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Comparison of Thermal Hydraulic Feedback Solutions between McCARD and DeCART2D/MASTER for SMART Benchmark Problem

Young Beom Shon [a], and Ho Jin Park [a*]
[a] *Kyung Hee University, 1732 Deokyoungdaero, Giheung-gu, Yongin-si, Gyeonggi-do, Korea, 17104*
[*] *Corresponding author: parkhj@khu.ac.kr*

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1. Introduction

Recently, the development of small modular reactors (SMR) has primarily aimed at miniaturization, sufficient thermal margins, and long-term operation compared to conventional nuclear power plants. These design objectives result in significant temperature gradients across the effective core height and variations in neutron economy, which in turn impact not only neutronics but also Thermal Hydraulics (T/H) analyses. According to it, high fidelity T/H feedback effect shall be considered for accurate reactor design and safety analysis.

Meanwhile, ^{135}Xe generated during operation has a large absorption cross section and impacts reactivity and power distribution. During reactor operation at a constant power, the number density of ^{135}Xe generally converges to an equilibrium state as a balance between nuclear reactions and decay. Because the equilibrium ^{135}Xe number density may be used as an initial condition in core design and safety analysis, it must be carefully considered.

In this study, SMART [1] SMR benchmark analyses were conducted to examine the capability of the T/H feedback for McCARD [2] Monte Carlo (MC) transport code and DeCART2D/MASTER [3,4] two-step procedure core design code system. The benchmark analyses were performed by considering two cases: one in which the T/H feedback and equilibrium xenon condition were considered, and one in which the T/H feedback and equilibrium xenon condition were not considered.

2. Computational Codes and Schemes

In this study, two codes, McCARD and MASTER, were utilized to calculate nuclear design parameters. The McCARD and MASTER codes use the MC transport method and the nodal diffusion method for neutronic analyses, respectively.

2.1 McCARD Monte Carlo Transport Code

McCARD is an MC neutron/photon transport code developed by Seoul National University, utilizing a continuous energy library for nuclear system design and analysis. In addition, using the MC method, a T/H feedback coupling neutronics and T/H and equilibrium xenon condition algorithm [5] were established and verified. Based on this, neutronics and T/H analysis are performed, allowing for precise analysis of the interaction driven by the Power distribution and temperature profile. Figure 1 illustrates the T/H feedback and equilibrium xenon condition algorithm in McCARD.

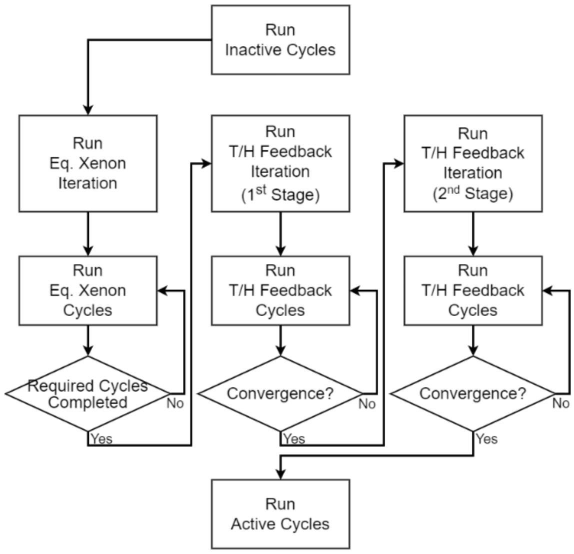

Fig. 1. McCARD T/H feedback & Eq. Xe Algorithm

For the T/H feedback calculation, it must be combined through repeated calculations due to the nonlinearity between the power distribution and the temperature profile. McCARD increased the efficiency of the calculation through the two-stage iteration scheme [6]. In the first step (1st stage), the number of histories increases linearly in the MC calculation for fast temperature convergence of the material. In a subsequent step (2nd stage), a precise temperature calculation is performed. The fifteenth-order Gauss-Hermite integration On-The-Fly Doppler Broadening method [7] is used to calculate the cross-section of the updated temperature at each iteration. The temperature convergence is determined to be satisfied when the temperature difference between the previous iteration and the current iteration is less than 10 K in the repetitive calculation process, and the temperature calculation is terminated based on this criterion.

