# Heat Partitioning Model with Bubble Tracking Method Considering Conjugate Heat Transfer

Ja Hyun Ku, Hee Pyo Hong, Hyoung Kyu Cho*
*Department of Nuclear Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826*
**Corresponding author: chohk@snu.ac.kr*

## 1. Introduction

Predicting boiling heat transfer is important in the nuclear industry, since boiling occurs under both normal and transient conditions of a water-cooled reactor. Accurate prediction of boiling heat transfer is still challenging since various phenomena in boiling heat transfer, such as bubble merger, sliding, stochastic distribution, needs be considered. Thus, various attempts have been made to reflect those phenomena mechanistically.

The heat partitioning model was proposed to predict the boiling heat transfer mechanistically, which calculates it by dividing heat transfer according to specific phenomena. The RPI model, the most widely accepted heat partitioning model, was developed by Kurul and Podowski [1]. This model divides boiling heat transfer into evaporation, single-phase convection, and transient conduction to calculate the total heat transfer. However, this model ignored some phenomena certainly exist, such as microlayer evaporation, bubble merging, random bubble distribution, etc. In this context, attempts to improve the RPI model have been continued [2-4].

Despite these attempts, since these are based on simplified assumptions, there are limitations in reflecting realistic phenomena. Kim and Cho [5] proposed the heat partitioning model incorporating a numerical bubble tracking method to complement these missing phenomena. In the bubble tracking method, the size and location of individual bubbles are numerically simulated based on various models. Hong et al. [6] improved this model by implementing microlayer evaporation term. However, in the previous study, the wall temperature was assumed to be constant in the whole heating surface, which is inconsistent with real phenomena observed in experiments. The wall temperature varies locally depending on the phenomena occurring on the heating surface and therefore, it is important to consider the wall temperature variation in space and time.

In this paper, the bubble tracking method was coupled with the conjugate heat transfer analysis. The local temperature distribution was used for the heat transfer evaluation and nucleation criteria. The present paper introduces the coupled simulation method and discusses the effect of the bubble nucleation temperature.

## 2. Simulation method

### *2.1. Bubble tracking method considering conjugate heat transfer*

The bubble tracking method was developed to simulate the behavior of bubbles on a heated wall, written in MATLAB code. The bubble tracking method analyzes individual bubbles and wall heat transfer associated with the corresponding bubbles. The simulation is performed according to the procedure in Fig.1 described below.

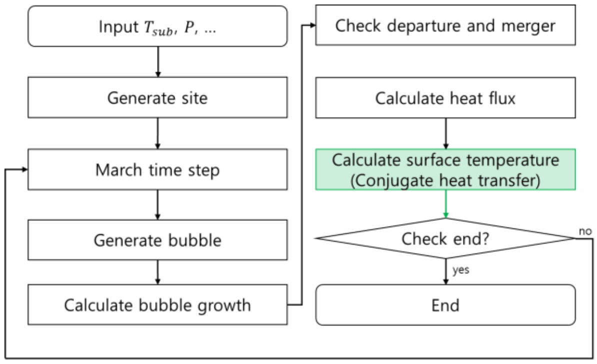


Fig. 1. Simulation procedure of the bubble tracking method (black) with conjugate heat transfer (green)

Firstly, a computational domain is determined. The fluid conditions such as initial wall superheat temperature, system pressure, etc., and factors related to the simulation, such as simulation time and time step, are determined. After the domain is set, the nucleation sites are distributed in the domain according to the designated method. One among three options can be selected; 1) uniform spacing distribution, 2) random distribution, and 3) predetermined locations from measurements. The nucleation sites become where bubbles are generated in the subsequent simulation process. The bubbles are generated according to a predetermined waiting time or nucleation temperature.

