Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 29-30, 2009

Modification and Validation of the MARS Reflood Model using FLECHT-SEASET 31504 Test

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1. Introduction

A thermal-hydraulic system code, MARS (Multi-dimensional Analysis of Reactor Safety) has been developed for realistic thermal-hydraulic system analysis of light water reactor transients. MARS has been assessed against various experimental data to qualify whether its performance is adequate for the reflood phase under a simulated loss-of-coolant accident conditions. Several studies concluded that MARS code had some deficiencies in the reflood model. MARS under-predicted the peak cladding temperatures and the quenching was predicted much earlier than experimental results.

In this study, to assure accurate prediction of the reflood thermal-hydraulic phenomena, MARS reflood model is carefully reviewed and modified. To investigate the effects of the modifications, the assessment is conducted using FLECHT-SEASET 31504 forced reflood test. Detail specifications and conditions of this test are described in [1-3].

2. System Modeling

The core is one-dimensionally modeled using 20 and 40 uniform cells. The schematics of input model and details of system modeling are demonstrated in [3]. The interpolation scheme for calculated results is used for valid comparison between calculation and experimental data.

3. Modifications of Reflood Model

To improve the predictability of code for peak cladding temperature and quenching time, film boiling wall-to-fluid heat transfer models of MARS, which are activated when the reflood option is invoked, are mainly modified.

In original version, the same wall-to-fluid heat transfer models are used for the entire film boiling regime. However, in modified version, the film boiling heat transfer regime is divided into three separate parts according to the void fraction. If the void fractions are under 0.6 and over 0.9, inverted annular film boiling (IAFB) and dispersed flow film boiling (DFFB) regimes are assumed to exist respectively. Inverted slug film boiling (ISFB) regime is assumed, if the void fraction is between 0.6 and 0.9. For each flow regime, appropriate wall-to-fluid heat transfer correlations are applied.

3.1 Wall-to-Liquid Convective Heat Transfer

In original version, the code takes the maximum of three heat transfer coefficients which are calculated by Bromley, empirical CATHARE and Forslund-Rohsenow correlations.

In modified version, for IAFB, empirical CATHARE correlation is used, and Forslund-Rohsenow correlation modified by Bajorek and Young is applied for DFFB. For ISFB, heat transfer coefficient is obtained by spline interpolation of IAFB and DFFB heat transfer coefficients.

$$h_{wl,ISFB} = y \cdot h_{wl,IAFB} + (1-y) \cdot h_{wl,DFFB} \quad (1)$$

$$y = x \cdot (2-x),\ x = (0.9-\alpha_g)/(0.9-0.6) \quad (2)$$

3.2 Wall-to-Vapor Convective Heat Transfer

In original version, h_{Ditt} is obtained by taking the maximum of a turbulent convective heat transfer coefficient calculated by Dittus-Boelter correlation, a laminar HTC using a laminar convective Nusselt number of 4.36 and a natural convective HTC calculated by Churchill-Chu correlation. Then, wall-to-vapor convective HTC is obtained by void fraction ramping of h_{Ditt} .

In modified version, IAFB wall-to-vapor convective HTC is obtained by considering only-conduction heat transfer from wall to vapor film.

$$h_{wg,IAFB} = 2 \cdot k_g / \delta \quad (3)$$

where k_g is the vapor conductivity and δ is the vapor film thickness for a rod bundle geometry.

