Modification of the Post-CHF Heat Transfer Model in the SPACE Code for SBLOCA Analysis

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1. Introduction

SPACE has been developed domestically to provide a tool for safety analysis of a nuclear power plant [1]. Meanwhile, the small-break loss-of-coolant accident (SBLOCA) methodology based on the Appendix K of 10 Code of Federal Regulations (CFR) 50 (Appendix K, hereinafter) with SPACE has been approved by KINS [2]. Recently, KNF has reviewed the SBLOCA methodology in the view point of the plant design analysis and found that several conservative approaches are included in this evaluation model (EM) [3]. These would result in not only the decrease in a safety margin but also distortions in the direction for the SBLOCA analysis. Among all those conservative approaches incorporated in SBLOCA methodology [2], the conservatism which lies in the post-CHF heat transfer correlations based on Appendix K in the SPACE code is investigated and assessed herein. Especially, the following sections are described in a focus on the use of option 81 corresponding to the transition boiling model in SPACE.

In Section 2, the assessment of the legacy model of SPACE for Appendix K post-CHF is described in detail. In addition, the comparisons of post-CHF models between SPACE and RELAP5 based on Appendix K are discussed in this section. The improved post-CHF model in SPACE for the SBLOCA analysis will be explained and then the assessment results in accordance with the new post-CHF model are presented in Section 3. Lastly the major conclusions are described in Section 4.

2. Assessment of the Previous Appendix K Post-CHF Model

In order to investigate the Appendix K post-CHF model in SPACE, the assessments related to post-CHF are performed against the Royal Institute of Technology (RIT) tube tests, the Bennett heated tube tests, the thermal-hydraulic test facility (THTF) tests, and APR1400 plant (or OPR1000 plant) as well. In these assessment calculations, the sensitivities related to the use of the option 81 are also performed.

Figure 1 shows the peak cladding temperature (PCT) behaviors of APR1400 with and without option 81. When the option 81 is turned on, an enormous PCT rise almost as high as a LOCA criterion [9] is observed at early stage of calculation. Whereas, the PCT rise disappears when the option is not used. This behavior so called a departure from nucleate boiling (DNB) PCT is unrealistic, since the negative feedback due to the void after break should give sufficient power reduction in considering that the coolablility of the core still remains by the reactor coolant pumps (RCPs) as far as the core is covered by coolant.

Figure 2 shows the nodalization diagram of the input model for the post-CHF tests. As shown in this figure, the hydraulic components included in this model are a pipe and two boundary components located at the inlet and outlet of the test section. A heat structure with the heat source is attached to the pipe. The heated section to simulate RIT, Bennett, and THTF tests was nodalized in detail 36, 30, and 20 nodes which are denoted by N in Figure 2, respectively. Table 1 presents the major geometrical information and the initial conditions for the post-CHF experiments.

Comparisons of measured and predicted surface temperatures with option 81 turned on and off along the axial heated length for RIT, Bennett, and THTF are presented in Figures 3 through 5, respectively. The surface temperature predictions with the activated and inactivated option 81 show the different behavior. The calculations using the option 81 turned on appear to be in relatively good agreement with the experimental data. According to NUREG-1230 [4], the DNB PCT is strongly corresponding to the stored energy in a fuel rod and the RCPs until the reactor is scrammed. As the result, the DNB PCT is insensitive to the break size while the boil-off PCT is judged by the several leak sizes resulting in a deep core uncover. In SBLOCA analysis, it is very important to determine the limiting break size for a safety analysis report (SAR). Hence SPACE SBLOCA EM is necessary to the alternatives without option 81 to satisfy the validation of Table 1 conservatively.

In order to understand the different temperature behaviors with option 81 turned on and off, a comparison analysis of Appendix K post-CHF Models in SPACE SBLOCA EM [2] and those in RELAP5 sEM [5] found that the option 81 is closely related to the transition boiling model. The model analysis germane to the option 81 is provided in Table 2.