The T/H model of the fuel assembly based on 1D energy conservation equation and heat transfer equation was used to calculated the temperature profile. The specific enthalpy of the moderator in the axial direction is expressed as follow:

$$h_{i+1} = h_i + \left[\frac{1}{GA}\right]\dot{q} = h_i + R_i'\dot{q} \qquad (1)$$

where G denotes the mass flux.

The temperature of the fuel component in the radial direction is expressed as follows:

$$T_c = T_w + \left[\frac{1}{h_w(2\pi r_c H)}\right]\dot{q} = T_w + R_w'\dot{q} \qquad (2)$$

$$T_g = T_c + \left[\frac{\ln\left(1 + (r_c - r_g)/r_g\right)}{2\pi H K_c}\right]\dot{q} = T_c + R_c'\dot{q} \qquad (3)$$

$$T_s = T_g + \left[\frac{1}{h_g(2\pi r_f H)}\right]\dot{q} = T_g + R_g'\dot{q} \qquad (4)$$

$$T_f = T_s + \left[\frac{1}{4\pi H k_f}\right]\dot{q} = T_s + R_f'\dot{q} \qquad (5)$$

where h_w and h_g denote the heat transfer coefficients of the moderator and the gap, respectively, and k_f and k_c represent the thermal conductivity coefficients of the fuel and the cladding.

2.2 DeCART2D/MASTER Two-Step Design Code System

The DeCART2D/MASTER is a deterministic neutron transport code system developed by Korea Atomic Energy Research Institute (KAERI), based on a two-step procedure for nuclear system design and analysis. DeCART2D uses the Method of Characteristic (MOC) to generate the Homogenized Group Constant (HGC) of the fuel assembly, and MASTER uses HGC to perform steady-state and transient-state analyses of the core based on the Source Expansion Nodal method (SENM).

For the T/H feedback calculation, the temperature profile using Cobra III-CP module [8] was calculated. Cobra III-CP performs T/H analysis of fuel assembly and calculates the moderator flow analysis of fuel assembly based on the homogeneous equilibrium model. Through Cobra III-CP, the temperature profile of fuel and moderator can be calculated more precisely. Based on these profiles, MASTER can accurately reflect Doppler Broadening and T/H feedback. The specific enthalpy within the Cobra III-CP module is defined as follows:

$$h_i = h_0 + \sum_{k=1}^{i-1}\frac{P_k}{\dot{m}}\Delta Z_k + \frac{1}{2}\frac{P_i}{\dot{m}}\Delta Z_i \qquad (6)$$

where P_k denotes the linear power density.

3. Numerical results

3.1 Description of SMART SMR Benchmark

The published data of SMART (System-Integrated Modular Advanced ReacTor) [1], a SMR developed by KAERI, has been set as a benchmark problem. The benchmark is designed to produce 365 MW at full power operation. The flow rate is maintained at 2090 kg/s, and the temperature difference is 30 K. There are two enrichment types of 17x17 fuel assemblies. Gadolinia, used as a burnable absorber for reactivity and peaking control, is used in both fuel assembly types. Figure 2 illustrates the schematic loading pattern.

	E	F	G	H	J
5	A2	A3	A2	B5	B3
6	A3	A2	A3	B5	B0
7	A2	A3	B5	B0	
8	B5	B5	B0		
9	B3	B0			

Fig. 2. Benchmark Core Loading Pattern

McCARD reference solutions according to the considering or not considering T/H feedback and equilibrium xenon condition for benchmark problems were performed based on the ENDF/B-VII.1 evaluated nuclear data library (ENDL). DeCART2D/MASTER calculation results were compared with the counterparts of the McCARD reference solutions. The DeCART2D library for comparison is based on ENDF/B-VII.1 ENDL with 47 energy group structure. In the calculation not considering T/H feedback, the moderator and fuel temperature were assumed to be 583.15 K and 873.15 K, respectively.

