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

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1. Introduction

The heat partitioning model [1] is a boiling heat transfer model mechanistically reflecting the principle of bubble generation and local heat transfer induced by it. In this model, the boiling heat transfer can be directly evaluated through the bubble-related variables such as the volume and velocity of bubbles. Because of these advantages, it is now widely used to predict boiling heat transfer including CFD.

Klausner et al. [2] have proposed a force balance model that can calculate the force acting on the bubble in order to accurately predict the behavior of the bubble and obtain the bubble main parameters. This has been developed for horizontal surface conditions and has been expanded by many researchers since then.

Accurate prediction of boiling heat transfer is important for nuclear reactor safety analysis. As new concepts of passive safety systems have been introduced, a boiling heat transfer analysis for particular configuration of the heating surface is required if they have not been sufficiently investigated in previous boiling heat transfer research.

The heat exchanger of Passive Auxiliary Feedwater System (PAFS), core catcher, IVR-ERVC, etc. which are passive safety systems applied to the advanced light water reactors, have a downward facing heating surface. On the downward facing heating surfaces, bubbles shows sliding motion directly affecting the heat transfer. However, the extant heat partitioning model has been studied mainly on the upward heating surface and not considered the sliding effect.

Therefore, in this study, we conducted experiments with the horizontal tube heater and measured the major parameters of the bubble, such as the speed and volume. The experiment used a special heater in order to measure the bubble parameters accurately and photographed the behaviors of single boiling bubbles. Based on the experimental observation, the force balance model was derived adequate for the lower part of the horizontal tube condition. Using the model, the velocity of the bubble was predicted and compared with the experiment.

2. Experiment

In this study, the main parameters such as the volume and velocity of bubbles were measured and analyzed by directly generating vapor bubbles under the horizontal tube condition. The experimental loop of this study is shown in Fig. 1 and was performed at atmospheric pressure, saturation temperature, and flow rate of 0.015 ~ 0.028m/s. The non-condensable gas was removed through de-aeration more than 2 hours before the experiment. The test section is an 11 cm × 11 cm transparent rectangular test section made of polycarbonate, and the bubble can be photographed through visualization.

In addition, since conventional cartridge heater cannot shoot single bubble properly due to interference of bubbles, 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), and a schematic view of the stacking of the heater is shown in Fig.3. On the surface of the heater, small dent with a diameter of approximately 100 μm were made to create an artificial cavity so that bubbles were generated at this location. The images were acquired at 1000 fps using shadow-graphy using two high-speed cameras (IDT Motionpro Y4 and Phantom V711-16G-M). The acquired image was reconstructed by binarizing the image through the image-processing process. The experimental procedre are described in detail in Kim et al. [3].

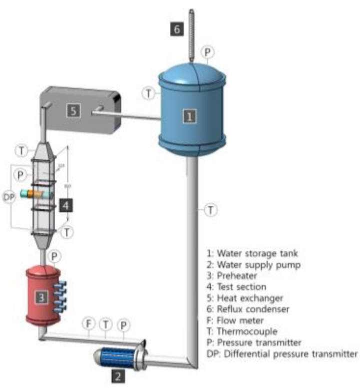

Fig. 1 Schematic of experiment loop [3]

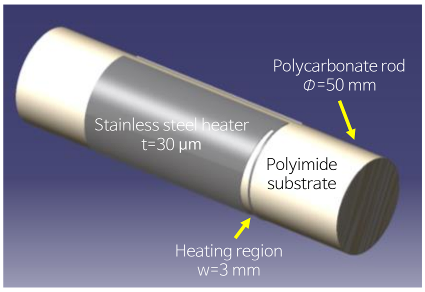

Fig. 2 Schematic of FPCB heater

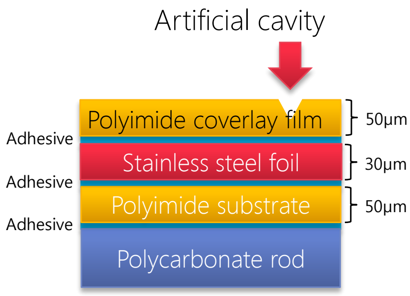

Fig. 3 Schematic of the heater layer

3. Force Balance Analysis

3.1 Force Balance for θ-direction

To analyze the bubbles obtained by this experiment, Klasuner 's force balance model was modified to fit the horizontal tube condition. In this paper, the force acting in the θ direction is analyzed and compared with the experimental results. The force induction in the r direction (outward normal direction) and its analysis results are listed in Kim et al. [3].

