International Journal of Heat and Mass Transfer 89 (2015) 42–58

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Review

Recent developments of jet impingement nucleate boiling

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, 637141, Singapore
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form 28 January 2015
Accepted 5 May 2015

Keywords:
Jet impingement
Boiling
Phase change
Heat transfer

ABSTRACT

Jet impingement boiling is one of important branches of flow boiling. Due to its high heat transfer rate, the application potential of this heat transfer approach is significant. Hence, it attracts many researchers attentions. This review examines the development of jet impingement boiling heat transfer that published in the past two decades. The topics covered are fully developed nucleate boiling regime and its two boundaries: onset of nucleate boiling and critical heat flux point. Free surface, submerged, confined circular/planer jet impingement boiling configurations are involved. Effects of jet parameters (impact velocity, impact distance, jet diameter, subcooling, jet array, etc.) and target surface parameters (surface condition, surface aging, etc.) on boiling heat transfer characteristics are emphasized and discussed. The review mainly focuses on experimental studies, but theoretical and numerical developments are also discussed.

Contents

1. Introduction . . . 43
2. Fundamentals of jet impingement boiling . . . 44
3. Experimental studies . . . 44
 3.1. Effects of system parameters on boiling heat transfer for free-surface, circular jets . . . 44
  3.1.1. Effect of jet velocity . . . 44
  3.1.2. Effect of jet subcooling . . . 47
  3.1.3. Effect of nanoparticles in liquid jet . . . 48
  3.1.4. Effect of nozzle dimensions . . . 48
  3.1.5. Effect of impact distance . . . 48
  3.1.6. Effect of multiple jets . . . 48
  3.1.7. Effect of surface condition . . . 48
  3.1.8. Coexistence of single-phase convection and boiling . . . 49
 3.2. Effects of system parameters on boiling heat transfer for submerged and confined jets . . . 49
  3.2.1. Effect of jet velocity . . . 49
  3.2.2. Effect of jet subcooling . . . 50
  3.2.3. Effect of non-condensable gas in liquid jet . . . 51
  3.2.4. Effect of impact distance (confinement) . . . 51
  3.2.5. Effect of multiple jets . . . 51
  3.2.6. Effect of surface condition . . . 51
  3.2.7. Coexistence of single-phase convection and boiling . . . 52
 3.3. Effects of system parameters on boiling heat transfer for planar jets . . . 52
  3.3.1. Effect of jet velocity . . . 52
  3.3.2. Effect of jet subcooling . . . 53
  3.3.3. Effect of jet width . . . 53

* 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.2015.05.025
0017-9310/

Nomenclature

Ar	area ratio ($Ar = A_{jets}/A_{heater}$)
AR	aspect ratio (AR = length/width)
A	area
Bo	boiling number ($Bo = q''/\rho U h_{fg}$)
C	correlation constants
C_p	constant pressure heat capacity
d	jet diameter
D_{bd}	bubble departure diameter
D_c	diameter of confined cylinder
D	heater diameter
g	gravity
f	bubble departure frequency
G	mass flow rate
h_{fg}	latent heat
H	impact distance
HTC	heat transfer coefficient
k	thermal conductivity
L	length
Nu	Nusselt number ($Nu = q''D/\Delta T_{sat} k_l$)
N_w	Nucleate site density
p	pitch of jet array
q''	heat flux
r	radius from the center of jet
T	temperature
Re	Reynolds number ($Re = \rho U d/\mu_l$)
U	jet velocity
W	width of slot jet
ρ	density
σ	surface tension
θ, CA	contact angle

Subscripts

0	correlation for saturated liquid
b	boiling
CHF	critical heat flux
e	evaporation
f	boiling front
FNB	fully developed nucleate boiling
l	liquid
ONB	onset of nucleate boiling
ref	reference
sat	saturation
sub	subcooling
sp	single-phase
v	vapor
w	wall

Superscript

m, n	*correlation constants*

3.3.4. Effect of impact distance . . . 53
3.3.5. Effect of multiple jets . . . 53
3.4. Hybrid configuration . . . 53
3.4.1. Effect of jet velocity . . . 53
3.4.2. Effect of jet subcooling . . . 54
3.4.3. Effect of jet pattern . . . 54
3.4.4. Effect of surface condition . . . 54
3.5. Other phenomena and jet impingement configurations . . . 54
3.5.1. Boiling hysteresis phenomenon . . . 54
3.5.2. Unsteady jet impingement boiling (quenching) . . . 54
3.5.3. Cylindrical target surface . . . 55
3.5.4. Rotating target surface . . . 55
3.5.5. Cryogenic jet impingement boiling . . . 55
4. Numerical models and simulations . . . 55
4.1. Eulerian based mixture models . . . 55
4.2. Eulerian based PRI boiling models . . . 55
4.3. Single-phase based jet impingement boiling models . . . 56
4.4. Other developments related to jet impingement boiling . . . 56
5. Conclusion . . . 56
Conflict of interest . . . 57
Acknowledgments . . . 57
References . . . 57

1. Introduction

Boiling bears a phenomenal heat transfer performance due to the bubble induced significant flow mixing as well as the phase change required latent heat, therefore, is usually employed in high heat flux thermal management applications, such as power electronics components cooling, large scale integrated circuits cooling, inverters cooling, and metal processing, etc. [1] Boiling investigations can be divided into three major categories: pool boiling, internal flow boiling and external flow boiling. As the simplest configuration in boiling family, pool boiling studies focused on very fundamental aspects of the boiling phenomenon, for instance, pre-existing nuclei, nucleate site density and bubble dynamics, etc. [2] However, purely theoretical approach for the boiling phenomenon has not been well developed yet. Empirical correlations are still applied for modeling boiling flow and heat transfer. Internal flow boiling configuration as tubes presents different heat transfer characteristics from the pool boiling due to the contribution of forced convection. Micro-channel flow boiling presents high heat transfer rate in a compact configuration without a large surface temperature gradient [3,4]. One typical external flow boiling configuration is jet impingement boiling. Single-phase jet impingement is good at heat transfer. It is interesting to know what happens if one combines jet impingement with boiling together. This topic has been studied for decades, many of which before 1993 had been summarized comprehensively by Wolf et al. [5], therefore, this review is a follow-up which shows the recent developments of jet impingement boiling in the last two decades. Jet