International Journal of Heat and Mass Transfer 118 (2018) 327–339

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental investigation of variability in bubble departure characteristics between nucleation sites in subcooled boiling flow

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ARTICLE INFO

Article history:
Received 9 June 2017
Received in revised form 6 September 2017
Accepted 28 October 2017

Keywords:
Subcooled boiling
Departure diameter
Departure frequency
Wall nucleation
Active nucleation site density

ABSTRACT

Experiments have been conducted in a vertical square channel for investigation of wall nucleation characteristics in subcooled boiling flow. Bubble departures from multiple sites are measured simultaneously for nine conditions. Existing bubble departure diameter models are benchmarked and are shown to be satisfactory in predicting condition-average bubble departure diameter. However, significant variations are observed in the bubble departure frequency across different nucleation sites of a given condition largely due to intermittent periods of inactivity. A benchmark of the existing bubble departure frequency models shows that the models are generally applicable to an ‘active’ frequency but cannot account for the impact of these periods of inactivity. This finding highlights an important issue in the current modeling and understanding of the gas-phase boundary condition. This periodic inactivity, if not incorporated into the wall nucleation modeling, will result in a large overprediction of bubbles generated at the wall. A physical justification for this inactivity is discussed based on the modeling of the active nucleation site density.

1. Introduction

The process of wall nucleation in subcooled boiling flow has generated significant interest among the scientific community given its importance in a wide range of industries. A substantial amount of effort has been invested to characterize wall nucleation in terms of active nucleation site density, bubble departure diameter, and bubble departure frequency. Active nucleation site density represents the number of bubble-producing sites; bubble departure diameter describes the size of the average bubble as it departs from a nucleation site, and bubble departure frequency defines the average rate of bubbles leaving a nucleation site. Accurate prediction of these parameters of wall nucleation is foundational to understanding boiling heat transfer and transport as emphasized by the wall heat flux partitioning model [1], the bubble number transport model [2], the Interfacial Area Transport Equation (IATE) [3,4], and the Multiple Size Group (MUSIG) Population Balance Model [5,6]. However, a good understanding of wall nucleation is still lacking in forced convective flows due to inherent fluctuations in driving mechanisms [7]. Although wall nucleation in pool systems can provide a foundational understanding of the bubble incipience, growth, and departure, forced convective boiling flows present additional complexity from exposure of the nucleation site and departing bubble to steep temperature gradients [8] and mechanical and thermal fluctuations [9]. Furthermore, the imaging technology required for detailed measurement of bubble nucleation characteristics in flow boiling systems is relatively new, and more comprehensive experimental data is needed to improve understanding and modeling efforts.

Measurements of bubble size and growth in flow boiling date back to the 1950s. Gunther [10] carried out a photographic study to investigate the impact of forced convection on the heat transfer mechanism of a boiling surface. The size and population of bubbles were measured in this study. The photographs of the boiling surface were obtained using a high-speed film camera that operated mechanically. A roll of film was accelerated to reach the desired frame rate of 20,000 frames per second (FPS), and an electro-optical shutter was used to expose the film in the camera. Since the shutter could only be exposed for a short time, roughly 0.05 s of film was recorded for each condition. A photographic study was performed by Griffith et al. [11] to study void volumes in subcooled boiling. For each test condition, ten photographs of boiling phenomena of a heated surface were taken manually by an operator using sheet films as the negatives. The films were then developed into photographs using chemical solutions. According to Griffith et al. [11], one of the challenges of this technique was ensuring uniformity between films during development.

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.116
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Nomenclature

Bo	boiling number [–]
C	non-dimensional constant [–]
C_D	drag coefficient [–]
C_{Dd}	departure diameter constant [–]
C_{fd}	departure frequency constant [–]
D_b	instantaneous bubble diameter [m]
D_d	departure diameter [m]
D^+	dimensionless diameter [–]
D_p	dry patch diameter [m]
f_a	active departure frequency [Hz]
f_d	classical departure frequency [Hz]
g	gravitational constant [m/s^2]
G	mass flux [kg/m^2 s]
h_c	heat transfer coefficient [W/m^2 K]
h_{fg}	latent heat of vaporization [J/kg]
Ja	Jakob number [–]
La	Laplace length [m]
m	number of active nucleation sites [–]
N_n	active nucleation site density [1/m^2]
N_T	non-dimensional temperature [–]
n	number of departures [–]
P	pressure [Pa]
Pr	Prandtl number [–]
q''_w	wall heat flux [W/m^2]
r_s	characteristic radius of active cavity [m]
T	temperature [°C]
ΔT_w	wall superheat [°C]
t	time [s]
$\overline{\Delta t}$	mean time difference between departures [s]
t'_a	accumulated active time [s]
t_G	growth time [s]
t_W	wait time [s]
v	liquid velocity [m/s]