The forces acting in the θ direction are buoyancy, quasi-steady drag, dynamic pressure, and surface tension (Fig.4., Table 1) The equation for calculating the total forces acting on the bubble is as follows

$$F_{tot,\theta} = \sum F_\theta = F_{b\theta} + F_{qs\theta} + F_{dp\theta} + F_{s\theta} \, ,$$

Considering the virtual mass and surroundings effect, the acceleration of the bubble is expressed as follows

$$F_{tot,\theta} = F_{v,\theta} + F_{l,\theta}, \;\; F = ma$$
$$F_{tot,\theta} = ma = (m_v + m_l)a = (\rho_v + \rho_l)V_b a$$
$$= (\rho_v + \rho_l)V_b (R + r_b)\alpha_\theta$$

As a result, the bubble velocity and position after a single time step were updated as follows.

$$v_b = v_{b0} + a\Delta t \qquad \text{(updated bubble velocity)}$$

$$\theta_b = \theta_{b0} + \frac{v_{b0}}{R}\Delta t \qquad \text{(updated bubble location)}$$

The time step for the force balance analysis was set to 0.001 second for the same speed as the experiment, and the measured experimental values of the bubble volume was used for each time step. The bubble cross section is assumed to be spherical bubbles one. Since the bubble volume has crucial effect on the force balance analysis but extant models on the bubble growth rate could not capture the experimental data with acceptable accuracy, the measured bubble volume was directly applied in the analysis. The bubble resistance coefficient, Cd, corresponds to the Newton's law region and is used as the commonly used value of 0.44 [4]. The average values of the experimental and the contact angles of the constant part and the sewage part were approximated to 45 ° and 30 °, respectively, based on the visual observation result.

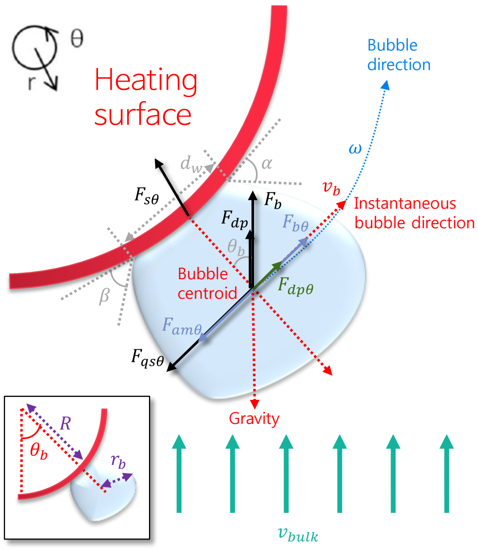

Fig. 4 The force acting on the bubble in the θ direction

Table 1 The force acting in the θ direction

Force	Equation
Buoyancy force	$F_{b\theta} = (\rho_l - \rho_v) g V_b \sin\theta_b$
Quasi-steady drag force	$F_{qs\theta} = -\frac{1}{2} C_D \rho_l (v_b - v_l)^2 A$
Dynamic pressure force	$F_{dp\theta} = \rho_l v_{bulk}{}^2 A \sin\theta_b$
Surface tension force	$F_{s\theta} = -\int_0^\pi d_w \sigma \cos\gamma \cos\phi d\phi$ $\sim d_w \sigma \frac{\pi(\alpha-\beta)}{\pi^2 - (\alpha-\beta)^2}[\sin\alpha + \sin\beta]$