For DFFB, HTC is determined from

$$h_{wg,DFFB} = \Phi \cdot [F_{lt} \cdot h_{lam} + (1-F_{lt}) \cdot h_{tur}] \quad (5)$$

where h_{tur} is calculated by Dittus-Boelter correlation with Reynolds number based on the vapor property only. MARS uses the Churchill's superposition method to obtain laminar convective HTC, h_{lam} .

$$h_{lam} = \left[h^3{}_{lam,FC} + h^3{}_{NC}\right]^{1/3} \quad (6)$$

where $h_{lam,FC}$ and h_{NC} are obtained by constant nusselt number of 10.0 and Churchill-Chu correlation respectively. F_{lt} is a linear function of gas Reynolds number. It has a value of 1.0 at $\mathrm{Re}_g = 3000$ and a value of 0.0 at $Re_g = 10000$. Φ is the two-phase enhancement factor to account for the enhancement of the convective component of wall-vapor heat transfer due to the relative motion of vapor and droplets. The factor can be represented using rough wall analogy.

$$\Phi = \sqrt{\frac{\tau_i + \tau_w}{\tau_w}} \quad (7)$$

where τ_i and τ_w are friction forces per unit volume due to interfacial and wall drags respectively.

For ISFB, the spline interpolation method is used to calculate wall-to-vapor convective HTC as mentioned above.

3.3 Wall-to-Fluid Radiation Heat Transfer

In original version, wall-to-liquid radiation HTC is obtained using radiation heat transfer model developed by Sun. The wall-to-vapor radiation heat transfer is neglected.

In modified version, for IAFB, radiative component is almost entirely from the wall to the liquid, and heat flux is approximated by

$$q''_{wl,rad} = \frac{\sigma_{SB} \cdot (T_w^4 - T_l^4)}{\frac{1}{\varepsilon_l \cdot \sqrt{1-\alpha}} \cdot \left(\frac{1}{\varepsilon_w} - 1\right)} \quad (8)$$

The radiation from the wall to vapor phase is ignored in IAFB. For DFFB, the wall-to-liquid and wall-to-vapor radiation heat transfer is considered using Sun's model which is applied in original version. The ISFB radiation HTC is determined using the spline interpolation method.

3.4 Code Error Corrections

In original version, the average droplet diameter during reflood is obtained as

$$d = \min(D_h, dcon2, diam) \quad (9)$$

where $dcon2 = 0.0015m$ for the post-CHF droplets and $diam$ is defined as

$$diam = \max(d\min, d_{We=1.5}) \quad (10)$$

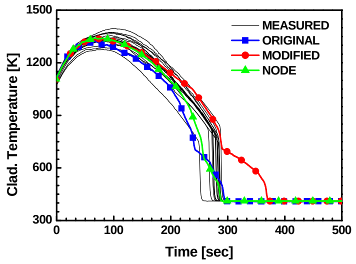
where $d\min = 0.0015m$ if the pressure is sufficiently low. However, dcon2 in (9) is not the maximum but the minimum average droplet diameter. Therefore in modified version, the correction is made as

$$d = \min(D_h, diam) \quad (11)$$

4. Results and Discussions

Figure 1 shows comparisons of predicted and measured cladding temperatures at the middle and high elevation, where "MODIFIED" and "NODE" denote the results for 20 and 40 cells models using modified reflood model respectively.

As shown in Fig. 1, the modifications of reflood model have great effects especially at the higher elevation. After the modifications, PCT increases and quenching times are made delayed. Code predictions are in good agreement with experimental data when using 40 cells model.



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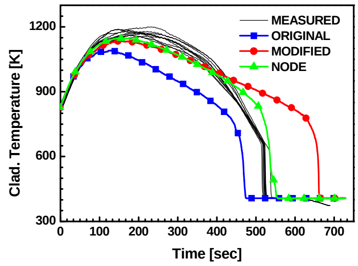

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Fig. 1. Comparisons of calculated and experimental cladding temperatures at the middle and high elevations

4. Conclusions

The modifications and assessment of MARS reflood model using FLECHT-SEASET 31504 forced reflood test have been conducted. After the modifications, not only PCTs but also quenching times are greatly improved and the increase of the number of the cells modeling the core improve the calculation results

Acknowledgement

This work was supported by Nuclear Research & Development Program of the National Research Foundation (NRF) grant funded by the Korean government (MEST).

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