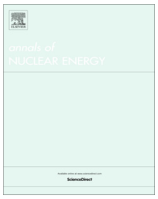
Annals of Nuclear Energy 111 (2018) 303–310

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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



A study on the lift-off diameter of bubbles generated on horizontal tube

Sung Uk Ryu [a,*], Seok Kim [a], Dong-Jin Euh [a,b]

[a] Thermal Hydraulics Safety Research Division, Korea Atomic Energy Research Institute, 111 Daedeok-daero989beongil, Yuseong-gu, Daejeon 305-353, Republic of Korea
[b] University of Science and Technology, Gajungro 217, Yuseong-Gu, Daejeon 305-350, Republic of Korea

ARTICLE INFO

Article history:
Received 27 May 2016
Received in revised form 6 December 2016
Accepted 25 August 2017

Keywords:
Bubble lift-off diameter
Horizontal tube
Force balance
Flow visualization
Nucleate

ABSTRACT

In this study, experiments and a theoretical analysis on the lift-off diameter of bubbles generated on a horizontal tube were conducted. A force balance analysis in the direction normal to the heated surface at the moment of the bubble lift-off was performed to develop the model. According to the developed model, the bubble lift-off diameter strongly depends on the azimuthal position of the horizontal tube, the relative velocity between a bubble and the surrounding liquid, and the properties of the bubble and liquid. To validate the prediction performance of the proposed model, the dynamics of the bubble growth and sliding process was visualized using a high-speed digital video camera. The proposed model agrees well with the experimental data within an averaged relative deviation of 19.6%.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

The boiling phenomena on the outside a horizontal tube is widely seen in many applications. PAFS (passive auxiliary feedwater system) adopted in the APR+ (Advanced Power Reactor Plus) of Korea is one of such applications. When PAFS is activated with an actuation signal, steam from the steam generator passes through heat exchanger tubes submerged in a water tank of the PAFS. (Song, 2010; Cheon, 2010; Kim et al., 2013) Outside these heat exchanger tubes, bubble growth and lift-off phenomena appeared. According to the previous studies for the PAFS performance evaluation, the model for the bubble size plays a significant role on the overall behavior or the thermal mixing and heat transfer rate in the heat exchanger.

The heat transfer model for pool boiling on curved surfaces, such as a horizontal tube, is different from the model on horizontal flat surfaces because the sliding bubble mechanism plays an important role. According to Sateesh et al. (2005), the model for boiling on non-horizontal surfaces should consider microlayer evaporation and transient conduction owing to the sliding of the bubbles, as shown in Eq. (1).

$$q_{tot} = (q_{me} + q_{tc})x_{st} + (q_{mes} + q_{tcs})x_s + q_{nc}, \qquad (1)$$

where q_{tot} is the total heat flux, q_{me} and q_{tc} are the microlayer evaporation and transient conduction heat flux from a stationary bubble, q_{mes} and q_{tcs} are the microlayer evaporation and transient conduction heat flux owing to the sliding bubbles, q_{nc} is the natural convection heat flux, and x_{st} and x_{s} are constants determined by the area ratio parameter R defined as the ratio of area available per nucleation site to the projected area of the bubble at departure.

In a model of wall heat flux partitioning, the microlayer evaporation from sliding bubbles q_{mes} can be defined by four sub-models, i.e., the bubble departure diameter d_{d}, bubble lift-off diameter d_{l}, bubble departure frequency f, and active nucleation site density n_{b}, as shown in Eq. (2)

$$q_{\mathrm{mes}} = \frac{1}{6}\pi(d_{\mathrm{l}}^3 - d_{\mathrm{d}}^3)\rho_{\mathrm{g}} h_{\mathrm{fg}} n_{\mathrm{b}} f, \qquad (2)$$

where ρ_{g} is the density of the vapor, and h_{fg} is the specific latent heat.

Among these sub-models, this paper focuses on the bubble lift-off diameter. Situ et al. (2005) stated that the bubble lift-off diameter, which is the bubble size when a bubble detaches from the heater surface, can be different from the bubble departure size, which is the bubble size when a bubble detaches from the nucleation site.

There have been a number of works performed on the departure and lift-off diameters of the bubbles generated on non-horizontal surfaces: Schömann et al. (1994), Luke and Gorenflo (2000), Luke (2004) (study on a horizontal tube) Unal (1976), Sateesh et al. (2005), Prodanovic et al. (2002), Situ et al. (2005), Cho et al. (2011) and Chu et al. (2011) (study on a vertical surface). Table 1

---

* Corresponding author.
E-mail address: rsu@kaeri.re.kr (S.U. Ryu).

http://dx.doi.org/10.1016/j.anucene.2017.08.056
0306-4549/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