Where,

ρ : density
V_b : volume of a bubble
m : mass
θ : angle of the surface normal to gravitational direction
C_D : coefficient of drag
A : cross section of a bubble
d_w : contact diameter
σ : surface tension
α : upstream contact angle
β : downstream contact angle
a : linear acceleration
α_θ : angular acceleration
v_l : local liquid velocity around a bubble
v_b : velocity of bubble centroid
v_{bulk} : bulk liquid velocity
ω : bubble angular velocity
R : distance between centroids of bubble and tube

3.2 Force balance analysis result

As a result of the force analysis, the magnitude of the force was found to be large in the order of buoyancy, quasi-steady drag, surface tension, and dynamic pressure in all cases. In Figs. 5 and 6 at q = 26 kW/m² and m=0.13 kg/s, the evaluations of each force are shown. From these results, it was confirmed that buoyancy and quasi-steady drag are the forces that have dominant influence on the bubble in the θ direction.

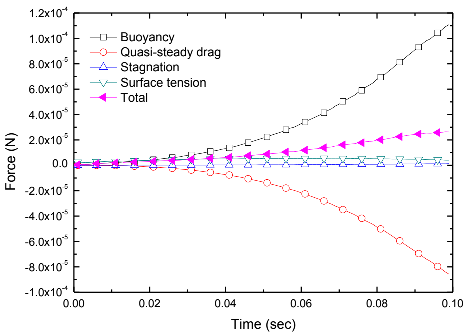

Fig. 5 Force analysis result (FPCB, A.C., q”=26kW/m², m=0.13kg/s, =23deg)

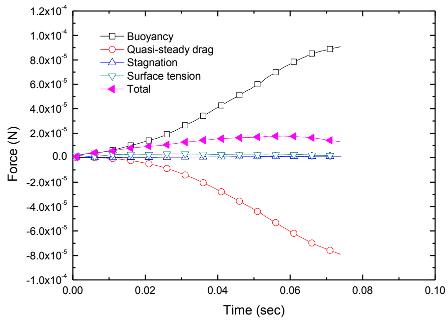

Fig. 6 Force analysis result (FPCB, A.C., q”=26kW/m², m=0.13kg/s, =45deg)

3.3 Prediction of bubble velocity values

Bubble velocity and bubble volume are two main parameters for predicting nucleate boiling heat transfer in a heat partitioning model. There have been attempts to model each of these two variables in many existing studies, but the phenomenon is complex and lacks of research to predict each variable independently. For example, the volume of a single bubble and the bubble frequency are related to each other, and it is difficult to reproduce the tendency when they are placed separately. Therefore, previous studies such as Chu et al. [5] have attempted to determine the tendency by multiplying these two variables. In this study, the bubble velocity was predicted using the volume and force balance model of the bubble obtained by the experiment.

In this study, the bubble velocity was predicted through the force analysis in the direction of θ described in the previous section. Figures 7-9 show the comparison between the experimental values of the bubble velocity and the force values obtained by θ force analysis. Experimental results show that bubbles are accelerated at the beginning of the generation and increasing tendency of the velocity gradually decreases with time but does not reach the terminal velocity. This is because the bubble volume is continuously increased by the heat transfer tube, and the terminal velocity that can be reached due to the nature of the horizontal tube structure where the wall inclination continuously increases with the position. It is also confirmed that the bubble velocity at the same position increases with the increase of the bulk flow rate. As a result of the calculation using the force balance model, it can be confirmed that the calculated value predicts the tendency of increasing the bubble velocity in the actual experiment according to the position. As shown in Fig. 10, the model predicts the bubble velocity within the error of about 15%. In case of 30kW/m² and 0.32kg/s case shown in Figs. 8 and 9, it can be seen that the speed increases faster than the case of the other cases regardless ofsa the generation angle. As a result, the error of bubble velocity appears to be large. This is because the effect of heat is not taken into account in the force balance model. Therefore, it is necessary to add the heat flux effect for proper use even in high heat. Also, as the bubble frequency increases under certain conditions and the effect of wake due to the leading bubble greatly affects the subsequent bubble, its effect should be reflected later.

