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Bubble departure frequency in forced convective subcooled boiling flow

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ABSTRACT

Forced convective subcooled boiling flow experiments were conducted in a vertical upward annular channel. Water was used as the testing fluid, and the tests were performed at atmospheric pressure. A high-speed digital video camera was applied to capture the dynamics of the bubble nucleation process. Bubble departure frequencies were obtained from the video for a total of 58 test conditions. The non-dimensional analysis was performed on the current data as well as available data from literature. Existing models and correlations were compared with the experimental data of bubble waiting time, growth time, and departure frequency. The correlations developed for pool boiling flow do not work well for forced convective subcooled boiling flow, while the models proposed for subcooled boiling flow cannot predict the bubble departure frequency in wide experimental ranges. Dimensionless bubble departure frequency is correlated with non-dimensional nucleate boiling heat flux. The new correlation agrees reasonably well with existing experimental data at lower wall superheat.

1. Introduction

The subcooled boiling region is characterized, in convective flow boiling, as boiling occurring close to the heated wall while the remaining bulk of the fluid is subcooled. Bubbles will be rapidly condensed if they move out of the developing saturation layer. In the subcooled region, there exists a small void fraction. Gradually, as the bulk is heated by conduction and convection, the saturation layer expands and eventually covers the entire flow channel. Subcooled boiling flow comprises all the interactive, complicated, and dynamic processes such as hydrodynamics, heat and mass transfer, nucleation, departure, coalescence and breakup of bubbles. Many industrial applications, for instance, boiler, boiling water reactor, and the new generation of electronic and computer system, are seriously interested in the understanding and modeling of subcooled boiling.

In spite of enormous efforts, bubble nucleation and departure in subcooled boiling flow still pose a challenge work. Bubble nucleation happens within the small activated cavities at the heater surface when the wall temperature exceeds the saturation temperature of the liquid at the local pressure. Bubbles subsequently detach from the nucleation site due to the forces acting on them in the axial and normal directions. Two important parameters associated with departure are the bubble departure frequency and bubble departure size, which are defined as the frequency and size of bubble when departing from the nucleation cavities, respectively.

The bubble departure phenomena in pool boiling have been studied since 1950s. Zuber [1] found that bubble departure and the flow regimes are similar to the formation of gas bubbles at orifices. According to Zuber [2], three regimes of vapor bubble departure from the nucleation site can be discerned: (1) Laminar regime: When vapor flow rates are very low, bubbles rise at a constant velocity, and do not interact with each other. The bubble diameter is almost independent of vapor flow rate, and the bubble departure frequency increases with increasing vapor flow rate. This regime is also referred as the region of static, separated or isolated bubbles. (2) Turbulent regime: When vapor flow rates are intermediate, the bubble departure diameter increases with flow rate while bubble departure frequency remains constant. A bubble interacts and may coalesce with its predecessor above the nucleation site, and the bubble size is non-uniform. This regime is also referred as the region of multiple or interfering bubbles. (3) When vapor flow rates are even higher, a swirling vapor stream is generated at the nucleation site. The vapor jet is similar to a tornado or a waterspout. The current study focuses on the bubble departure phenom-

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Nomenclature

A	area
b	constant
C_{ev}	coefficient
C_{p}	specific heat at constant pressure
D	diameter
F_{d}	drag force
F_{du}	unsteady drag force (growth force)
F_{g}	gravity force
F_{p}	pressure force
F_{qs}	quasi-steady force
F_{s}	surface tension force
F_{sl}	shear lift force
f_{d}	bubble departure frequency
G	mass flux
g	gravitational acceleration
h	heat transfer coefficient
i_{fg}	heat of vaporization (latent heat)
Ja	Jacob number
k	thermal conductivity
N_{a}	active nucleation site density
N_{fd}	dimensionless bubble departure frequency
N_{fG}	inverse of dimensionless bubble growth time
N_{fW}	inverse of dimensionless bubble waiting time
N_{q}	dimensionless heat flux
N_{qFC}	dimensionless single-phase forced convective heat flux
N_{qG}	dimensionless heat flux using bubble departure diameter
N_{qNB}	dimensionless nucleate boiling heat flux
N_{qW}	dimensionless heat flux using cavity diameter
p	pressure
Pr_{f}	liquid Prandtl number
q''	heat flux
r	radius
Re	Reynolds number
S	suppression factor
T	temperature
T_0	bubble surface temperature
t	time
u	velocity

