Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Extension of CRUD heat transfer model to low-pressure condition for boiling heat flux partitioning model

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***Keywords**: Bubble growth, CRUD heat transfer, Boiling heat transfer, wick boiling model.

1. Introduction

CRUD (Chalk River Unidentified Deposit) refers to the corrosion products deposited on the surface of nuclear fuel. These corrosion products form a porous structure on the surface of nuclear fuel by depositing fine-sintered bodies. The vapor generated within a porous medium escapes through more significant gaps, where the pressure drop is minimized, forming channels filled with vapor, known as steam chimneys. This complex structure facilitates a different heat transfer mechanism known as wick boiling.

CRUD can act as a thermal resistance[1] or enhance heat transfer through wick boiling within the CRUD [1-2]. Therefore, understanding the impact of CRUD on boiling heat transfer is crucial. In accidents where a significant loss of coolant occurs, the core pressure can decrease to atmospheric levels. In such scenarios, boiling can occur on the surfaces of high-burnup fuel with CRUD during the re-flooding process. For the safety analysis in these scenarios, the heat transfer model operating under high-pressure conditions needs to be extended to low-pressure conditions. This study adopted a CRUD heat transfer model operating under high-pressure conditions for low-pressure conditions. It was implemented into a wall heat partitioning model using a bubble tracking method called BHFP(boiling heat flux partitioning model with bubble tracking method)[3]. This implementation allowed for the prediction of the effects on the growth process of a single bubble on a CRUD-deposited surface.

2. Numerical methods

This section briefly explains the BHFP and the CRUD heat transfer model, along with the alterations implemented to adapt the CRUD heat transfer model for low-pressure conditions and to integrate it with the numerical heat partitioning model.

2.1 Boiling heat flux partitioning model

The BHFP is a numerical heat partitioning model developed by Seoul National University [3] that simulates individual bubble behavior. This model aims to realistically consider boiling phenomena such as stochastic nucleation sites, bubble mergers, and bubble sliding. Furthermore, the model considers evaporation at the microlayer and the bulk to accurately simulate bubble growth.

2.2 Wick boiling model for the CRUD

In CRUD, heat transfer primarily occurs through wick boiling. Wick boiling refers to a phase change mechanism where capillary force supplies water in a porous structure, and the generated steam escapes through the steam chimney. The model presented by Yeo [4] predicts heat transfer under high-pressure conditions. In this model, the water is transferred through a porous medium, and nucleate boiling occurs at the interface between the cladding and the CRUD. Steam moves through the steam chimney, as shown in Figure 1. Assuming that bubbles freely escape through the steam chimney, CRUD is divided into two regions: the steam chimney, which is the flow path of vapor, and the region saturated with liquid. The heat from the cladding surface is mainly transferred through nucleate boiling, and the remaining heat is diffused through conduction and transferred to the bulk.

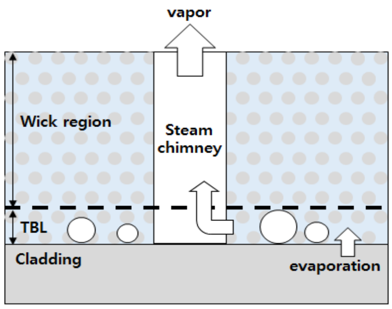

Figure 1. Schematic diagram of wick boiling model in CRUD structure

Eq. (1)~(3) are the governing equations of the wick boiling heat transfer model:

$$q = \frac{k_{sl}(T_w - T_{TBL})}{\delta_{TBL}} \tag{1}$$

$$q_{nb} = \frac{\beta \pi^{n-\frac{1}{2}}}{\sqrt{2}} \left(\frac{\rho_l^{2n-\frac{3}{4}} c_{p,l}^{n-\frac{1}{6}} k_{sl}^{n+\frac{1}{6}} v_{lv}^{2n-1}}{\mu_l^{n-\frac{1}{3}} h_{lv}^{2n-1} \sigma_{lv}^{\frac{1}{2}}} \right) \Delta T_{TBL}^{2n} \Delta P_{TBL}^{\frac{3}{4}} \tag{2}$$

