Core Follow Calculation for VERA Benchmark using DeCART2D/MASTER

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has developed the two-step procedure based the DeCART2D [1]/MASTER4.0 [2] code system for the nuclear design. MASTER4.0 is rewriting version of MASTER3.0 [3] and maintains most of all capabilities of MASTER3.0. MASTER4.0 has neutronics solution methods of the Source Expansion Nodal Method (SENM) for a rectangular geometry and the Triangle based Polynomial Expansion Nodal (TPEN) method for a hexagonal geometry. In addition, depletion of MASTER4.0 based on Krylov subspace method. DeCART2D that is a neutron transport code based on Method of Characteristic (MOC) has developed to generate assembly-wise homogenized group constants (HGCs) used in nodal diffusion core analysis codes such as MASTER for a two-step procedure. MASTER is a neutron diffusion nodal code for a nuclear design of PWRs and it has the capabilities to analyze the steady-state and transient core behaviors in 3-D geometry based on the two-group diffusion theory.

As a part of code system verification and validation (V&V) for DeCART2D/MASTER4.0, a core follow calculation for VERA benchmark core in cycle 1 was performed. The VERA benchmark problems were selected to assist software and methods developers and analysts in progressing through capabilities needed to model U.S. nuclear power reactors and their operations [4]. The problems provide a prioritization of the VERA requirements for the virtual reactor, beginning at the fuel pin level and progressing to full core, multi-physics problems. The problems represent geometries that are contained in the Watts Bar Nuclear 1 (WBN1) initial core. The benchmark problem used in this paper provides measured data for the initial startup of WBN1 for reactor methods benchmarking purposes. The computed results are then compared to the measured data from WBN1 as well as computed reference solution data generated by CE KENO-VI [5] in VERA benchmark problems.

2. Methods and Results

2.1 Generation of MASTER Cross Section Library

In order to perform core follow calculation using MASTER, HGC data from DeCART2D should be generated and converted to the suitable library format available in MASTER. HGC data are three types that fuel assemblies (FAs), radial reflectors and axial reflectors, respectively.

The VERA benchmark problems are based on actual fuel and core geometries used in the WBN1. The fuel is a Westinghouse 17 x 17 design utilizing discrete Pyrex burnable poisons and hybrid AIC/B_4C rod cluster control assemblies (RCCAs). The Pyrex burnable poison inserts may be placed in any assembly which is not located in a RCCA location. There are ten types of fuel assembly loaded in VERA benchmark core in cycle 1 with the variation of the fuel enrichment and the number of the Pyrex discrete burnable poisons. Therefore, ten types of fuel assemblies were modeled for FA HGC data generation. Fig. 1 presents the sample of 1/8 rotational FA.

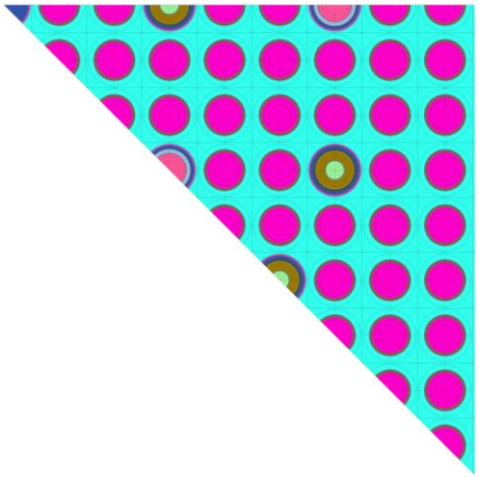

Fig. 1. Radial fuel configuration of fuel assembly

The radial reflector region for VERA benchmark core consists of the core baffle, moderator, and core support barrel and neutron pad. Fig. 2 shows the radial reflector model in order to generate radial reflector HGC data. Note that HGC of radial reflector nodes are generated simultaneously by solving the 2-D core problem in the DeCART2D/MASTER4.0 code system instead of adopting the simple FA/reflector two-node model used in various lattice codes. The 2-D core model is expected to predict the precise neutron spectrum and flux distribution at the reflector nodes compared to the conventional two-node model. In general, the core barrel can be easily modelled using the barrel card in DeCART2D. In this paper, however, a neutron pad should be considered, so the barrel and neutron pad were modelled in directly without the barrel card, and eight radial reflector assemblies were modeled.