Symbols

b_l	Constant in Eq. (18)
C_{sl}	Shear Lift Coefficient
C_r	Relative Velocity Coefficient
C_s	Empirical Coefficient in Eq. (17)
c_p	Specific Heat (J/kg K)
D_{lo}^*	Dimensionless Bubble Lift-off Diameter in Eq. (10)
d	Diameter of Bubble (m)
F	Force (N)
f	Frequency of Bubble Departure (s^{-1})
G_{bl}	Bubble Growth Constant
G_s	Dimensionless Fluid Velocity Gradient
g	Acceleration due to Gravity (m/s^2)
h_{fg}	Specific Latent Heat of Vaporization (J/kg)
Ja	Jacob Number
k	Conductivity (W/m K)
Lo	Lift-off Number in Eq. (12)
n_b	Nucleation Site Density ($1/m^2$)
p^*	Reduced Pressure (p_s/p_c)
p_c	Critical Pressure (Pa)
p_s	Saturation Pressure (Pa)
P_r	Prandtl Number
q	Heat Flux (W/m^2)
r	Radius (m)
$\dot{r_b}$	Derivative of Bubble Radius with Respect to Time (m/s)
$\ddot{r_b}$	Second Derivative of Bubble Radius with Respect to Time (m/s^2)
r^*	Non-Dimensional Radius
t	Time (s)
u_f	Liquid Velocity (m/s)
u_r	Relative Velocity between Bubble Center of Mass and the Liquid Phase
V_b	Bubble Volume (m^3)
x	Constants Decided by Area Ratio Parameter

Greek symbols

α	Thermal Diffusivity (m^2/s)
υ	Kinematic Viscosity (m^2/s)
ρ	Density (kg/m^3)
σ	Surface Tension (N/m)
θ_a, θ_r, θ_m	Advancing, Receding, and Mean Contact Angles
φ	Azimuthal Angle (°)

Subscript

B	Buoyancy
b	Bubble
D	Drag
du	Unsteady Drag
e	Effective
f	Fluid
g	Vapor
l	Lift-off
m	Mean
me	Microlayer evaporation (due to stationary bubble)
mes	Microlayer evaporation due to sliding bubble
min	Minimum
nc	Natural Convection
s	Sliding
sl	Sheer lift
st	Stationary
tc	Transient Conduction (due to Stationary Bubble)
tot	Total
tcs	Transient Conduction due to Sliding Bubble

Table 1
Previous studies on the bubble departure and lift-off diameter models in non-horizontal surfaces.

Reference	Correlation	
Bubble departure diameter models in horizontal tube		
Schömann et al. (1994)	$d_d = -2.38 \cdot 10^{-5} + 4.51 \cdot 10^{-5} \cdot P^{*-1} - 2.52 \cdot 10^{-5} \cdot P*-2$	(3)
	$d_d = -8.05 \cdot 10^{-6} + 6.67 \cdot 10^{-5} \cdot P^{*-1} - 5.53 \cdot 10^{-7} \cdot P^{*-2}$	(4)
Luke and Gorenflo (2000)	$d_d = d_{d,\ min}(P^*) + a_2(P^*) \cdot \varphi^2$ where $d_{d,\ min}(P^*) = a \cdot P^{*b}$ and $a_2(P^*) = c \cdot 10^{-5} \cdot P^{*d}$	(5)
Luke (2004)	$d_d = Z \cdot P^{*-b} \sqrt{\frac{2\sigma}{g(\rho_f - \rho_g)(1 + C\ con\varphi)}}$	(6)
Bubble departure and lift-off diameter models in vertical surface		
Unal (1976)	$D_{max} = 2.42 \times 10^{-3} P^{0.709} \frac{a}{\sqrt{b\alpha}}$, where $a = \frac{\Delta T_{sat} k_f \gamma}{2\rho_g h_{fg} (\pi\alpha_f)^{\frac{1}{2}}}$, $b = \frac{\Delta T_{sub}}{2\left(1 - \frac{\rho_g}{\rho_f}\right)}$, $\gamma = \left(\frac{k_s \rho_s c_s}{k_f \rho_f c_{p,f}}\right)^{1/2}$, $\alpha = \max\left(\frac{U_{bulk}}{0.61}, 1\right)^{0.47}$	(7)
Sateesh et al. (2005)	$d_d = \sqrt{\frac{12N}{Mg(\rho_f - \rho_g)}}$ where $M = \frac{(1 + \cos\theta_m)^2 (2 - \cos\theta_m)}{\pi - \theta_m + \sin\theta_m \cos\theta_m}$, $N = \frac{\sin\theta_m (1 - \cos\theta_m)}{\pi - \theta_m + \sin\theta_m \cos\theta_m}$	(8)
Prodanovic et al. (2002)	$D_{lo}^+ = 440.98 Ja^{-0.708} \vartheta^{-1.112} (\frac{\rho_f}{\rho_g})^{1.747} Bo^{0.124}$, where $D_{lo}^+ = \frac{D_{lo}\sigma}{\rho_f \alpha_f^2}$, $\vartheta = \frac{T_w - T_{bulk}}{\Delta T_{sat}}$, $Bo = \frac{q''}{Gh_{fg}}$	(9)
Situ et al. (2005)	$D_{lo}^* = \frac{4\sqrt{22/3}b^2}{\pi} Ja_e^2 Pr_f^{-1}$	(10)
Cho et al. (2011)	$d_d = 2\left(\frac{3(2\sin\theta_m)\sigma \frac{\theta_d}{\pi^2 - \theta_d^2}[\sin\theta_a + \sin\theta_r]}{g\Delta\rho}\right)^{0.5}$	(11)
	$d_l = d_l(1 + 2.073 Lo^{-0.505})$, where $Lo = C_{sl}\left(\frac{r_d u_r}{G_{bl}^2}\right)^2$	(12)
Chu et al. (2011)	$D_{lo}^+ = 12788.5 Ja^{-0.28} \vartheta^{-1.07} \left(\frac{\rho_f}{\rho_g}\right)^{1.36} Bo^{0.35}$	(13)

Download English Version:

https://daneshyari.com/en/article/5474804

Download Persian Version:

https://daneshyari.com/article/5474804

Daneshyari.com