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Force Balance Analysis for Sliding Bubble Velocity Prediction on the Lower Part of a Horizontal Tube Heater

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1. Introduction

A mechanistic boiling model can reflect the principle of boiling bubble and the actual phenomenon. In the heat partitioning model [1], the boiling heat transfer can be directly evaluated through the bubble-related variables such as the bubble volume and velocity. For these advantages, it is now widely used for prediction of boiling heat transfer.

A force balance model have proposed by Klausner et al. [2] that can calculate the force acting on a bubble. The model has been developed for horizontal upward heating surface and has been expanded by many researchers since the first proposal.

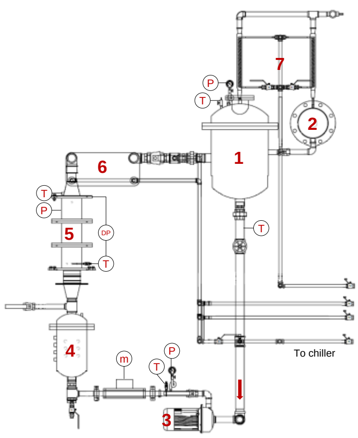
The phenomena of interest in the present study are the boiling heat transfer on a horizontal tube outer surface. For example, APR+, advanced GEN-III reactor developed by KHNP, is equipped with a Passive Auxiliary Feedwater System PAFS [3]. PAFS incorporates a large water tank in which the heat exchanger of a bundle of U-tubes is submerged and the heat exchanger is connected to the steam generator secondary side. The heat exchanger of the PAFS, has a lower curved structure. In this lower curved surface, bubbles generated as the boiling occurs, and the characteristics of the bubble behavior, directly affecting the boiling heat transfer amount. However, the previous heat partitioning model has been focused mainly on the planar surface condition.

Therefore, in this study, we conducted experiments on the horizontal tube outside and measured the velocity, the frequency, and the volume of the vapor bubble which are major parameters of the heat partitioning models. In order to accurately measure the bubble parameters, a special heater was fabricated and the 3-dimentional visualization method was newly developed. In addition, the force balance model was derived to the horizontal tube outside and the predicted bubble velocity based on the model was compared with the experimental data.

2. Experiment

In this study, the volume, the frequency, and velocity of bubbles were measured. The experimental loop of this study is shown in Fig. 1 and the experiments were performed at atmospheric pressure, saturation temperature, 26, 30kW/m² of wall heat fluxes (q'') and 0.015 ~ 0.028m/s of flow rates ($\dot{m}$). Nucleation sites (θ_0) were located at 23~45 degrees from the bottom of the horizontal tube. The non-condensable gas was removed through de-aeration more than 2 hours before the experiment. The test section is a 0.11 m × 0.11 m transparent rectangular duct and made of polycarbonate so that the bubble can be photographed through visualization.

Since conventional cartridge heater cannot generate a single bubble due to the interference of other bubbles, a flexible heater was fabricated facilitating visualization. The heater has a horizontal tube shape with a diameter of 50 mm and a heating width of 3 mm (Fig.2). On the surface of the heater, a small dent with a diameter of approximately 100 μm was made to create an artificial cavity so that bubbles were generated at this point. The images were acquired at 1,000 fps using shadowgraphy using a high-speed camera (Phantom V711-16G-M). The acquired images were reconstructed by binarizing through the image-processing. The experimental procedure is described in detail in Kim et al. [4]



1. Main water storage tank
2. Auxiliary water storage tank
3. Water supply pump
4. Preheater
5. Test section
6. Heat exchanger
7. Reflux condenser

T. Thermocouple
P. Pressure transmitter
dP. Differential pressure transmitter
m. Mass flow meter

Fig. 1 Schematic of experiment loop

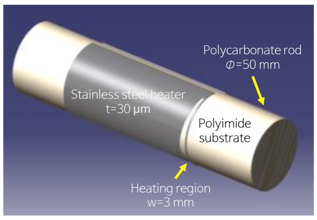


Fig. 2 Schematic of FPCB heater

2.1 Force Balance Model

Klasuner's force balance model was modified to analyze the bubble velocity obtained by the experiment on the horizontal tube condition. In this paper, the force acting in the tube angular direction (θ-direction) is analyzed.

