Numerical modeling of bubble sliding and merge for heat flux partitioning model on horizontal tube

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1. Introduction

The mechanistic boiling model [1] can reflect the principle of the boiling and the actual phenomenon. To evaluate heat transfer, the model needs the bubble-related sub-models such as bubble velocity, bubble growth, bubble generation frequency, and bubble merger. If accurate sub-models are reflected in the model, it is possible to predict boiling heat transfer based on actual phenomena. The mechanistic model is widely used for the prediction of boiling heat transfer because of this advantage.

To set up the closure models of the heat partitioning model, and to extend its capability to a non-vertical plate, various studies have been conducted. For example, Sateesh et al. [2] and Basu et al. [3] simplified complex boiling phenomena in their models by assuming the distribution of nucleation sites, bubble merger with average behavior, etc. The bubble nucleation sites were assumed uniformly arranged in a grid form and the sliding distance was assumed the same as the distance between nucleation sites in the model of Sateesh et al.. On the other hand, cases were divided into various situations and assumed uniformly located nucleation sites with a grid form in the model of Basu et al.. For an analytical approach, they assumed that new bubbles started to grow at the rear site when the bubbles generated at the front site departures. These simplifications were inevitable to close the models even if they do not reflect actual boiling phenomena.

In this study, the heat flux partitioning model was developed that considers the bubble sliding and merger as realistic as possible. The target application was a horizontal heat exchanger tube, where long bubble sliding length is expected. For this purpose, developed numerical bubble tracking and merging models with the bubble related sub-models on a horizontal tube. On the unfolded heating surface, place the bubble nucleation sites. After that, automatically determine the behavior and merger of the bubbles by the applied sub-models, and the force balance model. On the calculation result, categorize the wall surface into three depending on the heat transfer mechanisms, which include the microlayer evaporation, transient conduction, and single-phase convection. Finally, the categorized areas were used for the calculation of total heat transfer by averaging in time and area.

2. Numerical Bubble Tracking and Merger Modelling

2.1 Sub-models for numerical modeling

The sub-models related to the life-cycle of the sliding bubbles should be included in the numerical model to simulate the behavior of the bubbles on a horizontal tube outside and the heat transfer. The sub-models used in the present study are listed in Table 1.

Pressure, wall superheat, liquid subcooling, bulk flow velocity, and horizontal tube diameter are input conditions of the present model. Besides, the distribution of the nucleation site (random or uniform), and the number of calculations of the Monte-Carlo method for the random distribution are the calculation options. Finally, the average area ratios and the heat fluxes of each heat transfer mechanism, the total heat flux, and the lift-off diameter of the bubbles are calculated.

Table 1 Applied sub-models in numerical modelling

Sub-models	Author / model type	Description
Heat transfer coefficient	Jeon et al. [4]	$T_{sub} < 40K$
Area of influence	Amidu et al. [5]	$K = 0.5$
Nucleation site density	Hibiki & Ishii [6]	$P < 19.8MPa$
Bubble growth	Yoo et al. [7]	Mechanistic model, $T_{sub} < 13.5K$
Bubble frequency	Cole [8]	
Departure diameter	Mechanistic modelling in this study [9]	
Contact diameter	Experimental observation in this study [9]	$d_w = 0.35D_b$
Bubble velocity model	Mechanistic modelling in this study [10]	Modified force balance model (Table I)
Contact angle	Experimental observation in this study [9]	α=20º, β=15º
Drag coefficient	Newton's law[11]	$C_d = 0.44$
Bubble wake effect	Experimental observation in this study [9]	$L_{bubble} < 2D_b$
Lift-off diameter	Basu et al. [2]	$T_{sub} < 60K$

2.2 Concept of numerical modeling

In this study, numerical modeling to track their sliding and merging was developed to calculate the mechanistic boiling heat transfer on the horizontal tube. The computational domain is an unfolded heating surface of the horizontal tube with a square region corresponding to the area of a quarter arc length of the tube (Figure 1). For example, in the case of 50 mm diameter, it has an unfolded arc length of about 39 mm and a square (39.27 mm × 39.27 mm) calculation domain. Nucleation sites are distributed according to options within the unfolded area. As an option, the user can choose either of an uniform or random distribution of the sites. The uniform option is to distribute the nucleation site's position in a uniform grid. This approach corresponds to the assumptions made for the simplification of the problem in the previous studies (Basu et al., Sateesh et al.). The random option is to position the nucleation site completely randomly over the entire heating area. After the bubble nucleation sites are placed on the unfolded surface, the behavior and merger of the bubbles are automatically determined by the applied sub-models and the force balance model (Figure 2).