The liquid contact area fraction (ξ) in Table 2 seems to play an important role in the transition boiling model. According to Incropera [6], the hysteresis in transition boiling of post-CHF region can be classified into two curves: First, the cooling curve from the minimum film boiling to the nucleate boiling heat flux and Second, the heating curve from the critical heat flux to the burnout vapor heat flux. If the option 81 activated in the input model, those two curves are applied in the Bjornard and Griffith (BG) correlation [7] modifying the liquid contact area fraction to be determined depending on the cooling or heating. The option 81 may coincidently produce the conservative predictions and unrealistic behaviors of the figure-of-merits (FOMs) for the SBLOCA analysis which may lead the contaminated results as well. Therefore, it is determined to be the option 81 unused and to maintain the conservatism in the Appendix K post-CHF heat transfer model, simultaneously.

3. New Appendix K Post-CHF Model

As already described, the predictions of SPACE with option 81 inactivated show very poor agreement with the steady-state post-CHF experiments. In order to improve the Appendix K post-CHF model for SBLOCA, the modification to the transition boiling, the film boiling, and CHF models have been performed as follows. First, the Chen model [8] applied in RELAP5 instead of default transition boiling model has been implemented in SPACE. Second, the radiation heat transfer applied at the film boiling mode is not considered with respect to the conservative predictions. Finally, the B&W-2 CHF model of Appendix K in 10 CFR 50 used in sEM [5] reveals overly conservative predictions for the static quality more than 0.2 and less than 0.5 through the comparison analysis of the experimental data [10] which is shown in Figure 6. Figure 7 shows that the conservative prediction for a specific quality conditions is eliminated by means of better fitting the experimental data. A modified B&W-2 CHF model is well compatible with the experimental data trend, which is shown in Figure 7. In addition, the thermal equilibrium quality in B&W-2 correlation is corrected by the static quality which is identical to that of the original reference [10] instead of equilibrium quality. The aforementioned new post-CHF models in comparison with the legacy models are provided in Table 3.

Figures 8 through 9 show the code accuracy for Appendix K post-CHF with SPACE before and after modifications (see Table 3). In the SPACE predictions of the legacy model where the option 81 is not used, the surface temperature results are under predicted for the experimental data as shown in Figure 8. On the other hand, SPACE EM calculation with new post-CHF model presented in Figure 9 shows a conservative prediction for the surface temperature. From Figure 10, it is evident that the RELAP5 EM highly overestimated surface temperatures for THTF simulation equipped with multi rods in an assembly. Whereas this tendency is eliminated with the SPACE EM used in the new post-CHF model as shown in Figure 9. Therefore, the SPACE EM is judged to be conservatively in reasonable agreement with the data.

4. Conclusions

The capability of the Appendix K post-CHF heat transfer model of SPACE for SBLOCA analysis is reviewed and scrutinized thoroughly. The closer inspection of the heat transfer model of SPACE for Appendix K post-CHF has revealed that it is inappropriate to be applied to the plant calculations and the quasi steady-state test predictions. Therefore, the optional new model of Appendix K post-CHF model of SPACE is modified and in turn shows significant improvement in the predicted results in the aspects of SBLOCA analysis. In order to discuss the uncertainty related to the conservative calculations, the surface temperature bounded by one-sided 95% of new SPACE Appendix K post-CHF prediction is 485.1 K in contrast with the 646.7 K obtained with the RELAP5 EM. Eventually, the modified post-CHF model for SPACE can be judged to be used for the SBLOCA analysis of the domestic PWR.

Acknowledgements

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REFERENCES

[1] S. J. Ha et al., “Development of the SPACE code for nuclear power plants,” Nuclear Engineering and Technology, Vol. 43, February 2011.
[2] KHNP, “SBLOCA Safety Analysis Evaluation Methodology for APR1400 Type Nuclear Power Plants using the SPACE Code [Topical Report],” TR-KHNP-0031, March 2017.
[3] KNF, “SPACE SBLOCA 평가모델의 설계적용을 위한 문제점 분석 보고서,” KNF-TR-NAA-17016 Rev. 0, December 2017.
[4] U.S.NRC, “Compendium of ECCS Research for Realistic LOCA Analysis,” NUREG-1230, December 1988.
[5] KHNP, “한국표준형원전 SBLOCA 안전해석방법론 [Topical Report],” TR-KHNP-0011, June 2007.
[6] F. P. Incropera et al., “Fundamentals of Heat and Mass Transfer,” Wiley, 2007.
[7] T.A. Bjornard et al., “PWR Blowdown Heat Transfer,” Thermal and Hydraulic Aspects of Nuclear Reactor Safety, American Society of Mechanical Engineers, New York, 1, 17-41, 1977.
[8] J.C. Chen et al., “A Phenomenological Correlation for Post-CHF Heat Transfer,” NUREG-0237, 1977.
[9] U.S.NRC, “10 Code of Federal Regulations 50.46 Acceptance criteria for emergency core cooling systems for light water nuclear power reactors,” Aug. 28. 2007.