3.2 Results of T/H Feedback Analyses for FA Problem

The difference in nuclear design parameters between McCARD and MASTER for each FA and Checkerboard benchmark is analyzed. The Checkerboard benchmark was composed of alternating A3 and B3 FAs. McCARD calculations were performed using 100,000 histories per cycle, 200 inactive cycles, and 1000 active cycles. The stochastic uncertainties of the effective multiplication factors by the McCARD calculations are less than 7 pcm.

The T/H feedback calculations were performed in the two stages using a total of 2000 active cycles with 100,000 histories per cycle to ensure the convergence. In the first stage, the number of cycles was gradually increased by 200 from 200 to 600 to accelerate the temperature convergence. In the subsequent stage, 800 cycles were performed for a precise temperature calculation.

Tables I and II compare the effective multiplication factors and axial power distributions between McCARD and MASTER. A maximum difference of 134 pcm was calculated compared to the McCARD in the case where T/H feedback and equilibrium xenon condition were not considered, whereas a maximum difference of 156 pcm was calculated when considered. The axial power distribution remains consistent between McCARD and MASTER, and the RMS difference is within a maximum of 3%.

Table III shows the fuel and moderator temperature differences. The moderator temperature differences are observed in the range of 0.11 K to 0.61 K, indicating a negligible difference within 1 K, while the fuel temperature differences are observed to be around 13 K.

Table I. Difference in reactivity between McCARD and MASTER for FA and checkerboard problems

Benchmark	Difference in reactivity between McCARD and MASTER (pcm) [2]	
	w/o TFB & Eq.Xe	w/ TFB & Eq.Xe
A2	-21	-12
A3	-91	-68
B0	134	156
B3	38	9
B5	-76	-108
Checkerboard	-48	-61

1) Stochastic uncertainty (=1σ) is less than 0.00007.
2) Difference in reactivity (=$1/k_{MAS} - 1/k_{McC}$)

Table II. Difference in axial power distribution between McCARD and MASTER for FA and checkerboard problems

Benchmark	Difference in axial power distribution between McCARD and MASTER (%) [2]	
	w/o TFB & Eq.Xe	w/ TFB & Eq.Xe
A2	0.92	1.91
A3	2.54	1.18
B0	0.54	0.84
B3	2.74	1.46
B5	4.00	3.12
Checkerboard	2.78	3.05

1) Relative error is less than 0.050%
2) Difference in axial power distribution (=$\{(P_{MAS} - P_{McC})/P_{McC}\}$x100)

3.3 Results of T/H Feedback Analyses for Core Problem

Table IV shows the difference in the effective multiplication factor in the core benchmark at BOC. McCARD calculations were performed using 100,000 histories per cycle, 200 inactive cycles, and 1200 active cycles. The stochastic uncertainties of the effective multiplication factors by the McCARD calculations are less than 6 pcm.

Table III. Difference in temperature profiles between McCARD and MASTER for FA and checkerboard problems

Benchmark	Average difference of temperatures (Kelvin) [2]	
	Moderator	Fuel
A2	0.21	13.03
A3	0.61	13.00
B0	0.15	12.82
B3	0.11	12.95
B5	0.25	13.29
Checkerboard	0.14	12.88

1) Standard deviation of average temperature is less than 0.1 K
2) Difference in Temperature (=$Temp_{McC} - Temp_{MAS}$)

The T/H feedback calculations were performed using a total of 2800 active cycles with 100,000 histories per cycle to ensure the convergence. Consistent with the T/H feedback option applied in Section 3.2, the first stage gradually increased the number of cycles from 200 to 800 to accelerate temperature convergence, followed by 800 cycles in the second stage for accurate temperature evaluation. As a result, considering T/H feedback and equilibrium xenon condition reduces the difference compared to the case without these conditions.