The main forces acting in the θ-direction are buoyancy, quasi-steady drag, surface tension, and added mass (Fig.3, Table 1). The equation for calculating the total forces acting on the bubble is as follows.

$$\sum F_\theta = F_{b\theta} + F_{qs\theta} + F_{s\theta} + F_{am\theta} \qquad (1)$$

The bubble cross-sectional area A was calculated assuming that the shape of the bubble was a sphere to simplify the analysis. And the drag coefficient, Cd, corresponds to the Newton's law region and is used as the commonly used value of 0.44 [5].

2.2 Modeling of Liquid Velocity

As bubbles generated continuously, the velocity of the surrounding fluid is accelerated by the leading bubble and the effect needs to be reflected in the local liquid velocity (Fig.4.). If the distance between two consecutive bubbles is close, they make contact with each other. In this condition, it was assumed that the local liquid velocity is the average of the bubble velocity and liquid bulk velocity. On the other hands, if the bubble distance is far from each other to some extent, the local liquid velocity of the surrounding fluid would be equal to the liquid bulk velocity. In the present work, the distance that the acceleration by a leading bubble becomes negligible was selected to four times of the bubble radius. Then, the local bubble velocity can be evaluated by the linear interpolation between two bounding values with respect to the normalized bubble distance. The resulting equation is as below.

when $L_{bubble} = 0$,

$$U_l = \frac{U_{bulk} + U_b}{2} = U_{l,0} \qquad (6)$$

when $0 < L_{bubble} < D_b$,

$$U_l = (1-\omega) \cdot U_{l,0} + \omega \cdot U_b, \qquad (7)$$

$$\omega = L_{bubble}/D_b$$

when $L_{bubble} \geq D_b$, (8)

$$U_l = U_{bulk},$$

Table I The force acting in the θ direction

Force	Equation
Buoyancy force	$F_{b\theta} = (\rho_l - \rho_v) g V_b \sin\theta_b$ (2)
Quasi-steady drag force	$F_{qs\theta} = -\frac{1}{2} C_D \rho_l (U_b - U_l)^2 A$ (3)
Surface tension force	$F_{s\theta} = -\int_0^\pi d_w \sigma \cos\gamma \cos\phi \, d\phi$ $\sim d_w \sigma \frac{\pi(\alpha-\beta)}{\pi^2 - (\alpha-\beta)^2} [\sin\alpha + \sin\beta]$ (4)
Added mass force	$F_{am\theta} = -\frac{1}{2} \rho_l V_b \left(2U_r \omega_\theta + R \frac{d\omega_\theta}{dt} \right)$ (5)

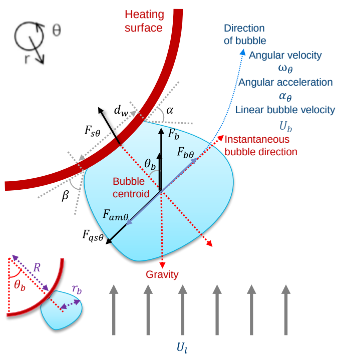


Fig. 3 The force acting on the bubble in the θ direction

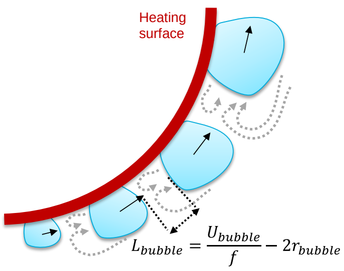


Fig. 4 Increase of local liquid velocity by continuous bubbles

2.3 Prediction of Bubble Velocity

The bubble velocity was predicted using the force balance analysis in the direction of θ. Figures 5~8 show a comparison between the experimental bubble velocity and the calculated bubble velocity. Experimental results show that bubbles are accelerated at the beginning of the generation. The increasing tendency of the velocity gradually decreases with time but does not reach the terminal velocity. This is because the bubble lifts off from the heater before it reaches the terminal velocity. The trend was reasonably reproduced using the force balance model and it was confirmed that the model predicts the tendency of increasing bubble velocity in the actual experiment according to the tube position. In the experiment, three cases (1. q"=30kW/m², $\dot{m}$ =0.26kg/s, θ_0 =23°), (2. q"=30kW/m², $\dot{m}$ =0.32kg/s, θ_0 =23°), (3. q"=30kW/m², $\dot{m}$ =0.32kg/s, θ_0 =45°) with the highest heat flux showed relatively larger bubble velocities than the other cases. This can be explained with the leading bubble effect that was described in the previous section. Fig. 9 shows the experimental bubble frequency. Higher bubble frequency appears with higher heat flux and it reduces the distance between two consecutive bubbles. Then, the subsequent bubble is accelerated and eventually, higher velocity is resulted in. By introducing local liquid velocity model, this tendency can be reproduced and the force balance model enables to capture the experimental data. As shown in Fig. 10, the model predicts the bubble velocity within the error of about -7 to +15%.

