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Measurement of the maximum bubble size distribution in water subcooled flow boiling at low pressure

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ABSTRACT

Bubbles of various sizes are produced at nucleation sites on a heated surface in subcooled flow boiling. However, although many correlations have been developed so far for the mean bubble size, systematic information is scarce for the bubble size distribution. In the present work, bubble nucleation process in water subcooled flow boiling at low pressure was observed in detail using an ITO-deposited transparent glass plate as the heated surface. It was found that bubbles of different sizes are produced at each nucleation site and moreover the mean bubble size differs considerably between different sites. It was hence considered that the reliability of subcooled flow boiling analysis codes can be improved if the effect of the bubble size distribution is included. In view of this, quantitative investigation was done for the bubble size distribution. It was shown that under the experimental conditions tested in this work, the distribution of the maximum size of individual bubbles produced at nucleation sites are fitted well with the gamma distribution. The dependences of the measured maximum bubble size distribution on important dimensionless numbers were explored to develop new correlations for the bubble size distribution.

1. Introduction

Numerical analysis of subcooled flow boiling is of considerable importance in the field of nuclear engineering since the void fraction in the subcooled boiling region in the light water reactor core influences the core flow rate, the onset of two-phase flow instability, the fuel burnup, and the consequence of the reactivity-initiated accident (RIA) [1]. To develop a mechanistic model of the subcooled flow boiling, it is required to accurately evaluate the fundamental quantities such as the bubble size, the bubble release frequency, and the number of active nucleation sites on the heated surface. Thus, a number of correlations have been developed so far for these quantities [2–7].

Among these fundamental parameters, the bubble size is particularly important since it directly affects the transport phenomena between the gas and liquid phases. In consequence, many photographic studies have been conducted to measure the bubble size in subcooled flow boiling. Ünal performed the experiments under wide range of experimental conditions to investigate the bubble diameter and the bubble-growth characteristics [8]. He postulated that spherical or ellipsoidal bubbles grow on a thin and hot liquid layer formed on the heated surface. Considering the heat transfer from the heated surface to the bubbles through this liquid layer, the following correlation was developed for the maximum bubble size d_1 in subcooled flow boiling.

$$d_1 = 2.42 \times 10^{-5} P^{0.709} \frac{a}{\sqrt{b\varphi}} \tag{1}$$

where P is the pressure, and a, b and φ are calculated by

$$a = \frac{[q_w - h_l \Delta T_{sub}]^{1/3} \lambda_l}{2C^{1/3} H_{lg} \sqrt{\pi \eta_l}} \sqrt{\frac{\lambda_w \rho_w c_w}{\lambda_l \rho_l c_{pl}}} \tag{2}$$

$$C = \frac{H_{lg} \mu_l [c_{pl}/(0.013 H_{lg} Pr^{1.7})]^3}{\sqrt{\sigma/(g(\rho_l - \rho_g))}} \tag{3}$$

$$b = \frac{\Delta T_{sub}}{2(1 - \rho_g/\rho_l)} \tag{4}$$

$$\varphi = \begin{cases} (u_l/0.61)^{0.47} & \text{for } u_l \geqslant 0.61 \text{ m/s} \\ 1.0 & \text{for } u_l < 0.61 \text{ m/s} \end{cases} \tag{5}$$

Prodanovic et al. [9] performed the experiments using a vertical annular channel as the test section to develop the correlations for the maximum bubble diameter and the bubble ejection diameter. They suggested that the bubble size and the bubble growth time

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Nomenclature

A_{bp}	the bubble projected area (m^2)
A_{win}	area of the measurement window (m^2)
Bo	boiling number
c_p	specific heat at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$)
D_h	hydraulic diameter (m)
d	bubble size (m)
d_{30}	volume average diameter (m)
d_{ave}	arithmetic mean of d_{max} (m)
$d_{ave,i}$	d_{ave} at i-th nucleation site (m)
d_{ejc}	bubble ejection diameter (m)
d_{lift}	bubble lift-off diameter (m)
d_{max}	maximum bubble diameter (m)
d_1	maximum bubble size in subcooled flow boiling (m)
E_a	radiation emitted from the media a ($W \cdot m^{-2}$)
E_c	total energy measured by the IR camera ($W \cdot m^{-2}$)
ER	mean relative error (%)
$F_{3.6\text{–}4.9\mu m}$	fraction of radiation energy within the wavelength interval 3.6–4.9 μm
G	mass flux ($kg \cdot m^{-2} \cdot s^{-1}$)
G_s	dimensionless liquid velocity gradient
g	gravitational acceleration ($kg \cdot m/s^2$)
H_{lg}	latent heat of vaporization ($J \cdot kg^{-1}$)
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
Ja	Jakob number
Ja_e	effective Jakob number
N_a	active nucleation site density ($sites \cdot cm^{-2}$)
N_{case}	the total number of experimental cases
N_s	the number of nucleation sites
n_b	the number of bubbles
P	pressure (Pa)
Pr	Prandtl number
q_w	heat flux ($W \cdot m^{-2}$)
Re	Reynolds number
T	temperature (K)
t_{meas}	measurement time (s)
x_{eq}	thermal-equilibrium quality

