Solution of the BEAVRS Benchmark using the DeCART2D/MASTER Code System

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1. Introduction

The DeCART2D/MASTER code system [1, 2] has been developed in Korea Atomic Energy Research Institute (KAERI) to design and analyze the Pressurized Water Reactor (PWR) including the Small Modular Reactor (SMR). DeCART2D, a Method of Characteristic (MOC) transport solver, generates assembly-wise homogenized group constant (HGC), and MASTER performs nodal diffusion core calculation with the HGCs.

For the verification and validation (V&V) of the DeCART2D/MASTER code system, the Benchmark of Evaluation And Validation of Reactor Simulations (BEAVRS) [3] core is modeled by the two-step code sequence. In this study, the calculation result of Cycle 1 Hot Zero Power (HZP) is compared to the HZP data of BEAVRS as a previous step of Hot Full Power (HFP) and depletion analysis.

2. DeCART2D Modeling for HGC Generation

The BEAVRS core consists of 193 fuel assemblies in 17×17 lattice and there are 264 rods in each assembly. Three different enrichments of UO_2 fuels are loaded in the fresh core. There are varying number of PYREX rods as a burnable poison for each assembly type, and some of them are asymmetry so additional care would be needed in modelling process. The detail design parameters and the operation conditions are provided in the benchmark specification [3].

Assembly-wise HGCs are generated by the DeCART2D calculation and they are converted into Cross Section Library (XSL) and Form-function Library (HFF) by using PROLOG [4], which is required to perform MASTER core calculation. The XSL file consists of the cross sections (XSs) for the fuel assembly, radial reflector, and axial reflector. The effective macroscopic XS generation by DeCART2D was performed with following options.

- 47/18 neutron/gamma energy group XS library based on the ENDF/B-VII.1
- 0.02 cm ray spacing, 8 azimuthal angles in 90º domain and 2 polar angles in 90º domain for ray discretization
- Subgroup method for resonance treatment
- Transport correction based anisotropic scattering treatment
- 45º symmetry angle with reflective boundary

2.1 Fuel Assembly Modelling

There are 10 different fuel assembly types for BEAVRS core cycle 1 with the variation of the fuel enrichment and the number of PYREX rods. Each assembly has 24 guide tubes and one instrument tube. Among the 10 fuel assembly types, 6-PYREX fuel assembly and 15-PYREX fuel assembly are asymmetry. It requires additional handling in the modelling process for exact simulation of the BEAVRS core since the DeCART2D calculation is performed by 45º symmetry angle with reflective boundary condition. MASTER code can handle this problem by declaring the asymmetric fuel assembly block which controls the form function rotation and nuclide adjustment in the 2×2 division within an assembly.

For the case of 6-PYREX fuel assembly, there are three 6-PYREX fuel assemblies in each side of the core, and the PYREX rods head toward the core center so the assembly shape is different for each core side. 6-PYREX fuel assembly is line symmetry as shown in Fig. 1 so it is possible to modelling this assembly with two fuel assemblies; a fuel assembly without PYREX and a fuel assembly with 12-PYREX. As for Fig. 1, the HGC of 12-PYREX is used for upper two division and that of 0-PYREX is used for lower two division.

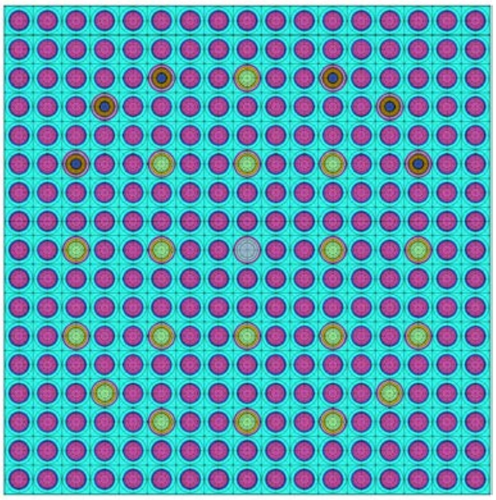

Fig. 1. Radial configuration of 6-PYREX fuel assembly modelling by DeCART2D.

There are four 15-PYREX fuel assemblies and they are located in each corner one by one. As for the 15-PYREX fuel assembly, it is impossible to model this assembly as it did for 6-PYREX since the PYREX arrangement is not symmetry as shown in Fig. 2.