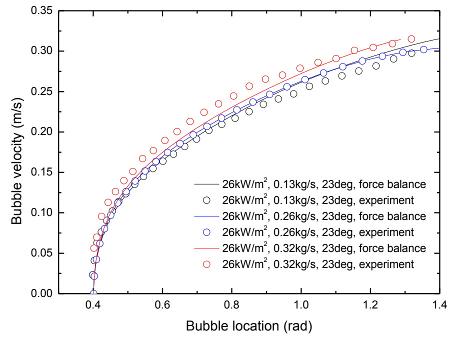

Fig. 7 Bubble velocity according to the position of the bubble (θ=23°, q”=26kW/m²)

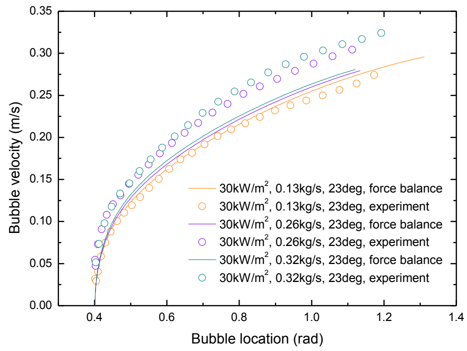

Fig. 8 Bubble velocity according to the position of the bubble (θ=23°, q”=30kW/m²)

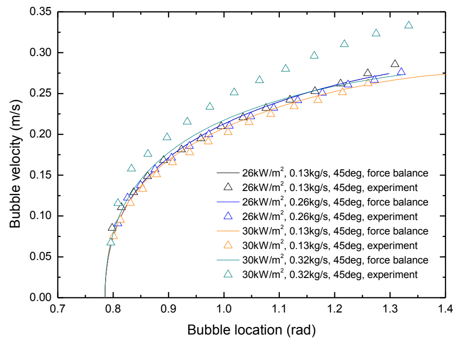

Fig. 9 Bubble velocity according to the position of the bubble (θ=45°)

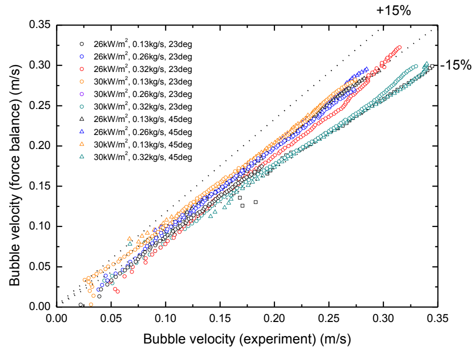

Fig. 10 Bubble velocity experimental value / calculated value comparison result

4. Conclusions

In this study, we conducted experiments on the conditions under the horizontal tube and measured the major parameters of the bubble, such as the speed and volume of the uncoated bubble. In order to accurately capture the bubble parameters, a special heater was made and the behavior of the single bubble was accurately photographed with the production of boiling bubbles. In addition, the force balance model was derived to fit the horizontal tube condition and the velocity of the bubble was predicted and compared with the experiment. With derived force balance model, the bubble velocity was predicted through the force analysis in the direction of θ and the model predicts the bubble velocity within the error of about 15%

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REFERENCES

[1] Kurul, N. and Podowski, M. Z., “Multidimensional effects in forced convection subcooled boiling”. Heat Transfer Conference, Vol 2, pp. 19-24. (1990)

[2] Klausner, J. F., “Vapor bubble departure in forced convection boiling”. Int.J.Heat Mass Transfer, Vol. 36(3), pp. 651-662, (1993)

[3] Y.N. Kim., et al. “Measurement of sliding bubble behavior on a horizontal heated tube using a stereoscopic image processing technique”, International Journal of Multiphase Flow, Vol. 94, pp. 156-172, (2017)

[4] R.H. Perry et al., “Perry's Chemical Engineers' Handbook”, McGraw-Hill, (1997)

[5] I.C. Chu et al., “Bubble Lift-off Diameter and Nucleation Frequency in Vertical Subcooled Boiling Flow”, Journal of Nuclear Science and Technology, Vol. 48, No. 6, p. 936–949 (2011)