Greek symbols

α	shape parameter of gamma distribution
β	scale parameter of gamma distribution (m)
Γ	gamma function
γ	incomplete gamma function
γ_b	vaporization rate ($kg \cdot s^{-1}$)
ΔT_w	wall superheat (K)
ΔT_{sub}	liquid subcooling (K)
δ	superheated liquid layer thickness (m)
ε	emissivity
η	thermal diffusivity ($m^2 \cdot s^{-1}$)
Θ	dimensionless subcooling
θ	contact angle (°)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
μ	viscosity ($Pa \cdot s$)
ν	kinetic viscosity (m^2/s)
ρ	density ($kg \cdot m^{-3}$)
$\rho_{a\text{-}b}$	reflectivity at the interface between a and b
σ	surface tension (N/m)
σ_{SB}	Stefan-Boltzmann constant ($W \cdot m^{-2} \cdot K^{-4}$)
σ_{all}	standard deviation of d_{max} (m)
σ_i	standard deviation of d_{max} at i-th nucleation site (m)
σ_v	standard deviation of the bubble volume (m^3)
$\bar{\sigma}_1^*$	average of σ_i scaled by $d_{ave,i}$
$\bar{\sigma}_2^*$	standard deviation of d_{max} scaled by d_{ave}
$\tau_{a\text{-}b}$	transmissivity between a and b

Subscripts

app	apparent
b	bubble
c	convection
g	gas phase
gamma	gamma distribution
ITO	Indium-Tin-Oxide film
∞	background
l	liquid phase
NB	nucleate boiling
sat	saturation
sap	sapphire
v	volume
w	wall

are correlated well using the Jakob number Ja, the dimensionless liquid subcooling Θ, the boiling number Bo and the density ratio. The correlation for the bubble ejection diameter d_{ejc} is given by

$$d_{ejc}^{+} = 440.98 Ja^{-0.708} \Theta^{-1.112} \left(\frac{\rho_l}{\rho_g} \right)^{1.747} Bo^{0.124} \tag{6}$$

where the dimensionless bubble ejection diameter d_{ejc}^{+} and the dimensionless liquid subcooling Θ are defined by

$$d_{ejc}^{+} = \frac{d_{ejc}\sigma}{\rho_l \eta_l^2} \tag{7}$$

$$\Theta = \frac{\Delta T_w + \Delta T_{sub}}{\Delta T_w} \tag{8}$$

Situ et al. [10] also performed the experiments of subcooled flow boiling using a vertical annular channel. Considering various forces acting on the bubbles attached to the heated surface, the following correlation for the bubble lift-off diameter d_{lift} was developed.

$$d_{lift} = \frac{\sqrt{352/3}}{\pi} \frac{\nu_l}{u_r \sqrt{C_l}} b^2 Ja_e^2 Pr_l^{-1} \tag{9}$$

where Ja_e is the effective Jakob number, u_r is the relative velocity between the gas and liquid phases, and C_l is calculated by

$$C_l = 3.877 G_s^{1/2} \left(Re_b^{-2} + 0.014 G_s^2 \right)^{1/4} \tag{10}$$

where G_s is the dimensionless liquid velocity gradient and Re_b is the bubble Reynolds number. Chu et al. [11] tested the predictive performances of the above-referenced bubble size models against various experimental datasets of the bubble lift-off diameter. In conclusion, it was reported that Ünal's correlation showed the best agreement with the data if some modification was done for the wall superheat correlation; the mean predictive error for all the experimental data tested was 31.4% although the correlation was originally developed for the maximum bubble diameter.

As discussed above, several correlations have been developed so far for the mean bubble size in subcooled flow boiling. It should however be noted that in subcooled flow boiling, numerous nucleation sites are activated and the bubbles of various sizes are produced [12]. In consequence, significant error may arise in predicting the void fraction if the distribution of the bubble size is neglected. For horizontal flow configuration, Klausner et al. [13] and Zeng et al. [14] measured the distribution of the bubble departure diameter. Klausner et al. [15] then proposed a