Therefore, the configuration of Fig. 2 itself was used for every side and only HFF rotation was applied in MASTER input.

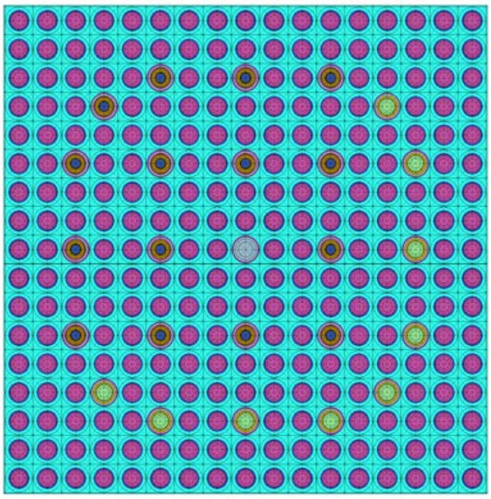

Fig. 2. Radial configuration of 15-PYREX fuel assembly modelling by DeCART2D.

2.2 Radial Reflector Modelling

Figure 3 shows the core radial configuration of the DeCART2D modelling. Three different enrichment for the fuel assemblies can be found in this figure and it is notable that the radial reflector region includes a neutron shield panel outside the core barrel. DeCART2D can easily add a core barrel by declaring a barrel diameter in the barrel card, and only three reflector assemblies are required to simulate an octant core. For the BEAVRS core, however, a neutron shield panel should be considered so the barrel and the neutron shield panel were modelled in manual way without the barrel card, and eight reflector assemblies are required.

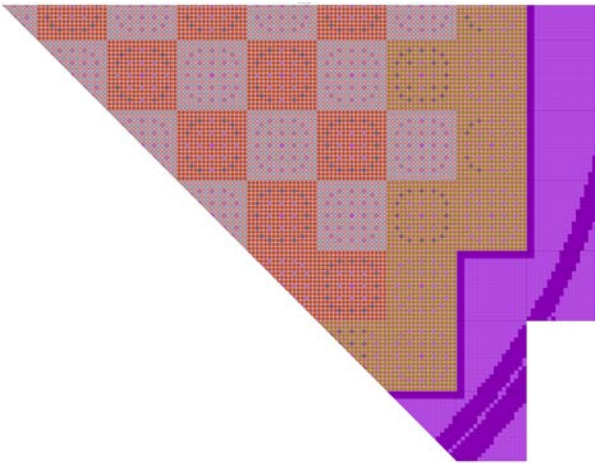

Fig. 3. Radial configuration of octant core modelling by DeCART2D.

2.3 Axial Reflector Modelling

For the axial reflector modelling, the design data of Hanbit Unit 1 was exceptionally used instead of the BEAVRS data because the axial information in the benchmark specification is not enough to model by DeCART2D. This is expected to have little effect on the calculation result since BEAVRS core is large enough, and the BEAVRS core specification is similar to that of the Hanbit Unit 1 core.

3. MASTER Modelling and Calculation Result

The assembly-wise XS was calculated by modelling each different fuel assembly, radial reflector, and axial reflector by DeCART2D. Consequently, the core calculation for BEAVRS Cycle 1 HZP was performed by MASTER with the XS data from the DeCART2D calculation. The calculation was done with the condition of Table I. As the result of the calculation, the Critical Boron Concentration (CBC), Control Rod Worth (CRW), and Isothermal Temperature Coefficient (ITC) were compared to the BEAVRS measurement data provided in the benchmark specification. In the BEAVRS core, the control rod banks are inserted in order of D, C, B, A, SE, SD, and SC so the MASTER calculations were performed for each rod insertion sequence following this rod insertion order.

Table I: Cycle 1 Hot Zero Power Physics Configuration

Parameter	Value
Core Power	25 MWth
Core Flow Rate	61.5×10^6 kg/hr
Inlet Coolant Temperature	560 ºF
Rod Bank A/B/C Position	Step 228
Rod Bank D Position	Step 213
Boron Concentration	975 ppm

3.1 Critical Boron Concentration

The CBC of BEAVRS HZP core was calculated by MASTER and the result is summarized in Table II. The calculation was performed in five different rod position states including All Rod Out (ARO) as shown in Table II. The difference between the measured data and the calculation result for each state, Δρ, is presented in pcm. This is derived by multiplying the CBC to the boron worth which can be also calculated by MASTER calculation.

