Improvement of the Wall Boiling and Bubble Diameter Models for the Analysis of Core Catcher by Using CUPID

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1. Introduction

A core catcher system is being developed for the severe accident mitigation by removing decay heat from the molten corium which is speeded on the cavity floor in the reactor containment by the Korean industries.

To evaluate the cooling performance of a core catcher, experiments and computational studies have been conducted by KHNP. In this system, a multi-dimensional flow behavior in an inclined channel with downward faced heating surface is one of prime important thermal-hydraulic concerns. Therefore, a multi-dimensional analysis is required to investigate these phenomena.

In this paper, the CUPID code, which is being developed by KAERI for the analysis of multi-dimensional two-phase flows in the nuclear reactor components, is improved to analyze natural circulation in the core catcher system under the boiling conditions.

2. The Improvement of Physical Models for the CUPID Code

2.1 Wall Boiling Model

In a subcooled boiling flow, the amount of vapor generation is computed by wall heat flux partitioning model. The heat transfer from the wall consists of the surface quenching, q_q, evaporative heat transfer, q_e, and single-phase convection, q_c, which are modeled, respectively, as follows [1]. The applied models and correlations for the heat flux partitioning model are listed in Table I.

$$q = q_q + q_e + q_c \, , \tag{1}$$

$$q_q = \left(2f\sqrt{t_w k_{c,l}\rho_l c_{p,l}/\pi}\right)A_{2f}\left(T_w - T_l\right) , \tag{2}$$

$$q_e = N'' f\left(\pi D_d^3/6\right)\rho_g h_{lg} \, , \tag{3}$$

$$q_c = h_c A_c\left(T_w - T_c\right) . \tag{4}$$

In this study, the bubble departure diameter model suggested by Kocamustafaogullari [2] is implemented.

$$D_d = 2.64\times10^{-5}\theta\left[\sigma/g\left(\rho_l-\rho_g\right)\right]^{0.5}\left[\left(\rho_l-\rho_g\right)/\rho_g\right]^{0.9} . \tag{5}$$

This model is based on a Fritz`s model which is formulated by balance of gravity and surface tension forces. Kocamustafaogullari added a density difference ratio term to the Fritz`s model to take into account pressure effect. This model predicts large bubble departure diameter at the low pressure as in this study.

Hibiki [3] suggested the empirical correlation for ANSD (Active Nucleation Site Density) which includes effects of surface conditions such as a cavity size and a contact angle as follows,

$$N = 4.72\times10^5\left\{1-\exp\left(-\theta^2/8\mu^2\right)\right\}\left[\exp\left\{f\left(\rho^+\right)\lambda'/R_c\right\}-1\right] . \tag{6}$$

It is validated against extensive experimental data. In the present work, Hibiki's model replaced the existing Kurul`s model in the CUPID code.

2.2 Bubble Diameter

Yun [4] proposed a bubble size correlation based on the Hibiki`s one dimensional model for the application in the CFD code which is derived from Interfacial Area Transport Equation. Advantage of the model is it considers local two-phase flow turbulence and thus it is expected to predict bubble size well compared to original Yoneda`s model. Therefore, Yun`s model is implemented in the CUPID.

$$D_b = 39.32\alpha^{0.36}N_{\mathrm{Re}_d}^{-0.696}N_\rho^{0.571}Lo \, , \tag{7}$$

$$N_{\mathrm{Re}_d} \equiv \varepsilon^{1/3}Lo^{4/3}/\nu_l , \quad N_\rho \equiv \rho_l/\rho_g , \quad Lo = \sqrt{\sigma/g\Delta\rho} \, . \tag{8}$$

3. Calculation and Results

3.1 Core Catcher Test Facility

Recently, KAERI is performing experimental investigations for the evaluation of cooling performance of the core catcher. In the present study, numerical simulation was performed against KAERI's experimental test facility by using CUPID code to quantify degree of improvements by each model.

