPI) boiling model is applied. The simulation results agree well with the reported experimental data. The RPI boiling model is able to simulate the subcooled jet impingement boiling heat transfer in submerged and confined configurations. Finally, the effect of conjugation on jet impingement boiling heat transfer is investigated. The conjugation makes a great difference in this case. The results suggest that the data obtained in the experiments with the different heating schemes (thick copper block or thin-film heater, corresponding to with or without conjugation), although the jet parameters are same, can be significantly different and incomparable. Attention should be paid on heating scheme in the experimental and numerical studies.

1. Introduction

Jet impingement boiling is a typical external flow boiling, which has extensive applications in thermal managements. A high heat transfer rate could be reached since bubble induced fluid mixing promotes the energy transportation whereas the boiling phase change absorbs the latent heat. Wall superheat is an important indicator for the strength of boiling heat transfer. With an increase of wall superheat, the flow regime develops from single phase forced convection to nucleate boiling, then to transition boiling, and finally to film boiling. Operating in the nucleate boiling regime is desired for a thermal management device since high heat transfer can be produced with a relatively low wall superheat. By the end of the fully developed nucleate boiling regime, a critical heat flux (CHF, also known as burn-out heat flux) is observed, after which the wall heat flux reduces abruptly.

The fundamentals of jet impingement boiling were firstly investigated by Copeland [1] in 1970. Later, Katto and Kunihiro [2] employed a water jet to remove the vapor mass in pool boiling, and found the significant different burn-out characteristics. In the following decades, a variety of jet impingement boiling studies were published regarding different configurations, such as free surface, submerged, confined, plunging or wall jet [3]. The effects of hydrodynamic parameters of jets (jet velocity, jet subcooling, and jet fluid), geometrical parameters of jets (nozzle dimension, impact distance, and multiple jets), and target surface (contact angle and surface structure) on the boiling heat transfer were investigated. For the free surface jet impingement boiling, the effect of jet velocity on nucleate boiling heat transfer with the low speed (V_j <10 m/s) circular [4–7] and slot [8] jet impingement boiling, and those with the high speed (V_j >10 m/s) circular [9–11] and slot [12] jet impingement boiling were reported. The effect of subcooling was also studied [10,13,14]. The agreement had been reached that higher jet velocity and subcooling resulted in higher CHF. Moreover, the influences of jet diameter [4–6], jet array [15] and surface condition [7,9,16] were investigated as well. CHF was found to be proportional to the $(V_j/d_j)^{1/3}$ for both saturated and subcooled water. Multiple jets increased the area-averaged heat transfer but produced a more significant temperature gradient. The effect of contact angle was independent of the other parameters. Regarding the submerged and confined jet impingement boiling, it was found that the jet velocity had little effect on the boiling curve [17–22], whereas the others found that increasing jet velocity resulted in better boiling heat transfer [23–27]. It was found that the wall heat flux was independent of subcooling for both smooth and porous surfaces [19], whereas the subcooling were found apparently influence the boiling curve [23]. Besides,

* Corresponding author. Tel.: +65 6790 5510; fax: +65 6792 4062.
E-mail address: feiduan@ntu.edu.sg (F. Duan).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.121
0017-9310/

Nomenclature

Ar	area ratio ($Ar = A_{jets}/A_{heater}$)
A_b	nucleate bubble covered area of wall
A_i	interfacial area density
C	correlation constants
C_p	constant pressure heat capacity
d	diameter
D_w	bubble departure diameter
f	bubble departure frequency
F	force
g	gravity
G_K	turbulence production rate
h_{ls}	liquid side interfacial heat transfer coefficient
h_{lw}	wall-to-liquid convective heat transfer coefficient
H	enthalpy
HTC	heat transfer coefficient
Ja	Jacob number
K	turbulent kinetic energy
L	latent heat
m	mass source
N_w	nucleate site density
p	pressure
Pr	Prandtl number
q''	heat flux
Q	heat energy
R	interfacial drag force
S	source
t	time
T	temperature
V,v	velocity
α	volume fraction
ε	dissipation rate
λ	thermal conductivity
μ	viscosity
ξ	variable
ρ	density
σ	surface tension
τ	shear stress