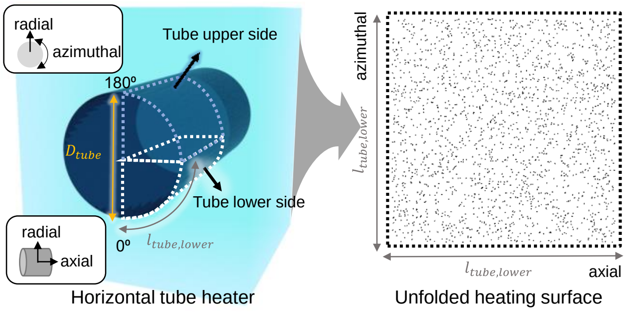

Figure 1 Concept of a computational domain of horizontal tube heater

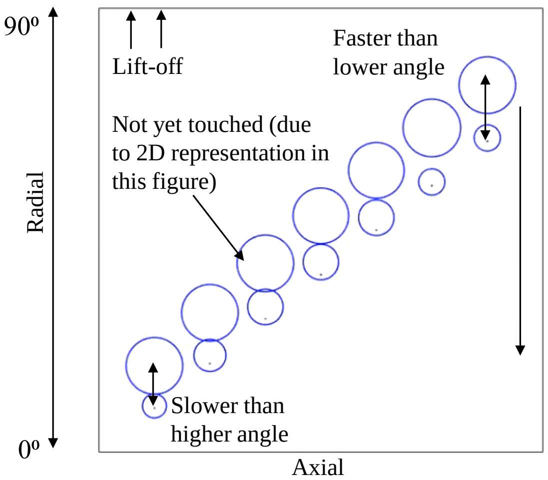

Figure 2 Still image of bubble tracking on the horizontal tube

2.3 Heat transfer calculation from bubble tracking

Transient conduction refers to a phenomenon in which quenching occurs and heat transfer is temporarily enhanced as the surrounding fluid flows into the place of the superheated layer that has been removed apart as the bubble passes. The degree of heat transfer enhancement can be expressed as shown in Figure 3. From the numerical modeling, the location and radius of the bubbles over time are given. After that, the model multiplies the radial distance of the bubble from the center point location and the area of influence constant $\sqrt{K}$. This calculation determines the area where transient conduction occurs. Besides, the area where microlayer evaporation occurs is obtained using d_w, the contact diameter, and its location (Figure 4).

As the transient conduction heat transfer decays after the moment of bubble passing, the present model stores the time after the bubble passing at each pixel if it is recognized as the transient conduction area. Using these time data, the decay of the transient conduction over time can be predicted. Figure 5 shows the still shot of the bubble and the corresponding transient conduction time index.

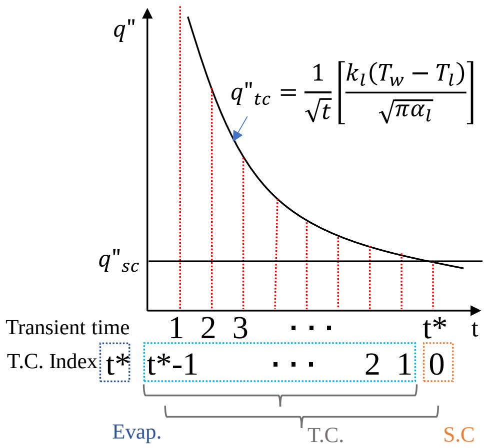

Figure 3 Heat transfer enhancement by transient conduction and transient conduction index