After the bubbles are generated, the bubbles grow according to the evaporation from both microlayer and superheated liquid layer. In this simulation, the evaporation rate from the superheated liquid layer is evaluated based on microlayer evaporation volume [7]. At each nucleation site, a bubble grows over time, and when the dry area collapses, the bubble departs from the nucleation site. After the bubble departure, the code checks whether the nucleation criterion is satisfied at each nucleation site. A new bubble is created when the nucleation criterion is satisfied.

Meanwhile, when a bubble contacts adjacent bubbles during the growth process, the bubbles are assumed to merge immediately, and the merged bubble grows in a new position, which is calculated based on the center of mass of the two merging bubbles. Once the location and size of individual bubbles are calculated in each simulation loop, the heat transfer in the domain is divided into microlayer evaporation, transient conduction, and single-phase convection according to the heat partitioning model, and the heat flux is evaluated accordingly. Finally, the simulation steps above are repeated until the end time is satisfied.

### *2.2. Calculating heat flux with area partitioning*

Fig. 2 shows the partitioned area with respect to the location of the bubble. The region underneath a bubble on the heating surface has dry area and microlayer. Dry area radius of the bubble is determined by the relation between the bubble radius and the dry area radius from experimental observation by Jung and Kim [8], which is shown in Fig.3.

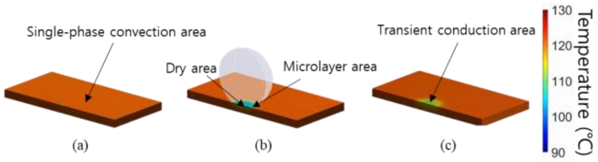


Fig. 2. Partitioned area (a) at nucleation, (b) at growth, (c) at departure

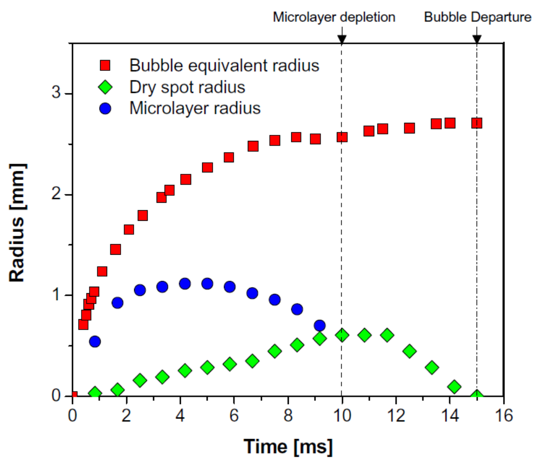


Fig.3. Time evolution of radius of bubble, micro-layer and dry spot (Jung and Kim [8])

Modeling of the microlayer precedes the calculation of microlayer evaporation heat flux. First, using the relation between the bubble radius and the microlayer radius according to the growth of the bubbles observed in Jung and Kim's experiment [8], the microlayer area of the bubble is determined in the domain during the growth stage of the bubble. After determining the microlayer area, the microlayer thickness is determined. It is assumed that the thickness of the microlayer increases linearly from the triple contact line to the end of the microlayer area radius based on the experimental results of Utaka et al. [9]. From the assumption above, the microlayer evaporation heat flux in the microlayer area is calculated by Eq. (1) below, presented by Susann Hänsch and Simon Walker [10]:

$$q''_{ml} = \frac{T_{wall}-T_{bulk}}{\frac{1}{h_{ev}}+\frac{\delta_l}{k_l}} \quad (1)$$

where $T_{wall}$, $T_{bulk}$, $h_{ev}$, $\delta_l$, and $k_l$ are wall temperature, liquid bulk temperature, evaporative heat transfer coefficient, microlayer thickness, and liquid thermal conductivity, respectively.

The transient conduction area is determined as the area affected by the bubble departure. The transient conduction heat flux is calculated as follows:

$$q''_{tc} = \frac{k_l}{\sqrt{t\pi\alpha_l}}(T_{wall} - T_{bulk}) \quad (2)$$

where $t$ and $\alpha_l$ are the time after the bubble departure and liquid thermal diffusivity, respectively.