$$T_{TBL} = T_{bulk} + (q - q_{nb}) \left[\frac{1}{h_0} \mathrm{e}^{\left(-\frac{\rho_l c_{p,l} \mu_l}{k_{sl}}\right)(l-\delta_{TBL})} + \frac{h_{lv}}{q_{nb} c_{p,l}} \left\{ 1 - e^{\left(-\frac{\rho_l c_{p,l} \mu_l}{k_{sl}}\right)(l-\delta_{TBL})} \right\} \right] \tag{3}$$

where q is wall heat flux, q_{nb} is the evaporative heat flux, k_{sl} is the thermal conductivity of the liquid saturated state of the CRUD, $T_w, T_{TBL}, and\ T_{bulk}$ represent the temperature of the wall, TBL (thermal boundary layer), and the bulk respectively, ρ_l is the density of the liquid, $c_{p,l}$ is the specific heat of the liquid, v_{lv} is the changes in specific volume during evaporation, μ_l is the dynamic viscosity of the liquid, h_{lv} is the latent heat of evaporation, σ_{lv} is the surface tension of the saturated state, ΔT_{TBL} , ΔP_{TBL} is the temperature and pressure difference between vapor and liquid at the TBL, l, δ_{TBL} is the thickness of the CRUD and the TBL, and h_0 is the heat transfer coefficient on the CRUD-coolant interface.

2.3 Extension of Wick boiling model into low pressure

Eq. (2) is Forster and Zuber's pool boiling correlation [5], where β and n are the empirical constants. The wick boiling model derived these values from the WALT[6] experiment, a wick boiling experiment within CRUD conducted under high-pressure conditions. To apply Eq. (2) for low-pressure conditions, nucleate boiling data on the CRUD surface at low-pressure conditions needs to be used. This study used β and n, proposed by Forster and Zuber [5], obtained from a pool boiling experiment under atmospheric pressure conditions.

Under low-pressure conditions, the specific volume of bubbles increases. As a result, the thickness of the TBL increases vastly, eventually exceeding the CRUD thickness. When the thickness of the TBL exceeds that of the CRUD, it is not possible to calculate the temperature distribution in the Wick region, making it impossible to solve Eq. (1), (2), and (3). For this reason, the wick boiling model does not work under low-pressure conditions. Therefore, this study assumes that the TBL grows up to the CRUD surface. The bubbles at the interface between CRUD and cladding can grow throughout the entire CRUD layer. Eq. (3) is the analytic solution of the heat diffusion equation Eq. (4) in the wick region above the TBL. Under the new assumption, Eq. (3) can be replaced with Eq. (5).

$$\frac{d}{dx}\left(\alpha_m \frac{dT}{dx}\right) = u_f \frac{dT}{dx} \quad (4)$$

$$q_w - q_{nb} = h_0[T_0 - T_{bulk}] \quad (5)$$

2.4 Implementation of wick boiling model into BHFP

To predict the effect of CRUD on bubble growth, the wick boiling model has been added to the BHFP, as shown in Figure. 2 and 3. In the model, the projection area of a growing bubble to the heating surface is partitioned into the dry area region and the microlayer region. Then, the amount of evaporation from the microlayer region is calculated. The wick boiling model is implemented in this area partitioning process to describe the effects of the CRUD.

