International Journal of Heat and Mass Transfer 127 (2018) 515–533

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Direct experimental measurement for partitioning of wall heat flux during subcooled flow boiling: Effect of bubble areas of influence factor

Muritala Alade Amidu [1], Satbyoul Jung [1], Hyungdae Kim *

Department of Nuclear Engineering, Kyung Hee University, Yongin-si, Republic of Korea

ARTICLE INFO

Article history:
Received 6 February 2018
Received in revised form 8 June 2018
Accepted 14 July 2018

Keywords:
Bubble area of influence
Infrared thermometry
Subcooled flow boiling
Total reflection
Wall heat flux partitioning

ABSTRACT

Heat transfer models in liquid-vapor two-phase flow with wall boiling rely on the wall heat flux partitioning to quantify heat transfer to liquid and vapor separately. Several wall heat flux partitioning models have been proposed over the years based on variety of heat transfer mechanisms, but the three basic mechanisms that form the core of these models are liquid convection, surface quenching and evaporation heat transfer. A key parameter commonly used to determine the relative contribution made by each mechanism is area fraction of influence of bubble which is determined by multiplying maximum bubble projected area fraction with bubble area of influence factor (K). In classic wall heat flux partitioning models, K accounts for the area within which heat is transferred to liquid that moves in towards the heated wall as bubbles lift-off. The value of K has been a subject of controversy over the years with no unanimous conclusion among researchers. Therefore, in this paper, advanced diagnostic approach involving the combination of infrared thermometry and total reflection principle was employed to experimentally study nucleate flow boiling. Rigorous data analyses was performed to partition the wall heat flux into the aforementioned three basic heat transfer mechanisms using different values of K. All three heat transfer mechanisms were significantly sensitive to varying values of K, but setting K = 0.5 with percentage uncertainties of −60%/+50% closely predicted the experimental measurements. In addition, overlapping area of influence due to merging bubbles was observed to be significant in the model at high heat flux condition and must be discounted to get the true bubble area of influence. A correction method for the overlapping area of influence was therefore proposed to enhance accuracy of the predictive model.

1. Introduction

Subcooled flow boiling finds many industrial applications particularly in systems where removal of large amount of heat is of paramount importance. Several empirical and mechanistic models have been proposed in literature to predict heat transfer characteristic of such boiling phenomenon. However, the use of mechanistic wall heat flux partitioning models (based on relevant heat transfer mechanisms) to determine the individual component of wall heat flux (convection, evaporation, quenching etc) is common in the application of computational fluid dynamics (CFD) for the analysis of systems featuring subcooled flow boiling. Therefore, the importance of the refinement of these wall heat flux partitioning models to enhance their predictive accuracy cannot be over emphasized.

It is worth noting that most of the mechanistic wall heat flux partitioning models require sub-models of some key parameters such as heat transfer coefficient of single-phase convection, bubble departure diameter, bubble departure frequency, bubble waiting time, active nucleation site density and so on. Appropriate sub-models must be selected as closure relations to ensure accurate prediction by the heat flux partitioning model and sensitivity calculations have been performed over the years for these sub-models. However, the bubble areas of influence factor (K) has usually been assumed to be constant in previous studies even though it plays a vital role in determining the dominant heat transfer mechanism and the partitioning of heat flux on the heated wall. The physical meaning of factor K emanates from earlier observed phenomenon whereby heat is transferred to the liquid that moves in towards the wall after bubble departure. The departing bubble takes a part of the superheated liquid layer away with it (through vortex ring created in its wake) as shown in Fig. 1. This affected area is generally referred to as bubble area of influence and it is normally estimated by multiplying the maximum projected bubble

* Corresponding author.
E-mail address: hdkims@khu.ac.kr (H. Kim).
[1] These two authors contributed equally to this work.