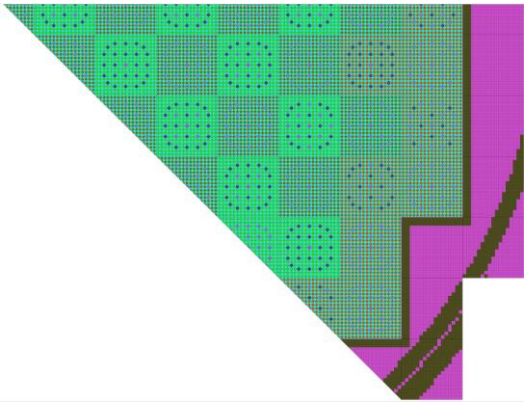

Fig. 2. Radial reflector model of VERA benchmark

In general, the FA-reflector two-node method has been used to generate radial as well as axial reflector HGC data. However, this method cannot consider the actual flux shape at the interface between the FAs and reflector. In this paper, a simplified 1-D model is used to generate axial reflector HGC data instead of using the two-node model for more realistic modelling [6]. In addition, for the axial reflector modelling, the design data of Hanbit Unit 3 was used instead of the VERA benchmark data since the information of axial reflector in the VERA specification is not enough to model by DeCART2D. The effect of a replacement for axial reflector model is expected to be small because VERA benchmark core is large enough. Fig. 3 shows the simplified 1-D axial reflector model.

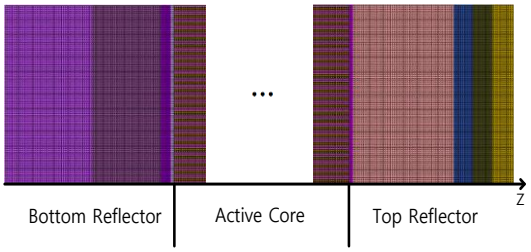

Fig. 3. Simplified 1-D axial reflector model

PROLOG [7] and PROMARX [6] codes are used to convert HGC data of fuel assemblies and reflectors to MASTER cross section library format, respectively.

2.2 Core Follow Calculation

A core follow calculation for VERA benchmark core in cycle 1 at hot zero power (HZP) isothermal condition was performed using DeCART2D/MASTER4.0. The purpose of this benchmark problem is to successfully perform the calculations associated with the zero power physics tests (ZPPTs) that are performed at the beginning of each fuel cycle startup. These include predictions of several critical configurations, the RCCA bank reactivity worth, the isothermal temperature coefficient (ITC), the differential soluble boron worth (DBW), and radial assembly power distribution.

The core loading pattern, control rod map, axial core configuration, and other core conditions are applied to make the MASTER core follow analysis input model. The reference cases for benchmark problem are a variety of different control rod bank positions, soluble boron concentrations, and temperatures consistent with the actual WBN1 cycle 1 ZPPTs. Fig. 4 shows the detailed specification for the cases. In Fig. 4, bank IDs A through D are the index for regulating and SA through SD are the index for shutdown bank. The results of core follow calculation were compared to the measured and computed reference data.