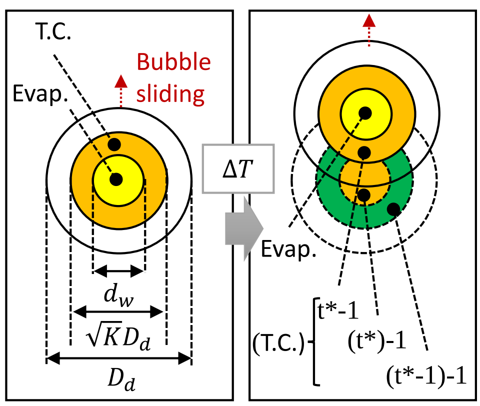

Figure 4 Calculating transient conduction index

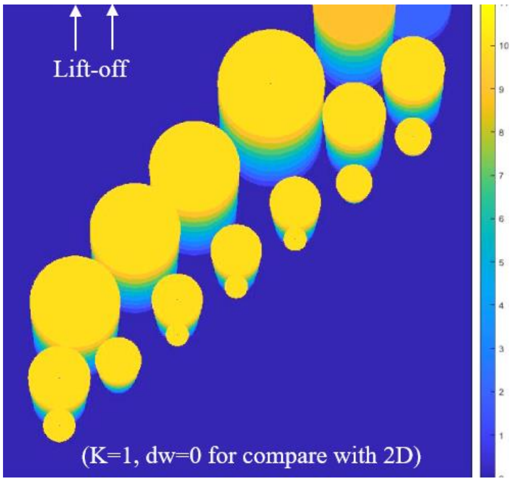

Figure 5 Still image of transient time index of the calculation domain

3. Results

3.1 Bubble tracking and merger results

Figure 6 is the result of the calculation displayed using three-dimensional reconstruction. Comparing (b) and (c) of Figure 6, the arrangement of the uniform site is significantly different from the actual boiling phenomenon. Conversely, the randomly arranged site shows much closer reconstruction results to the actual boiling phenomenon. For the randomly distributed sites, the results were averaged after repeating the calculation using the Monte-Carlo method as shown in Figure 7. The specific calculation formula and method are contained in the author's previous study [9].

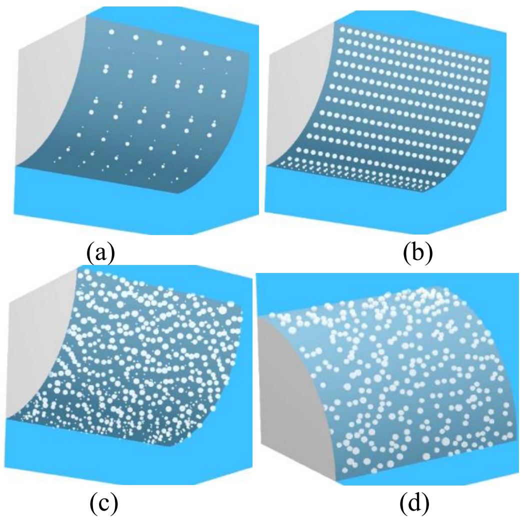

Figure 6 Three dimensional calculation results, Tsub=15K
(a) lower side, Tsup=1K, uniform distribution
(b) lower side, Tsup=8K, uniform distribution
(c) lower side, Tsup=8K, random distribution
(d) upper side, Tsup=8K, random distribution

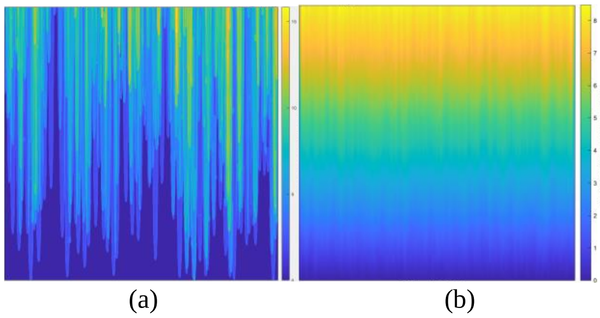

Figure 7 Transient conduction time index of calculation domain (a) single random distribution case (b) 2,000 cases averaged random distribution