The single-phase convection area refers to the areas not included in the microlayer evaporation and transient conduction areas. In the single-phase convection area, the single-phase convection heat flux is calculated as follows:

$$q''_{sp} = h_{sp}(T_{wall} - T_{bulk}) \quad (3)$$

where $h_{sp}$ is convective heat transfer coefficient. The partitioned area and the calculated heat flux in each area affect the growth of the bubble, and heat flux calculation results vary according to the change in partitioned area and the bubbles.

### *2.3. Conjugate heat transfer*

Based on the heat flux calculated from the bubble tracking method, the temperature distribution of the substrate is calculated in three-dimension using OpenFOAM [11]. Among the solvers in OpenFOAM, the laplacianFoam solver is used. The implemented differential equation in the solver is as follows:

$$\frac{\partial}{\partial t}T - \nabla\cdot(D_T\nabla T) = 0 \quad (4)$$

where $D_T$ is diffusion coefficient which cannot reflect different material properties. In this paper, boiling heat transfer analysis on a boiling surface with joule heating was performed. In the typical boiling experiment, joule heating materials such as ITO film and substrate are used, so the different material properties must be considered in the simulation. Therefore, to reflect the joule heating effect and different material properties, the solver was modified as follows:

$$\rho c_p\frac{\partial}{\partial t}T - \nabla\cdot(k\nabla T) = q''' \quad (5)$$

where $\rho$, $c_p$, and $k$ are density, specific heat, and thermal conductivity of material, respectively.

The initial temperature condition was the wall superheat temperature from the bubble tracking method. The boundary condition of the boiling surface was set to the Neumann boundary condition using the heat flux obtained from the bubble tracking method. The boundary conditions at the remaining boundaries were set as the adiabatic condition.

After calculating the temperature of the boiling surface, the boiling surface's temperature distribution is transferred to the bubble tracking program and used for calculating heat partitioning in the next step. In this way, code coupling of the bubble tracking method and the conjugate heat transfer continues until the end of the simulation.

## 3. Simulation results

To validate the simulation results with the experimental results of Jung and Kim [12], the experimental and simulation conditions were matched as shown in Table 1. Accordingly, five cases of wall superheat were selected in the range of 3.1 to 7.7 degrees, and the corresponding heat fluxes applied to the surface were selected in the range of 92 to 485 kW/m². In addition, the nucleation site distribution and the departure diameter of the bubbles at each site were consistent with the experimental conditions. In addition, the nucleation frequency was simulated by allocating the waiting time observed in the experiment to each site.

Fig. 4 is an example visualization result that can be obtained during simulation. As described in Section 2, in each time step, the heat flux is calculated by dividing the surface into microlayer evaporation, transient conduction, and single-phase convection area according to the bubbles on the domain. Accordingly, the conjugate heat transfer calculation also updates the temperature distribution of the surface.

Table 1. Simulation condition

| | |
|---|---|
| System pressure | 1 bar |
| Wall superheat | 3.1-7.7 K (five case) |
| Applied heat flux | 92-485 kW/m² |
| Influence area | 0.2 |
| Single-phase heat transfer coefficient | From experiment [12] |
| Departure diameter | From experiment [12] |
| Nucleation frequency | Controlled by waiting time from experiment [12] |
| Nucleation site distribution | From experiment [12] |

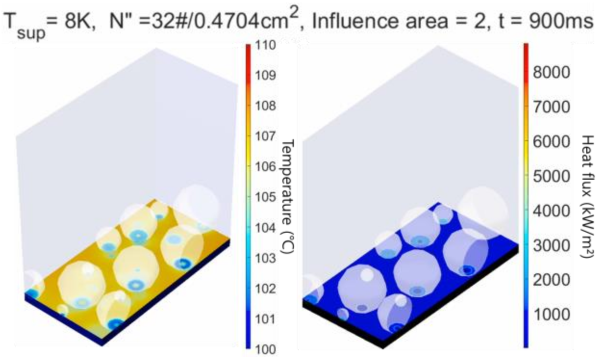


Fig. 4. Simulation result of temperature (left) and heat flux (right)