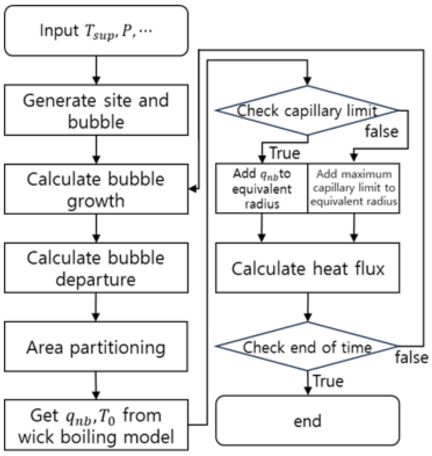

Figure 2. Simulation procedure of the BHFP with wick boiling model

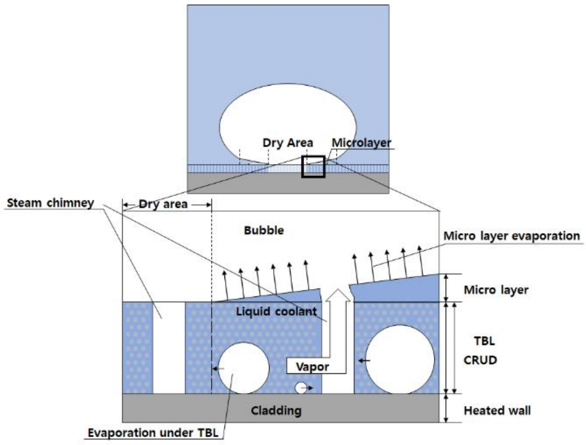

Figure 3. Schematic diagram of BHFP with wick boiling model

It calculates the temperature distribution and heat partitioning in CRUD based on boundary conditions received from BHFP. The temperature information of the CRUD given by the wick boiling model describes the thermal resistance effect of the CRUD. The heat flux of wick boiling from the wick boiling model is added to the evaporation rate in the BHFP. Since the liquid in the CRUD is driven by capillary force, the capillary limit should be considered. When wick boiling heat flux reaches the capillary limit, no more coolant can be supplied to the CRUD. Therefore, boiling is constrained to occur only up to that limit. This approach qualitatively analyzes how bubble growth is affected by wick boiling of CRUD under atmospheric pressure.

As shown in Figure 1, the structure of the wick boiling model consists of the steam chimney and the sintered wick structure. The capillary limit for the sintered wick heat pipe[7] was used to evaluate the capillary limit of the wick boiling in CRUD

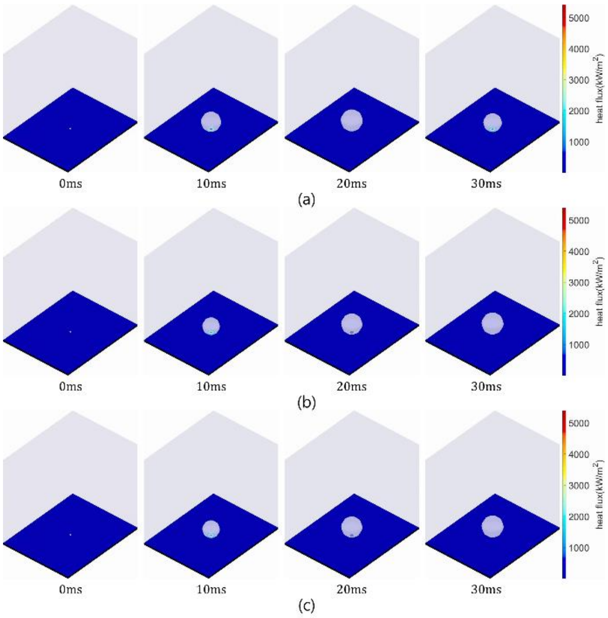

Figure 4. Bubble growth of BHFP (a) without CRUD, (b) with CRUD without dry area wick boiling, and (c) with CRUD with dry area wick boiling

3. Results

The heat partitioning of the wick boiling model and the modified model were compared to verify the modified model. As shown in Figure 5, the modified model performed well under low-pressure conditions, and the heat was appropriately partitioned qualitatively. The specification of the CRUD used for the simulation is listed in Table 1, and the operating conditions for each model are shown in Table 2. The bulk temperature of the original wick boiling model was set to the coolant temperature at the normal operating PWR. The modified model was set to the saturation temperature for observing saturated boiling, and the wall heat flux was used under conditions where nucleate boiling occurs to observe nucleate boiling.