Table II: Critical Boron Concentration

	Measured, ppm	MASTER, ppm	Boron Worth, pcm/ppm	Δρ, pcm
ARO	975	989	-12.6	-176
D in	902	934	-12.8	-414
C/D in	810	842	-12.6	-403
A/B/C/D in	686	709	-12.7	-292
A/B/C/D/SE/SD/SC in	508	533	-12.6	-318

3.2 Control Rod Worth

The control bank worth was calculated for full control rod insertion each and the result is presented in Table III. The relative deviation between measured data and the calculation result is also presented in percent. The MASTER result for bank worth agrees with the measured data with minor deviation while that of rod A and rod SE has large error which is to be investigated.

Table III: Control Rod Bank Worth

	Measured, pcm	MASTER, pcm	Deviation, %
D in	788	762	-3
C with D in	1203	1163	-3
B with C/D in	1171	1299	11
A with B/C/D in	548	429	-22
SE with A/B/C/D in	461	379	-18
SD with SE/A/B/C/D in	772	750	-3
SC with SD/SE/A/B/C/D in	1099	1051	-4

3.3 Isothermal Temperature Coefficient

The ITC was also calculated for the three different rod insertion states and the result is presented in Table IV. The BEAVRS benchmark specification provides the measured ITC data in degree Fahrenheit so the measured data value in Table IV is the converted one as degree Celsius.

Table IV: Isothermal Temperature Coefficient

	Measured, pcm/°C	MASTER, pcm/°C	Δρ, pcm/°C
ARO	-3.15	-5.23	-2.08
D in	-4.95	-7.52	-2.58
C/D in	-14.42	-15.53	-1.11

3.4 Power Distribution

MASTER output also provides the assembly-wise normalized power distribution. Figure 4 shows the normalized power distribution for octant BEAVRS core of cycle 1 HZP. The power profile is peripheral-peak shape that is the general characteristic of the fresh core. The peaking factor is 1.45 and this peak-power assembly is located in the periphery region of the core corner.

Figure 5 shows the same figure but it is from the calculation result of DeCART3D code, and the difference between the calculation result of the DeCART2D/MASTER code system and that of DeCART3D is presented in Fig. 6. Both results show the same trend that peripheral-peak shape but the relative error is up to 5.8% which is expected to be reduced by trial and error with more sophisticate modelling in DeCART2D/MASTER code system and DeCART3D.

0.60	0.71	0.71	0.89	0.82	0.98	0.98	1.07
	0.67	0.84	0.79	0.96	0.89	1.21	1.10
		0.78	0.96	0.87	1.03	0.98	1.00
			0.90	1.10	1.04	1.26	0.81
				1.45	1.28	1.31	
					1.36	0.95	

Fig. 4. Normalized power distribution from MASTER calculation.

0.64	0.72	0.74	0.90	0.83	0.95	0.96	1.04
	0.70	0.86	0.81	0.96	0.89	1.16	1.10
		0.81	0.97	0.89	1.01	0.97	0.98
			0.92	1.09	1.05	1.23	0.82
				1.46	1.25	1.33	
					1.32	1.00	

Fig. 5. Normalized power distribution from DeCART3D calculation.

-5.8	-2.3	-4.3	-1.4	-2.0	2.7	2.0	2.5
	-4.5	-2.2	-3.4	0.1	0.0	4.5	0.0
		-3.8	-0.8	-1.6	2.4	1.2	2.2
			-2.2	1.1	-0.6	2.0	-1.0
				-0.9	2.9	-1.8	
					3.2	-4.2	

Fig. 6. Relative error of normalized power distribution between DeCART2D/MASTER and DeCART3D.

4. Conclusions

A study of the BEAVRS core benchmark analysis has been performed by simulating cycle 1 HZP for V&V of the DeCART2D/MASTER code system in KAERI. Some core parameters such as CBC, CRW, and ITC have been compared to the measurement data in the benchmark specification. The power distribution was compared between the DeCART2D/MASTER code system and DeCART3D. HFP analysis with depletion calculation would be the next step of the BEAVRS core benchmark analysis.

ACKNOWLEDGMENT

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