Table IV. Difference in reactivity between McCARD and MASTER for core problems

Benchmark	Difference in reactivity between McCARD and MASTER (pcm) [2]	
	w/o TFB & Eq.Xe	w/ TFB & Eq.Xe
Core	-115	-76

1) Stochastic uncertainty (=1σ) is less than 0.00006
2) Difference in reactivity (=$1/k_{MAS} - 1/k_{McC}$)

Figures 3 and 4 show the axial and FA-wise power distributions, respectively. RMS differences in the axial power distribution are 1.37% and 2.59% when T/H feedback and equilibrium xenon conditions are not considered and considered, respectively. Considering T/H feedback in the axial power distribution results in a more uniform distribution. The FA-wise power distribution is also consistent except near the reflector region. The RMS difference is within 1%, regardless of T/H feedback and equilibrium xenon condition. The peaking factor confirms the consistency of power distribution between McCARD and MASTER. The peaking factor (Fq) is calculated at the same location, with values of 1.32 in McCARD and 1.34 in MASTER. The consistency in both the peak position and magnitude of the peaking factor demonstrates the accuracy of the overall power distribution.

The coolant temperature profile based on the power distribution demonstrates similar behavior between McCARD and MASTER. The corresponding axial temperature profile is shown in Figure 5. In contrast, the fuel temperature maintains a difference of about 13 K between the two codes, with more difference observed near the reflector. The FA-wise temperature profile is shown in Figure 6, and the overall fuel temperature difference is mainly due to differences in the fuel temperature calculation methods used in each code.

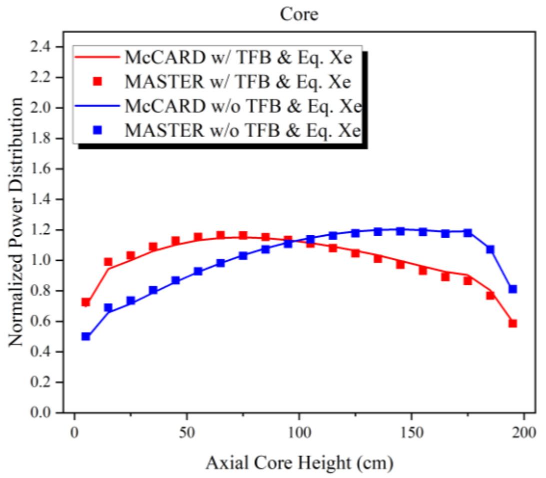

Fig. 3. Axial Power Distribution for SMART Core

	E	F	G	H	J
5	A2 0.981 0.979 -0.20%	A3 0.954 0.953 -0.12%	A2 1.028 1.027 -0.08%	B5 1.163 1.163 0.03%	B3 0.923 0.913 -1.06%
6	A3 0.953 0.953 0.00%	A2 1.005 1.003 -0.17%	A3 0.970 0.973 0.37%	B5 1.110 1.110 -0.04%	B0 0.873 0.848 -2.85%
7	A2 1.024 1.027 0.26%	A3 0.965 0.973 0.86%	B5 1.117 1.123 0.50%	B0 0.981 0.961 -1.99%	
8	B5 1.150 1.163 1.13%	B5 1.098 1.110 1.03%	B0 0.976 0.961 -1.56%		
9	B3 0.908 0.913 0.60%	B0 0.859 0.848 -1.31%			Assembly McCARD MASTER Diff. (%)