Greek symbols

α	thermal diffusivity
δ	thermal layer thickness
θ_{i}	inclination angle
ρ	density
σ	surface tension
μ	viscosity

Subscripts

b	bubble or bulk
c	cavity or convective
d	departure
e	effective
ev	evaporation
f	liquid phase
FC	forced convective
G	growth
g	vapor phase
H	hydraulic
h	heated
NB	nucleate boiling
r	relative
s	saturation
sub	subcooling
W	waiting
w	wall
x	coordinate
y	coordinate

ena in subcooled boiling condition, which falls in the laminar and turbulent regimes.

Literature review shows that bubble departure frequency at pool boiling have been studied extensively. Jokob [3] found that the product of bubble departure frequency and departure diameter to be a constant. Zuber [4] correlated this constant to be half of the bubble rising velocity in a gravitational field. Ivey [5] offered three correlations with the product of departure frequency and different power of departure diameter for three regions: (1) hydrodynamic region in which buoyancy and drag forces predominate; (2) transition region where buoyancy, drag, and surface tension forces are in the same order; and (3) thermodynamic region where bubble growth dominates. In literature, researchers also attempted to mechanistically model the bubble departure frequency in pool boiling. The first step is to divide the reciprocal of departure frequency, i.e., one nucleation cycle, into two parts. In one nucleation cycle, there exists a waiting time, i.e., t_{W}, defined as the period from the moment of the former bubble departs to the moment of the current bubble nucleates, and a growth time, t_{G}, which is defined as the period from the moment of bubble appearance until the moment of bubble departure. Han and Griffith [6] proposed that the waiting time from the criterion of bubble nucleation and potential flow theory. While for bubble growth time, Hatton and Hall [7] offered a model by taking account of the bubble departure diameter and thermally-controlled bubble growth rate.

Recently, several investigations have been performed on the bubble departure frequency in convective boiling. Thorncroft et al. [8] reported bubble waiting time and departure diameter of electronic fluid FC-87 under vertical up-flow and down-flow boiling in a 12.7 mm ID square duct with one side heated by a 30 cm-length nichrome strip. The data were captured at mass flux varying from 190 to 666 kg/m^2 s, heat flux changing from 1.32 to 14.6 kW/m^2, and bulk subcooling ranging from 1.0 to 5.0 °C. Basu et al. [9,10] measured waiting time, growth time, departure size and frequency in an upward-vertical subcooled flow boiling facility using water as working fluid. The experimental data were taken at pressure of 0.103 MPa, mass fluxes from 235 to 684 kg/m^2 s, and heat flux changing from 160 to 963 kW/m^2. The test section is almost square in cross section with 16.33 cm^2 in flow area. The heated surface is a 3.175 cm × 30.5 cm flat copper plate with contact angle varying from 30° to 90°. The waiting time was correlated against wall superheat, while the growth time was correlated with bulk subcooling, bubble departure diameter, and superheated liquid layer. It shall be noted that the correlation is proposed for limited test scope and heated surface. Podowski et al. [11] proposed mechanistic models for both waiting time and growth time. However, the model has not been directly validated.

In summary, few works have been attempted to examine the existing correlations and models of bubble departure frequency in forced convective subcooled boiling conditions, where both experimental and analytical works are deficient. Hence the purpose of this paper is to study the bubble departure frequency in vertical upward forced-convective subcooling boiling flow. The investigation will be carried out by performing experimental test, and analyzing the existing experimental data and model/correlation in literature.