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.079
0017-9310/

Nomenclature

A	area, m^2
A_{1f}	single phase heat transfer area, m^2
A_{2f}	two-phase heat transfer area, m^2
C_p	specific heat capacity, J/kg K
D_b	bubble departure diameter, m
f	bubble departure frequency, s^{-1}
h_c	convective heat transfer coefficient, W/m^2 K
h_{fg}	latent heat, J/kg
I	current, A
k_l	liquid conductivity, W/m K
k_s	sapphire thermal conductivity, W/m K
L	thickness, m
N_a	nucleation site density, m^{-2}
N_f	number of frames
N_p	number of pixels
$N_{p\lambda}$	photon flux per unit wavelength, photo/m^2 sm
q''_c	convective heat flux, W/m^2
q''_e	evaporative heat flux, W/m^2
q''_q	quenching heat flux, W/m^2
q''_w	wall heat flux to water, W/m^2
q''_s	wall heat flux to sapphire W/m^2
q''_s	average wall heat flux in region r, where r could be convection area, evaporation area or quenching, W/m^2
$\bar{T}_r$	average wall temperature in region r, where r could be convection area, evaporation area or quenching, °C
T_w	wall temperature, °C
T_l	bulk temperature, °C
T	temperature, °C
t	time, s
t_w	bubble waiting time, s
t_g	bubble growth time, s
T	temperature, K
T^+	dimensionless temperature
y^+	dimensionless distance
V	voltage, V
x	spatial coordinate, m
y	spatial coordinate, m
z	spatial coordinate, m

Greek letters

α	absorption coefficient, 1/m
ε	apparent emissivity
ρ	density, kg/m^3
ρ	reflectivity
u_τ	friction velocity, m/s
λ	wavelength, m
τ	transmissivity
μ	bubble area fraction of influence

Subscripts

1	single phase
2	two phase
a	ambient
c	center
dc	dark current
ew	empty well
fw	full well
g	gas
h	heater
hs	heater/sapphire interface
int	integration time
ito	indium tin oxide film
l	liquid
ml	microlayer
pixel	pixels
sa	sapphire/heater interface
tot	total
w	wall

area by a factor K. Therefore, a concise literature review of the evolution of mechanistic wall heat flux partitioning models and the respective treatment of bubble area of influence factor is given below.

Mechanistic models seek to capture thermal-hydraulics phenomenon based on complete description of its macroscopic physics. In the past, Del Valle and Kenning [1] developed a mechanistic wall boiling model for subcooled flow nucleate boiling by dividing the heated wall into four zones with different heat transfer mechanisms. These zones (based on bubble dynamics) are maximum bubble projected area, surrounding area of influence, overlapping area of influence and non-boiling area. Microlayer evaporation and transient conduction were considered to occur in maximum bubble projected area while transient conduction, enhanced transient conduction and single-phase forced convection were considered to occur in surrounding areas of

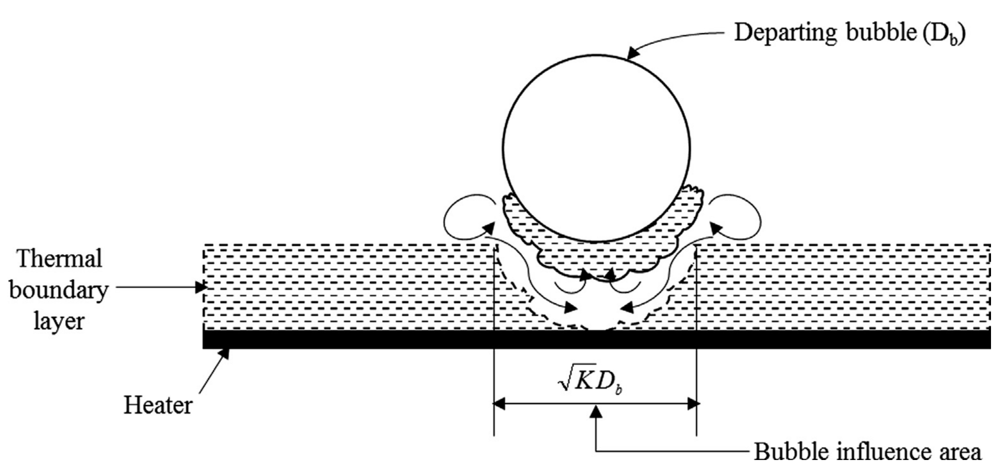

Fig. 1. Illustration of bubble area of influence after bubble departure from heater surface.