### *3.1. Reproduction of experimental results*

In order to confirm the effect of considering conjugate heat transfer, a comparison with the experimental results of Jung and Kim [12] was performed. Two kinds of simulation were conducted, one is the bubble tracking method, and the other is the bubble tracking method with conjugate heat transfer analysis. The experimental results, the simulation results of standalone bubble tracking method, and bubble tracking method considering conjugate heat transfer were compared, as shown in Figure 5. It can be confirmed that considering conjugate heat transfer showed better results than the standalone bubble tracking method. This is because the temperature distribution underneath the microlayer decreases due to the evaporation of the microlayer in the boiling process and the evaporation heat flux is affected by the decreased temperature. Also, the decrease of the surface temperature affects transient conduction and single-phase convection heat transfer, resulting in an average decrease of 62% and 54% in the simulation results of the heat flux, respectively. As described in Section 2, microlayer evaporation, transient conduction, and single-phase convection heat flux are proportional to the wall superheat, so the result of the simulation also decreases with the decreasing wall temperature.

In the simulation, transient conduction heat flux becomes smaller than that of the experiment. This is because, unlike the conventional model that calculates evaporation and transient conduction heat flux according to the presence or absence of bubbles in the nucleation site, this study evaluates transient conduction heat flux at the location of the bubble departure, and if single-phase convection heat flux is more significant than transient conduction heat flux in that area, the heat flux in that area is calculated as single-phase convection heat flux. In addition, using 0.2 as the influence area obtained from the experiment is one of the reasons for evaluating the transient heat flux to be smaller.

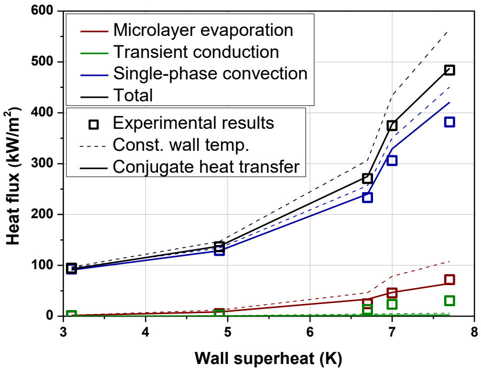


Fig. 5. Comparison of heat flux between experiment and simulations

### *3.2. Applying nucleation temperature criteria*

Since surface temperature distribution varies spatially and temporally due to the conjugate heat transfer, the simulation was repeated changing the nucleation criterion when the nucleation site reached a specific nucleation temperature instead of the waiting time for each nucleation site. The simulation results are shown in Fig.6. The results present that the microlayer evaporation heat flux and the transient conduction heat flux increase if the nucleation temperature decreases and subsequently, the nucleation frequency increases. On the other hand, the single-phase convection heat flux decreases.

The nucleation temperature criterion can replace the waiting time model making the simulation more mechanistic. But a proper value of nucleation temperature criterion is necessary for accurate prediction of the boiling heat transfer.

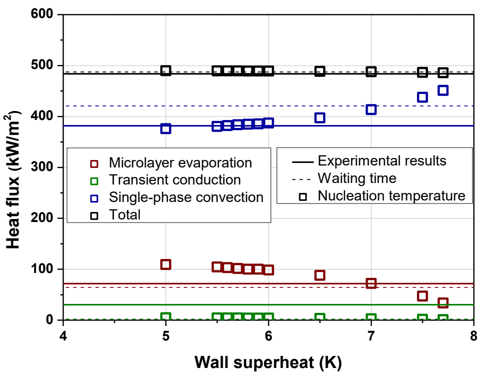


Fig. 6. Comparison of heat flux between experiment and simulations varying nucleation temperature criteria

