Preliminary Analysis of Boron-Free Operation Small Modular Reactor using McCARD and DeCART2D

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1. Introduction

The primary goals of a boron-free operation small modular reactor (SMR) such as innovative SMR (i-SMR) currently being developed in South Korea is to operate with an enhanced fuel thermal margin, extended operational cycles, and under soluble boron-free (SBF) conditions [1,2]. Therefore, new and optimized design and operating conditions are required, differing from those of the commercially operating Pressurized Water Reactors (PWRs). This implies that directly applying the existing core design analysis code system could result in errors. Therefore, it is necessary to first apply the core design analysis codes to the new boron-free operation SMR system to confirm any errors, followed by improvements to related input data such as nuclear reaction cross-section libraries.

The goal of this study is to prepare and establish a high-fidelity nuclear core analysis code system for a new boron-free operation SMR core design. In this study, the boron-free SMR which was proposed by J. S. Kim [1] has been selected as the target system, and DeCART2D/MASTER two-step code system [3,4] has been used as the design code system. Meanwhile, McCARD [5] Monte Carlo (MC) neutron/photon transport code was used as a reference code to provide the solutions for the quantification of the errors.

2. Numerical Results

2.1 Specifications of Boron-free Operation SMR

The design of the fuel assembly (FA) in the boron-free SMR by J. S. Kim is based on the common Westinghouse (WH) type 17x17 FA. There are 69 FAs in the core. Unlike commercially operating PWR, stainless steel was used as the reflector material. Table I shows the detailed specifications of the boron-free SMR.

To achieve the extended operational cycle and boron-free operation, highly enriched uranium and a larger amount of gadolinium than in PWR are required. Accordingly, burnable absorbers (UO_2-Gd_2O_3) using enriched gadolinium were placed in each FA. Table II shows the isotopic abundance of concentrated gadolinium used in the burnable absorbers. In this case, 50% and 70% enrichment of Gd-155, Gd-157 were used. Table III and Figure 1 show the composition and configuration of the burnable absorbers in FA. respectively.

Table I. Boron-free SMR specifications by J. S. Kim [1]

Parameter		Value
Core	Power (MW_{th})	540
	Number of fuel assemblies	69
	Coolant inlet Temp. (Kelvin)	548.15
	Coolant outlet Temp. (Kelvin)	598.15
Fuel Assembly	Fuel assembly array	17x17
	Assembly pitch (cm)	21.5
	Rod pitch (cm)	1.26
	U_{235} Enrichment (wt.%)	4.0
	Pellet outer radius (cm)	0.4096
	Cladding inner radius (cm)	0.4178
	Cladding outer radius (cm)	0.4750
	Guide tube inner radius (cm)	0.5613
	Guide tube outer radius (cm)	0.6124

Table II. Abundance of natural and enriched Gadolinium isotopes [1,2]

Isotope	Abundance (%)		
^{152}Gd	0.20	0.14	0.09
^{154}Gd	2.18	1.57	0.94
^{155}Gd	14.80	24.30	34.02
^{156}Gd	20.47	14.72	8.83
^{157}Gd	15.65	25.70	35.98
^{158}Gd	24.84	17.86	10.71
^{160}Gd	21.86	15.72	9.43
Sum (=^{155}Gd+^{157}Gd)	30.45 (Nat.)	50.00	70.00

Table III. Composition of Burnable Absorber Rods by Assembly Type [1]

FA Type	Gd atomic ratio (a/o)	Gd_2O_3 (wt.%)		U_{235} Enrichment (wt.%)	
		High	Low	High	Low
A01	50	8.00	-	2.30	-
A02	50	8.00	2.00	2.30	2.90
A03, A04	70	8.00	0.30	2.30	3.90
A05	70	8.00	-	2.30	-

2.2 FA Benchmark

In this study, a new DeCART2D library (i.e., PV05-iSMR-CR04) optimized for the boron-free SMR was generated for high-fidelity core analyses [6]. The DeCART2D library is based on ENDF/B-VII.1 evaluated nuclear data library (ENDL) with 47 energy group structure. For the validation of the PV05-iSMR-CR04 library, 4 FA benchmark problems (i.e., A01, A02, A03, and A05) were calculated and compared with the McCARD reference solutions with ENDF/B-VII.1 ENDL. For the DeCART2D calculations, the old library (i.e., PV01-CR08) and the newly generated PV05-iSMR-CR04 library were used for comparison. Table IV shows the multiplication factors by DeCART2D and McCARD for the FA problems. The stochastic uncertainties of the multiplication factors by the McCARD calculations are less than 14 pcm. The maximum error by the PV01-CR08 library was 152 pcm while that by the PV05-iSMR-CR04 library was 45 pcm. Overall, it is noted that the accuracy of reactivity analysis was significantly improved.