Fig. 4. FA-wise Power Distribution for SMART Core

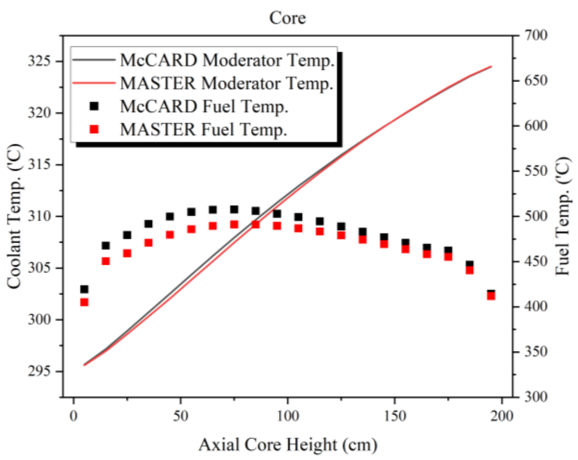

Fig. 5. Axial Temperature profile for SMART Core

4. Summary and Conclusions

In this study, SMART SMR T/H benchmark analyses were conducted by McCARD MC code and MASTER deterministic core design code. Against the FA, checkerboard, and core analyses, it was noted that the capability of the T/H feedback modules in the two codes was validated and verified by code-to-code comparison.

To examine the detailed results, considering T/H feedback and equilibrium xenon in the core benchmark, the RMS differences between the axial and FA-wise power distribution are 2.59% and 1.00% respectively, and the effective multiplication factor difference is less than 100 pcm. For the overall temperature of the system, the temperature difference of the moderator is less than 0.5 K, and the difference in the fuel is less than 15 K. Considering that the two codes may use different T/H conductivity and resistance conditions, the results show considerable difference.

In the near future, a burnup analysis involving T/H feedback and equilibrium Xe will be conducted for the SMART core benchmark problem.

	E	F	G	H	J
5	A2 0.09 11.64	A3 0.11 11.56	A2 0.17 12.85	B5 0.11 12.36	B3 0.18 11.21
6	A3 0.07 11.24	A2 0.09 11.81	A3 0.04 11.20	B5 0.16 12.83	B0 0.44 13.55
7	A2 0.08 12.09	A3 -0.02 10.63	B5 0.18 13.11	B0 0.53 15.80	
8	B5 0.12 12.46	B5 0.10 12.32	B0 0.45 14.98		
9	B3 0.24 12.11	B0 0.48 14.23			Assembly Mod. Err (K) Fuel Err (K)

Fig. 6. FA-wise Temperature profile for SMART Core

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REFERENCES

[1] H. O. Kang, B. J. Lee, S. G. Lim, “Light water SMR development status in Korea,” Nucl. Eng. Des., 419, 112966, 2024.
[2] H. J. Shim et al., “McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis,” Nucl. Eng. Technol., 44, pp.151-176, 2012.
[3] J. Y. Cho, et al., “DeCART2D v1.1 User’s Manual,” KAERI/UM-40/2016, 2016.
[4] J. Y. Cho, et al., “MASTER v4.0 User’s Manual,” KAERI/UM-41/2016, 2016.
[5] Y. I. Kim, S. H. Jang, D. H. Lee, and H. J. Shim, "Validation of Activation Analysis Method on RV/RVI of Kori Unit 1

Using McCARD/ORIGEN2," Proc. Reactor Phys. Asia 2019 (RPHA19) Conf., Osaka, Japan, Dec. 2–3, 2019.
[6] H. G. Joo, et al., "Consistent Comparison of Monte Carlo and Whole-Core Transport Solutions for Cores with Thermal Feedback," PHYSOR 2004, Chicago, IL, 2004.
[7] S. M. Kang, H. J. Shim, L. C. Leal, "Development of an On-The-Fly Doppler Broadening Module in McCARD," Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 29–30, 2014.
[8] H. G. Joo, et al., "Implementation of Refined Core Thermal-Hydraulic Calculation Feature in the MARS/MASTER Code," Proc. Korean Nuclear Society Autumn Meeting, 2000.