Greek symbols

α	thermal diffusivity [m^2/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
ϕ_s	static contact angle [rad]

Superscripts

$*$	non-dimensional
N	number mean
S	surface mean
V	volume mean

Subscripts

a	active
b	bulk
c	condition
cal	calculated
exp	experimental
f	liquid
g	gas
ONB	onset of nucleate boiling
s	site
sat	saturated
sub	subcooled

Nearly two decades later, Treshchev [12] studied the formation of vapor on a heated surface during boiling. The influence of experimental conditions such as pressure, flow rate, and heat flux on bubble diameters and active nucleation site density was the focus of the study where the author reported that the bubble diameter decreased with the system pressure. Abdelmessih et al. [13] used the same method to investigate the effect of fluid velocity on the growth and collapse of bubbles on a heated surface where the size of ten bubbles from each nucleation site was measured. The study reported that bubbles nucleating from the same active nucleation site under the same condition had varying maximum sizes and lifespans. Abdelmessih et al. [13] attributed the variation to the microscopic eddies in the liquid. Akiyama and Tachibana [14] used a photographic technique to investigate the growth, collapse, and motion of bubbles on a heated surface in subcooled boiling under atmospheric pressure. Photographs of bubble formation and collapse were taken using a high-speed camera at 14,000 FPS. Similar to the results by Abdelmessih et al. [13], Akiyama and Tachibana [14] observed bubbles with varying sizes and lifetimes even though the bubbles nucleated from the same site under the same condition.

With improving imaging capability came more flow boiling nucleation data and attempts to present the statistical distribution of bubble departure sizes. Unal [15] studied subcooled boiling flow to investigate the size and growth of bubbles on the heated surface. Bubble sizes were measured by recording bubble formation at a frame rate of 5000 FPS and enlarging the developed films. Unal [15] noted that the maximum bubble diameter followed an approximate normal distribution from samples of 65–450 bubbles and reported an average for seven conditions. Klausner et al. [16] carried out flow boiling experiments with Refrigerant-113 to measure bubble departure diameter focusing on the size distributions. Klausner et al. [16] observed that the departure diameter resembled a normal distribution. Furthermore, it was observed that even though the mean departure diameter varied with the flow condition, the standard deviation of departure diameter from the mean was similar to the mean value for different cases which demonstrated the random nature of the bubble departure process. Klausner et al. [16] suggested that the randomness exhibited by the experimental data most likely originated from both the turbulent fluctuations inherent in two-phase flow and the variations of wall superheat on the heated surface, also later cited by Martinez-Cuenca et al. [7] and Dhir [17]. The authors then extended their analysis of the bubble size distribution in Klausner et al. [18] by modeling the distribution based on an assumed normal distribution for the wall superheat and the liquid velocity. The good agreement between the predicted distribution and existing data suggested that the normal distribution of bubble departure diameter was caused by the variations of liquid velocity and wall superheat in a boiling system. Thorncroft et al. [19] investigated bubble detachment in upward and downward forced convection subcooled boiling flow with refrigerant FC-87, reported bubble distributions based on approximately fifty measured bubble departures, and observed a distribution resembling a Gaussian although slightly skewed in some cases. Thorncroft et al. [19] also measured the nucleation site wait time, which is the time from a bubble departure until the next bubble is initiated, and suggested evidence of a correlation between the bubble departure size and the subsequent wait time. Zou and Jones [20] investigated the effects of heater surface material on subcooled flow boiling heat transfer of R134a using high-speed photography. Using a copper surface and a stainless steel surface, it was observed that the bubble