[10] J.S. Gellerstedt et al., "Correlation of Critical Heat Flux in a Bundle Cooled by Pressurized Water," Two-Phase Flow and Heat Transfer in Rod Bundles, ASME, New-York, 1969.
[11] K. M. Becker et al., "An experimental Investigation of Post Dryout Heat Transfer," KTH-NEL-33, Royal Institute of Technology Stockholm, Sweden, May 1983.
[12] A. W. Bennett et al., "Heat Transfer to Steam-Water Mixtures Flowing in Uniformly Heated Tubes in which the Critical Heat Flux has been Exceeded," AERE-R5373, October 1976.
[13] C. B. Mullins et al., "ORNL Rod Bundle Heat Transfer Test Data Volume 7." NUREG/CR-2525, Vol. 7, May 1982.
[14] J. J. Carbajo et al., "A Study on the Rewetting Temperature," Nuclear Engineering and Design, Vol. 84, 21, 1985.

Table 1. Summary of the Geometry and Initial Conditions for Post-CHF Tests

Parameters	Geometrical/Initial Value		
	RIT[11]	**Bennett[12]**	**THTF[13]**
Heated Length (m)	7.0	5.537	3.66
Inner Diameter (cm)	1.5	1.2624	0.95 (Rod Dia.)
Pressure (bar)	30~200	69	40~128
Mass Flux (kg/m^2-s)	500~3,000	380~5,181	255~806
Heat Flux (W/cm^2)	9~125	5.12~17.5	38~94
Subcooling (K)	10	13~34	20~60

Table 2. Comparison of Transition Boiling Models for SPACE

Opt. 81	**Transition Boiling Model**
On	$q''_{TB} = \xi \cdot q''_{CHEN_{NB}}$ where, At cooling $\xi = C \cdot \left[\frac{T_W - T_{MFB}}{T_{CHF} - T_{MFB}}\right]^{0.25}$ At heating $\xi = C \cdot \left[\frac{T_W - T_{MFB}}{T_{CHF} - T_{MFB}}\right]^{4.0}$ $C = \begin{cases} \max(0.2, 1-\alpha_g) & for\ reflood \\ 1 & for\ others \end{cases}$
Off	$q''_{TB} = \xi \cdot q''_{CHF} + (1-\xi) \cdot q''_{MFB}$ where, $\xi = \left[\frac{T_W - T_{MFB}}{T_{CHF} - T_{MFB}}\right]^2$

Table 3. Comparison of the Appendix K Post-CHF Models

HT Mode	**Previous Model**	**New Model**
Transition Boiling	Bjornard-Griffith (Option 81 On)	Modified Chen(1977) [8]
Film Boiling	App.K Model (Groeneveld 5.7)	App.K Model (Groeneveld 5.7) Without Radiation HT
CHF	B&W-2	Modified B&W-2 (See Fig. 7)
T_{min}	Carbajo (1985) [14]	Carbajo (1985) [14]

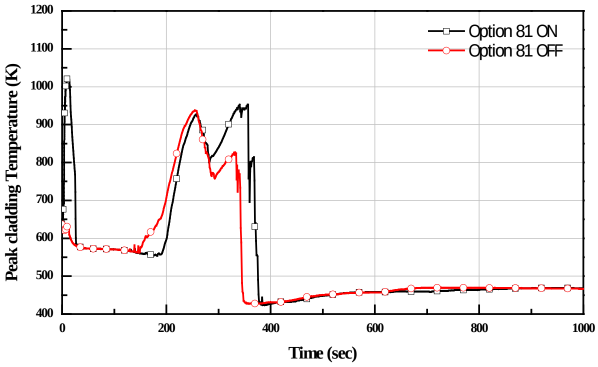

Fig. 1. Comparison of the PCT Predictions with Option 81 On/Off for 0.4 ft^2 DVI Line Break in APR1400 [3]