Table 1. Material properties of the CRUD

Parameter	Value
Chimney diameter[μm]	5
Chimney number density[#/m^2]	2.0×10^9
CRUD thickness[μm]	50
Solid thermal conductivity[W/mK]	1.18

Table 2. Test conditions for wick boiling models

Parameter	Model	
	Original	Modified
Pressure[bar]	155	1.01325
Wall Heat flux[MW/m^2]	1.0~1.7	0~0.15
Bulk Temperature[°C]	328.4	99.9664

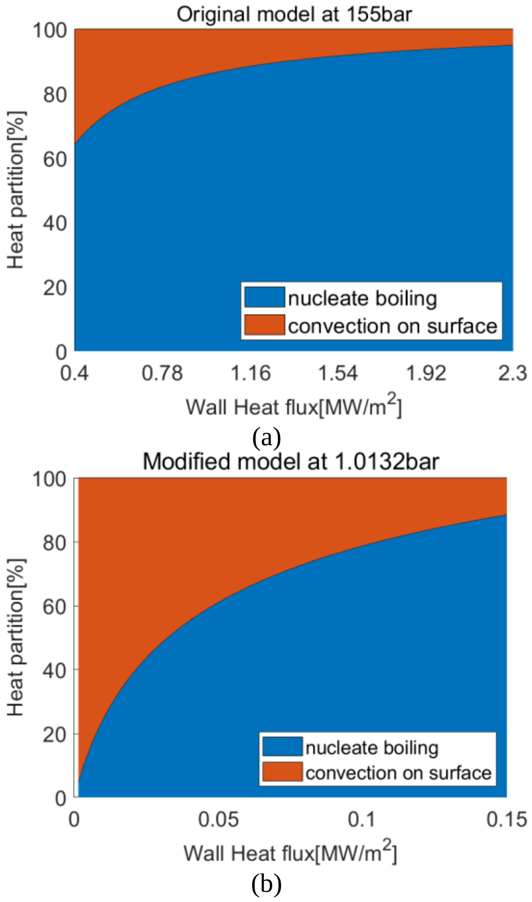

Figure 5. Heat partition of (a) Original and (b) modified wick boiling model

A comparison simulating a single bubble was conducted between the BHFP with the wick boiling model and without the model to examine the effect of the CRUD. When calculating BHFP with CRUD, two scenarios were considered: the CRUD beneath the dry area is filled with liquid coolant, and the other where the liquid coolant has completely evaporated. The wall superheat was set at 5K. The results demonstrate that bubble growth was slightly slowed with the presence of the CRUD structure, as illustrated in Figure 6.

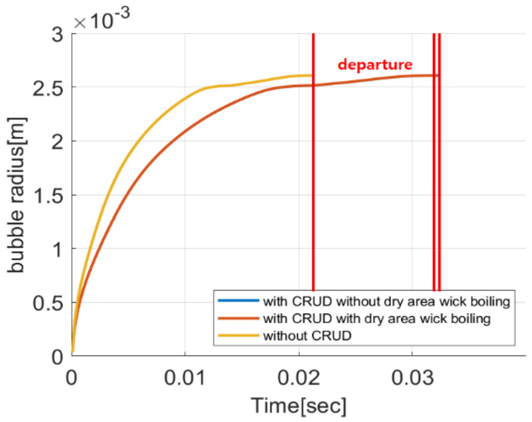

Figure 6. Effect of applying CRUD geometry on bubble growth

4. Conclusions

This study modified an existing CRUD heat transfer model for high-pressure conditions to extend an operation region to low-pressure conditions. The correlation for the nucleate boiling was adjusted to the low-pressure condition, and TBL was extended. As a result, a new wick boiling heat transfer model that operates in low-pressure conditions was proposed. This model was integrated with a BHFP to qualitatively observe that wick boiling within the CRUD layer accelerates bubble growth. In single bubble simulations, it was confirmed that CRUD slowed down bubble growth.

Since the empirical constant used in the new model is fitted to the pool boiling experiments on a clean surface, the model requires further improvement and validation through the experiments. Furthermore, the model cannot determine whether coolant is penetrating under the dry area, so further improvement is needed.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korean government(MSIT) (No. RS-2022-00144494).

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