The computational mesh and the boundary condition are presented in Fig. 1. A total computation grid with 3204 cells was used for this calculation. The cooling channel in the core catcher has a gap size of 0.1 m and an angle of inclination of 10 degrees to the horizontal line. Downcomer pipe is also simulated with 0.1-m-diameter.

3.2 Parametric Study for the Models

In this study, the effect of each model was separately evaluated. Table II shows simulation matrix.

Table III shows the comparison of departure bubble size predicted by two models. It shows that Kocamustafaogullari, which predicts larger one than that of the default model, is similar with experimental data [5]. The evaporation rate and the void fraction are proportional to the bubble departure diameter and then it enhances buoyancy force. Thus, the flow rate of the Kocamustafaogullari`s model is higher than the default model as depicted in Fig. 2.

Table IV shows that Hibiki`s ANSD model predicted lower value than that of default model. Because the default model has a tendency to overestimate compared to the experiment [3], the prediction of the Hibiki`s model is expected to be more proper than the default model. And, the flow rate of the Hibiki`s model is lower than that of the default model due to the low evaporation rate.

According to a flow boiling experiment in an inclined channel with downward facing heated wall [6], the elongated bubble which has about 100 mm in length is observed. This elongated bubble is estimated as a 50-mm-diameter of a sphere bubble. The results of Case A and D show that Yun`s bubble diameter model can predict more realistic bubble size than the default model. In addition to this, it revealed that the larger the bubble size, the higher the two-phase natural circulation flow rate as depicted in Fig. 2.

4. Conclusions

In this study, the wall boiling model and the bubble diameter model in the CUPID code was improved for the analysis of the core catcher. The calculation results showed that newly implemented model predicted more realistic simulation results compared to default models for the core catches in which multi-dimensional two-phase natural circulation is dominant.

ACKNOWLEDGEMENTS

This work was supported by Nuclear Research & Development Program of the NRF (National Research Foundation of Korea) grant funded by the MEST (Ministry of Education, Science and Technology) of the Korean government.

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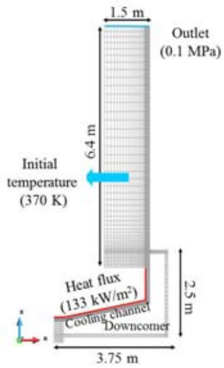

Fig. 1. Calculation domain for the core catcher

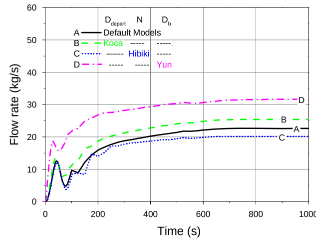

Fig. 2. The parametric study for the model: flow rate

Table I: Heat flux partitioning model [1]

Parameter	Model
ANSD	$N'' = [185(T_w - T_{sat})]^{1.805}$
Bubble departure diameter	$D_d = 0.6\times10^{-3}\exp(-\Delta T_{sub}/45)$
Bubble departure frequency	$f = \sqrt{4g(\rho_f - \rho_g)/(3D_d\rho_f)}$
Bubble waiting time	$t_w = 0.8/f$
Bubble influence factor	$K = 4$
Heat transfer coefficient	$h_c = St\cdot\rho_f C_{pf} u_f$

Table II: The simulation matrix for model evaluation

Case	Bubble departure diameter	ANSD	Bubble diameter
Default	Tolubinsky	Kurul	Yoneda
A	Default	Default	Default
B	Koca.	Default	Default
C	Default	Hibiki	Default
D	Default	Default	Yun

Table III: The comparison of the bubble departure diameter model

	Case A	Case B
Bubble departure diameter (mm)	~0.9	~0.4

Table IV: The comparison of the ANSD model

	Case A	Case C
ANSD (sites/m^2)	~5 x 10^5	~3 x 10^5

Table V: The comparison of the bubble diameter model

	Case A	Case D
Bubble diameter (mm)	~12	~55