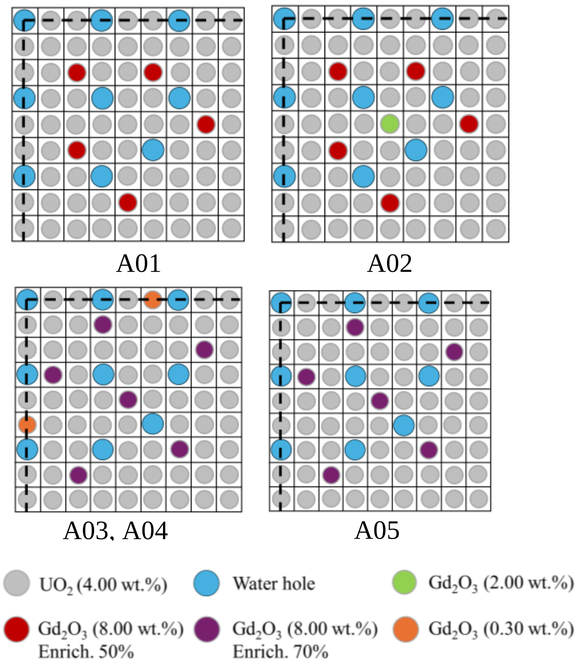

Fig. 1. Configuration of the FA problems in a boron-free operated SMR system

Table IV. Multiplication factors of FA benchmark problems by McCARD and DeCART2D with ENDF/B-VII.1

Type	McCARD[1]	DeCART2D difference with McCARD (pcm)	
	k_{eff}	Old[2]	New[3]
A01	1.09874	152	13
A02	1.06743	140	41
A03	1.01797	139	45
A05	1.03422	146	1

1) Stochastic uncertainty (=1σ) is less than 0.00014.
2) PV01-CR08 library
3) PV05-iSMR-CR04 library

2.3 2D Core Benchmark

Figure 2 plots the configuration of the 2D core model for McCARD and DeCART2D calculations. The 2D core calculations were conducted at the moderator temperature of 573K, which is the specification temperature. Table V compares the multiplication factors by McCARD and DeCART2D. In the same manner as the FA benchmark results, the PV05-iSMR-CR04 library leads to the good improvement of the accuracy in reactivity analysis for 2D core problem.

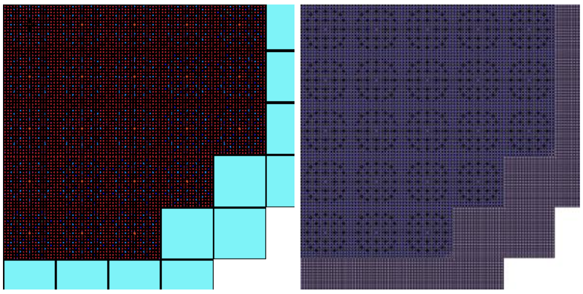

Fig. 2. Configuration of 2-D core model for McCARD (Left) and DeCART2D (Right)

Table V. Multiplication factors by McCARD and DeCART2D for 2D core problem

Case		k_{eff}	Difference with McCARD (pcm)
McCARD		1.04240±0.00013	-
DeCART2D	Old[1]	1.03809	399
	New[2]	1.04258	17

1) PV01-CR08 library
2) PV05-iSMR-CR04 library

Figure 3 shows the relative errors in FA-wise power distribution between the DeCART2D results with PV01-CR08 library and PV05-iSMR-CR04 library. The root mean square (RMS) error for power distribution was reduced from 1.08% with PV01-CR08 library to 0.47% with PV05-iSMR-CR04 library. Moreover, it is observed that the maximum error of the FA-wise power distribution difference was also reduced.