Subscripts

b	boiling
cell	first cell adjacent to the wall
C	single-phase convection
d	drag
E	evaporation
j	jet
l	liquid
m	mixture
p,q	phase
Q	quenching
sat	saturation
sub	subcooling
t	turbulence
v	vapor
w	wall

Superscript

m	correlation constant

the effects of impact distance [20], multiple jets [20,25,26] and surface conditions [19,24] were also investigated. The boiling curve was independent of impact distance, but CHF was apparently influenced by the impact distance. A higher jet density resulted in a better overall heat transfer. Moreover, the target surface roughened with the porous surface [19] and pin–fins were tested [24].

Compared to the experimental studies, only limited numerical simulations regarding the jet impingement boiling heat transfer have been reported. A simple way to address the boiling effect is adding additional diffusive terms into the momentum and energy equations of single-phase simulation [28]. Omar et al.[29] conducted experiments to determine the relation between the artificial diffusivity and the dimensionless bubble parameters. Wang et al. [30] employed Eurlerian based multi-phase mixture model to simulate a jet impingement boiling case that had been experimentally investigated by Chrysler et al. [31]. The significance of boiling was shown by the interphase transfer models. The interphase mass transfer rate must be given in order to make the prediction. However, the significant boiling heat and mass transfer happens in the vicinity of boiling wall, and this method fails to address the issue. Therefore, the wall heat flux partitioning model was developed, in which the wall heat flux was partitioned into several parts. Narumanchi et al. [32] employed the RPI boiling model to study a confined circular jet impingement boiling configuration via commercial ANSYS-Fluent solver. They proposed a bubble departure diameter model in which the effects of system pressure and wall superheat were concerned. Two validation cases showed that the RPI boiling model worked well to predict the boiling heat transfer. Besides, Abishek et al. [33] also employed the RPI model to study a confined subcooled jet impingement cooling configuration. After the validations, the effect of heater size was investigated. It showed that the smaller heater presented a higher heat transfer all the time.

An interesting phenomenon was observed that the single-phase convection and nucleate boiling coexisted in some jet impingement boiling configurations. For example, Dukle and Hollingsworth [34,35] observed a boiling front though the thermal liquid crystal technique. Single-phase convection and nucleate boiling dominated inside and outside of the boiling front respectively. This boiling front was stable and reproducible, and a correlation for it was proposed. Similarly, Rau and Garimella [15] employed a thin-foil heater, and measured the wall temperature distribution with the infrared camera. The coexistence was also observed with a moderate wall heat flux. The boiling dominated region was spreading into the stagnation zone with the increase of wall heat flux. Once boiling dominated on the entire heating surface, the wall temperature distribution became quite uniform. Coincidentally, the distinguished observation was made only in the experiments with the thin-foil heater (isoflux boundary condition) inside which the span-wise conduction was negligible. It is different from the traditional thick copper heating block ones. Therefore, a question arises, what is the role of the solid domain in jet impingement boiling configurations?.

To sum up, a great heat transfer rate variation across the target surface would be produced due to the jet impingement. Given that the nucleate boiling heat transfer is sensitive to wall superheat, the conjugation would play an important role in jet impingement boiling heat transfer. Different observations were made in the previous experiments that with different heating schemes: heating indirectly with high conductivity material substrate (conjugation) or directly with the thin-foil heater (non-conjugation). On the other hand, the RPI boiling model was proved to be effective to predict jet impingement boiling heat transfer. Therefore, the objective of current study is to numerically study the effect of conjugation on jet impingement boiling heat transfer and make attempts to offer the fundamental perspectives.