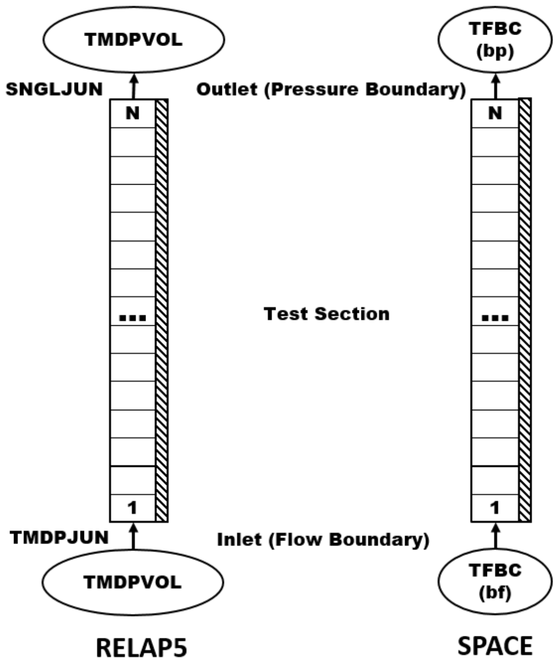

Fig. 2. SPACE and RELAP5 Nodalization Diagrams for the Post-CHF Test Facilities

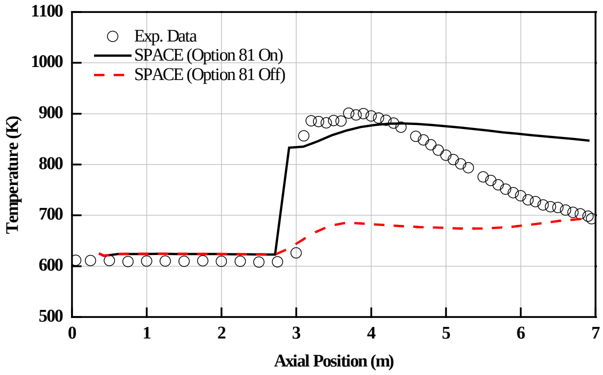

Fig. 3. Measured and Calculated Tube Surface Temperatures for RIT Tube Test 139 with Option 81 On/Off in SPACE

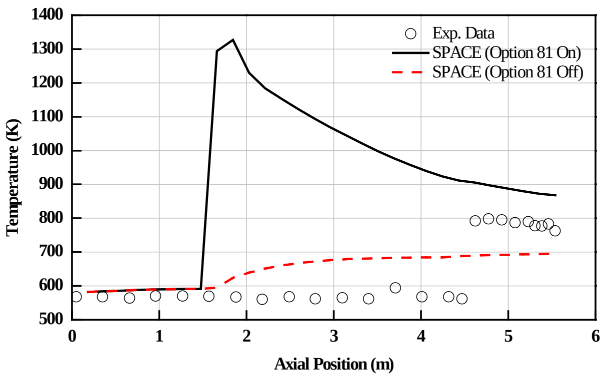

Fig. 4. Measured and Calculated Tube Surface Temperatures for Bennett Tube Test 5394 with Option 81 On/Off in SPACE

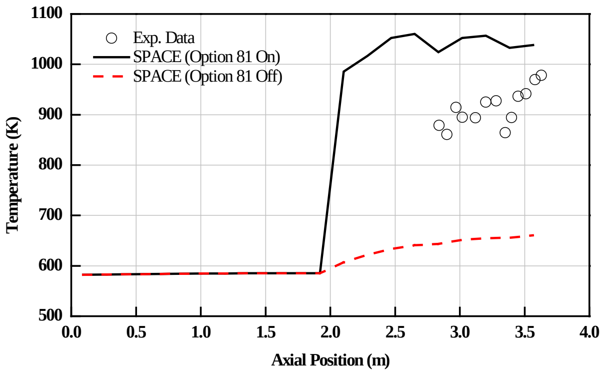

Fig. 5. Measured and Calculated Tube Surface Temperatures for ORNL THTF Test 3.07.09H with Option 81 On/Off in SPACE