3.2 Heat transfer calculation results

Figure 8 shows the ratio of the area occupied according to the mechanisms in the total calculation domain. When this ratio is unity, heat transfer occurs by the corresponding mechanism in the entire area. Figure 9 shows the transient conduction time index. This is the value of the transient conduction time term that occurs on the average in the area where the transient conduction occurs. Figure 10 shows one of the calculation results. This case is calculated in the conditions D=33mm, saturation temperature, and atmospheric pressure. Solid symbols represent the results from the random sites distribution case, and hollow symbols are used for the uniform sites distribution case. For all wall superheats, the random case has a slightly higher heat flux than the uniform case, and this trend is reversed at Tsup=16K. In the uniform case, the site is placed on the path of bubble trajectory, and the transient conduction is limited in a relatively small area compared to the random case. On the other hand, the degree of the transient conduction in the area is relatively high because of the overlapping of the transient conduction area.

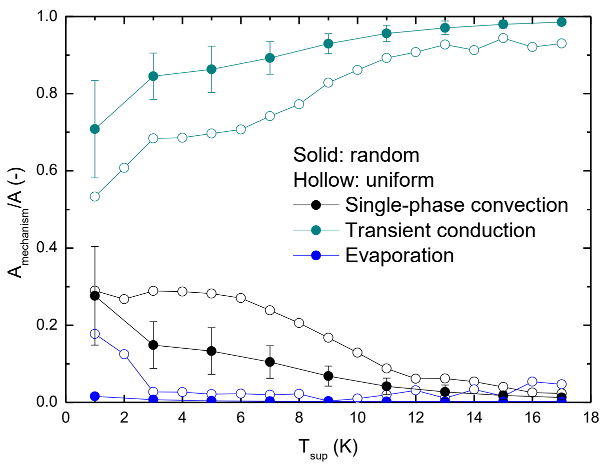

Figure 8 Calculated occupied area ratio for each mechanism (D=33mm, P=1.013bar, Tsub=0.1K)

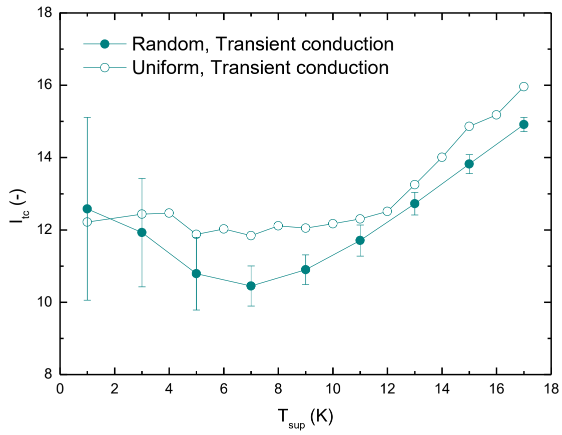

Figure 9 Calculated transient conduction time index (D=33mm, P=1.013bar, Tsub=0.1K)

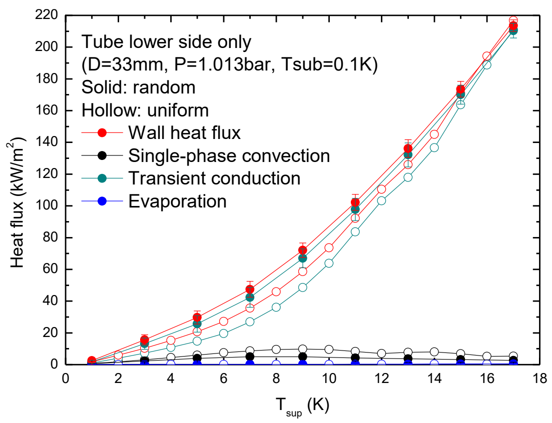

Figure 10 Heat flux calculation results for surface superheat (D=33mm, P=1.013bar, Tsub=0.1K)

4. Conclusions

For the complex bubble tracking including bubble merger, conducted numerical modeling. The model reflected the realistic phenomenon of the upper and lower side of the horizontal tube. Finally, the mechanistic heat transfer model was completed by determining the area ratio and heat flux for each heat transfer mechanism. The distribution of the nucleation sites in the model is determined by the options. Distribution options are uniform, or random. In the case of random sites, the average value and range of the calculation results are obtained using the Monte-Carlo method.

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