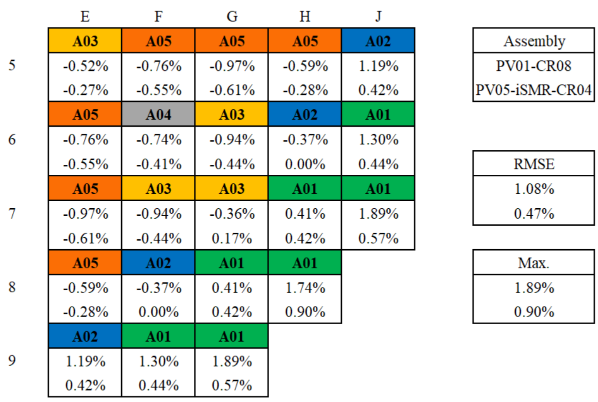

Fig. 3. FA-wise power distributions by McCARD and DeCART2D for 2D core problem

2.4 Depletion Benchmark

To verify the depletion capability of the DeCART2D design code, the depletion benchmark calculation of the fuel assembly was conducted using two codes. In the McCARD burnup analyses, Matrix Exponential Method (MEM) with sub-step method and Quadratic Extrapolation Quadratic Interpolation (QE/QI) higher-order burnup analysis schemes [7] for strong burnable absorber isotopes (e.g., Gadolinium) were applied for efficiency. Figure 4 shows the difference in reactivity between the McCARD with and without the QE/QI option for the A03 FA problem. The QE/QI burnup analyses were performed with 98 depletion time steps (DTS) whereas the MEM burnup analyses for reference were conducted with 198 DTS. The stochastic uncertainties (=1σ) in McCARD depletion analyses are less than 40 pcm. The QE/QI method is known for accurately predicting one-group reaction rates of strong burnable isotopes in burnup equations, even without fine burnup intervals [7]. Accordingly, for all the McCARD reference solution in the depletion analyses, QE/QI option will be activated.

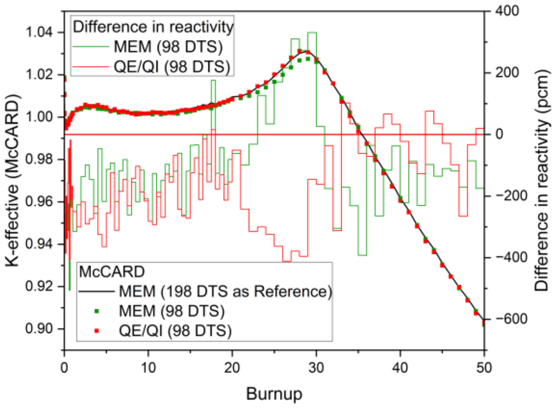

Fig. 4. Differences in reactivity among McCARD burnup analyses with various burnup options

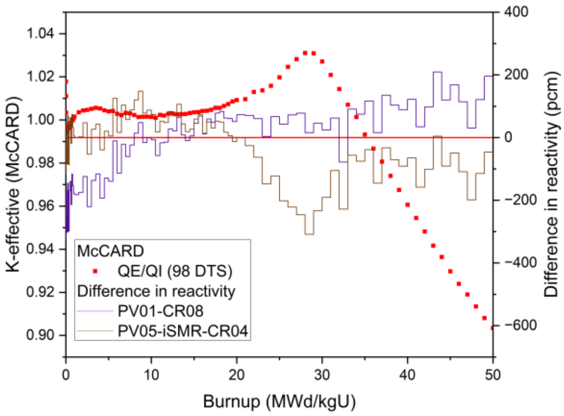

Fig. 5. Differences in reactivity between McCARD with the QE/QI methods and DeCART2D for depletion benchmark

3. Conclusions

In this study, preliminary neutronics analyses are performed to establish a high-fidelity nuclear core analysis code system suitable for boron-free operation SMR. The boron-free SMR proposed by J. S. Kim and the DeCART2D/MASTER code system were selected as the target system and the target nuclear core analysis code system. For verification and validation, the FA benchmarks, 2D core benchmark, and depletion benchmarks were calculated by DeCART2D and McCARD.

Moreover, to improve the accuracy of the DeCART2D lattice code, a new DeCART2D library optimized for the boron-free operation SMR was generated and applied to the benchmark analyses. Based on the McCARD reference solutions, the maximum difference in the multiplication factor was confirmed to have been reduced from 152 pcm to 45 pcm in the FA benchmark problem, and from 399 pcm to 17 pcm in the 2D core benchmark problem. Following these results, RMS error for FA-wise power distribution was also reduced from 1.08% to 0.47%. For the improvement in burnup analyses, nuclear reaction cross sections for plutonium and minor actinides will be adjusted.

It is noted that the new DeCART2D library generally improved the accuracy of the DeCART2D/MASTER for the boron-free operation SMR system. As future works, a 3D core multi-cycle analysis by MASTER code will be performed and library improvements will be made simultaneously to enhance the accuracy of the depletion analysis results.

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