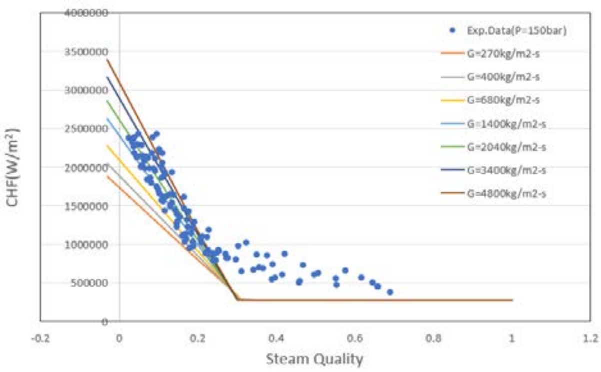

Fig. 6. Comparison of Experimental Data and Previous Correlation for B&W2 CHF (P=150 bar)

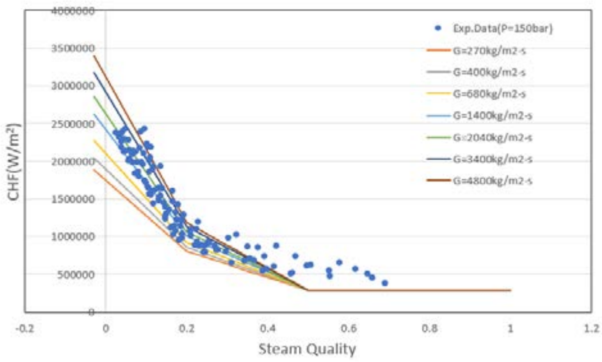

Fig. 7. Comparison of Experimental Data and New Correlation for B&W2 CHF (P=150 bar)

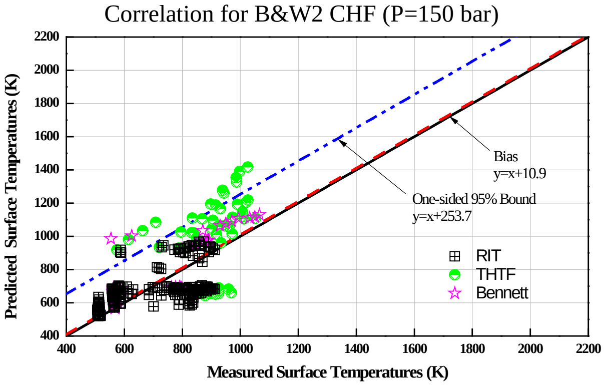

Fig. 8. Code Accuracy for Previous Appendix K Post-CHF Model (SPACE)

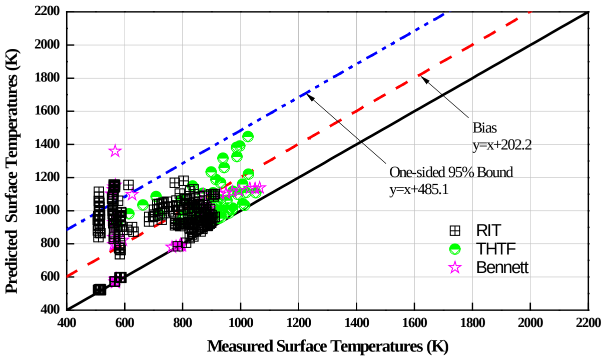

Fig. 9. Code Accuracy for New Appendix K Post-CHF Model (SPACE)

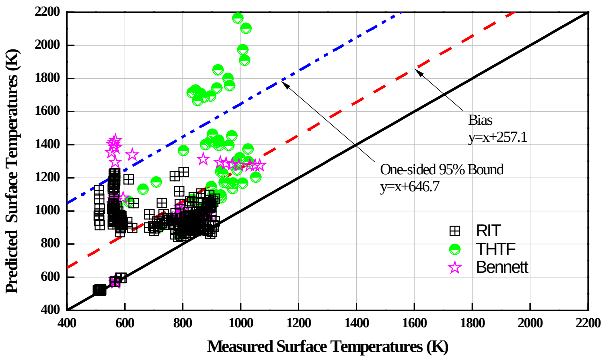

Fig. 10. Code Accuracy for Appendix K Post-CHF Model (RELAP5)