## 4. Conclusions

In this paper, the boiling heat transfer was calculated by the previously developed bubble tracking method incorporating conjugate heat transfer analysis. As a result, it was confirmed that the boiling heat transfer observed in the experiment was better predicted compared to the previously developed bubble tracking simulation. In addition, it was confirmed that there was a difference in the boiling heat transfer prediction according to the nucleation temperature criteria. In detail, microlayer evaporation and transient conduction heat flux increase with the decreasing nucleation temperature criteria, while single-phase convection heat flux decreases.

For future work, it is necessary to compare the various boiling heat transfer experiments to examine the effect of nucleation temperature in the simulation. In addition, some parts of the bubble tracking method simplify the realistic phenomena of bubble behavior. Therefore, the code should be improved by applying realistic models. Finally, calculating domain geometry extensions such as vertical or inclined flow boiling should be performed through validation with various experimental condition data.

## ACKNOWLEDGEMENT

The authors would like to thank Professor Hyungdae Kim and his laboratory at Kyung Hee University for providing insight and experimental data for this paper. This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. RS-2022-00144494).

## REFERENCES

[1] Kurul, N., and Michael Z. Podowski, Multidimensional effects in forced convection subcooled boiling, International Heat Transfer Conference Digital Library, Begel House Inc, 1990.

[2] Basu, Nilanjana, Gopinath R. Warrier, and Vijay K. Dhir, Wall heat flux partitioning during subcooled flow boiling: Part 1—model development, J. Heat Transfer 127.2, pp. 131-140, 2005.

[3] Basu, Nilanjana, Gopinath R. Warrier, and Vijay K. Dhir, Wall heat flux partitioning during subcooled flow boiling: part II—model validation, J. Heat Transfer 127.2, pp. 141-148, 2005.

[4] Gilman, Lindsey, and Emilio Baglietto, A self-consistent, physics-based boiling heat transfer modeling framework for use in computational fluid dynamics, International Journal of Multiphase Flow 95, pp. 35-53, 2017.

[5] Kim, Jae Soon, and Hyoung Kyu Cho, Advanced boiling heat transfer model for a horizontal tube with numerical analysis of bubble behaviours, International Journal of Heat and Mass Transfer 175, 121168, 2021.

[6] Hee Pyo Hong, Moonhee Choi, and Hyoung Kyu Cho, Heat partitioning model with bubble tracking method considering bubble merger and stochastic nucleation site distribution, Transactions of the Korean Nuclear Society Virtual Autumn Meeting, 2021.

[7] Utaka, Yoshio, et al, Heat transfer characteristics based on microlayer structure in nucleate pool boiling for water and ethanol, International Journal of Heat and Mass Transfer 68, pp.479-488, 2014.

[8] Jung, Satbyoul, and Hyungdae Kim, An experimental method to simultaneously measure the dynamics and heat transfer associated with a single bubble during nucleate boiling on a horizontal surface, International Journal of Heat and Mass Transfer 73, pp. 365-375, 2014.
[9] Utaka, Yoshio, Yuki Kashiwabara, and Michio Ozaki, Microlayer structure in nucleate boiling of water and ethanol at atmospheric pressure, International Journal of Heat and Mass Transfer 57(1), pp. 222-230, 2013.
[10] Hänsch, Susann, and Simon Walker, Microlayer formation and depletion beneath growing steam bubbles, International Journal of Multiphase Flow 111, pp. 241-263, 2019.
[11] Weller, Henry G., et al., A tensorial approach to computational continuum mechanics using object-oriented techniques, Computers in physics 12.6, pp. 620-631, 1998.
[12] Jung, Satbyoul, and Hyungdae Kim, Effects of surface orientation on nucleate boiling heat transfer in a pool of water under atmospheric pressure, Nuclear Engineering and Design 305, pp. 347-358, 2016.