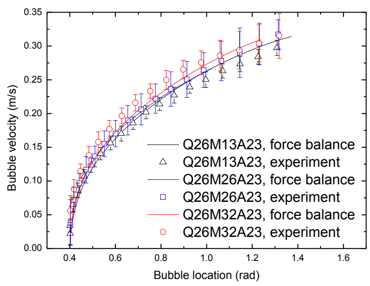


Fig. 5 Bubble velocity according to the position of the bubble (θ_0 =23°, q"=26kW/m²)

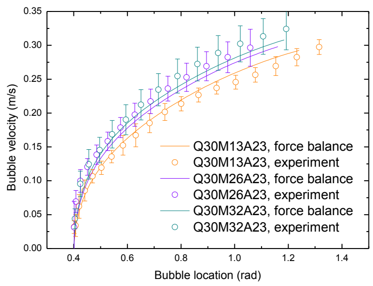


Fig. 6 Bubble velocity according to the position of the bubble (θ_0 =23°, q"=30kW/m²)

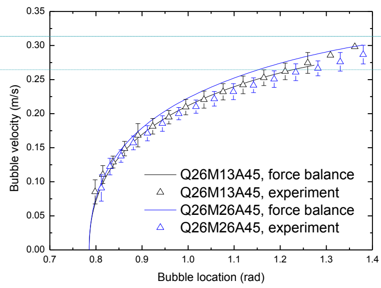


Fig. 7 Bubble velocity according to the position of the bubble (θ_0 =45°, q"=26kW/m²)

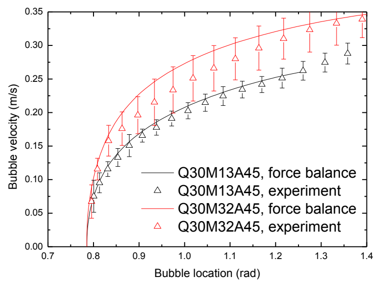


Fig. 8 Bubble velocity according to the position of the bubble (θ_0 =45°, q"=30kW/m²)

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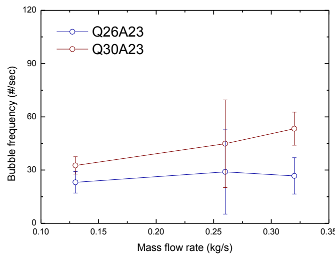
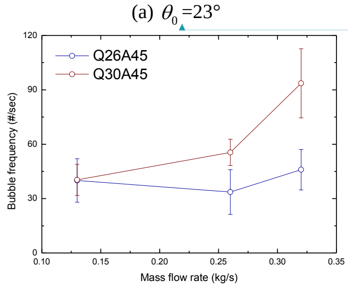


(a) θ_0=23°



(b) θ_0=45°

Fig. 9 Bubble frequency by inlet mass flow rate

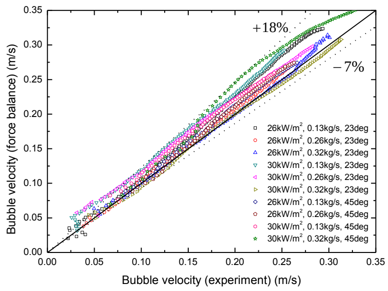


Fig. 10 Estimation of calculated bubble velocity

CONCLUSION

In this study, the volume and velocity of bubbles were measured by directly generated vapor bubbles under the horizontal tube outside. And Klausner's force balance model was modified to analyze the bubble parameters obtained by the experiment on the horizontal tube condition. The model predicts the bubble velocity within the error of about under -7% ~ +15%.

NOMENCLATURE

Term	Description	Units
A	cross section of a bubble	m^2
C_D	coefficient of drag	-
d_w	contact diameter	m
F	force	N
R	distance between centroids of bubble and tube	m
U_b	velocity of bubble centroid	m/s
U_{bulk}	bulk liquid velocity	m/s
U_l	local liquid velocity around a bubble	m/s
V_b	volume of a bubble	m^3
α	upstream contact angle	deg
β	downstream contact angle	deg
θ_0	angle of the nucleation site	deg
θ_b	angle of the surface normal to gravitational direction	deg
ρ	density	kg/m^3
σ	surface tension	N/m
Subscript		
l	Liquid	
v	Vapor	
b	Bubble	

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변경된 필드 코드

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