			Bank Position (steps withdrawn)*									
Case	Boron (ppm)	Temp (K)	A	B	C	D	SA	SB	SC	SD	Description	
1	1285	565	-	-	-	167	-	-	-	-	Initial	Criticals
2	1291	↓	-	-	-	-	-	-	-	-	ARO	
3	1170	↓	0	-	-	97	-	-	-	-	Bank A	
4	↓	↓	-	0	-	113	-	-	-	-	Bank B	
5	↓	↓	-	-	0	119	-	-	-	-	Bank C	
6	↓	↓	-	-	-	18	-	-	-	-	Bank D	
7	↓	↓	-	-	-	69	0	-	-	-	Bank SA	
8	↓	↓	-	-	-	134	-	0	-	-	Bank SB	
9	↓	↓	-	-	-	71	-	-	0	-	Bank SC	
10	↓	↓	-	-	-	71	-	-	-	0	Bank SD	
11	↓	↓	-	-	-	-	-	-	-	-	ARO	Rod Worths
12	↓	↓	0	-	-	-	-	-	-	-	Bank A	
13	↓	↓	-	0	-	-	-	-	-	-	Bank B	
14	↓	↓	-	-	0	-	-	-	-	-	Bank C	
15	↓	↓	-	-	-	0	-	-	-	-	Bank D	
16	↓	↓	-	-	-	-	0	-	-	-	Bank SA	
17	↓	↓	-	-	-	-	-	0	-	-	Bank SB	
18	↓	↓	-	-	-	-	-	-	0	-	Bank SC	
19	↓	↓	-	-	-	-	-	-	-	0	Bank SD	
20	1291	560	-	-	-	-	-	-	-	-	Low temp	ITC
21	↓	570	-	-	-	-	-	-	-	-	High temp	
22	1230	565	-	-	-	0	-	-	-	-	D @ 0%	Bank D Integral Worth
23	↓	↓	-	-	-	23	-	-	-	-	D @ 10%	
24	↓	↓	-	-	-	46	-	-	-	-	D @ 20%	
25	↓	↓	-	-	-	69	-	-	-	-	D @ 30%	
26	↓	↓	-	-	-	92	-	-	-	-	D @ 40%	
27	↓	↓	-	-	-	115	-	-	-	-	D @ 50%	
28	↓	↓	-	-	-	138	-	-	-	-	D @ 60%	
29	↓	↓	-	-	-	161	-	-	-	-	D @ 70%	
30	↓	↓	-	-	-	184	-	-	-	-	D @ 80%	
31	↓	↓	-	-	-	207	-	-	-	-	D @ 90%	
32	↓	↓	-	-	-	-	-	-	-	-	D @ 100%	

*Fully withdrawn banks (230 steps) are indicated with a dash (-)

Fig. 4. Problem cases for VERA benchmark ZPPTs

2.3 Results

In this paper, the measured data means the measured value from WBN1 and reference solution data from CE KENO-VI. The eigenvalues calculated by CE KENO-VI for the reference cases are provided in Table I. Table I also presents the reactivity differences between calculated by DeCART2D/MASTER and CE KENO-VI, as well as eigenvalue results calculated by DeCART2D/MASTER.

For the ten critical configurations (Cases 1 through 10), WBN1 is assumed to be critical. The core initial criticality was achieved by positioning of the main regulating bank, Bank D, at a position of 167 steps withdrawn and a boron concentration of 1285 ppm. Nine other critical configurations (Cases 2 through 10) are modeled as shown Fig. 4, including the all rods out (ARO) condition, and each bank insertion during critical position testing. For all banks other than Bank D, the measured bank is fully inserted and Bank D is partially inserted at the measured critical position. For

the inserted bank cases, the dilution boron concentration of 1170 ppm is used.

Table I: VERA benchmark reference solution calculated by CE KENO-VI eigenvalue results and differences between CE KENO-VI and DeCART2D/MASTER

Case	k-effective		Deviation (pcm)
	C (Reference)	D	
1	0.999899	0.996891	302
2	1.000321	0.997301	303
3	0.998797	0.996165	265
4	0.999358	0.995982	339
5	0.999039	0.996344	271
6	0.999084	0.996089	301
7	0.999022	0.995686	335
8	0.999324	0.996365	297
9	0.998983	0.995876	312
10	0.998976	0.995879	311
11	1.012841	1.009598	317
12	1.003716	1.000930	277
13	1.003941	1.000481	344
14	1.002843	1.000001	283
15	0.998815	0.995813	302
16	1.008281	1.004719	352
17	1.002018	0.998955	306
18	1.007749	1.004412	330
19	1.007745	1.004412	329
20	1.000608	0.997578	304
21	1.000034	0.996991	305
22	0.992755	0.989850	296
23	0.993162	0.990321	289
24	0.994555	0.991833	276
25	0.997369	0.994516	288
26	1.000279	0.997288	300
27	1.002542	0.999534	300
28	1.004163	1.001139	301
29	1.005300	1.002228	305
30	1.006073	1.002948	310
31	1.006468	1.003357	308
32	1.006584	1.003456	310

C: CE KENO-VI
D: DeCART2D/MASTER4.0

The reference ZPPTs solutions are calculated based on the data form WBN1. Table II shows the initial criticality results measured and computed data.

Table II: VERA benchmark problem measured and calculated initial criticality results

k-effective		
M	C	D
1.00000	0.999899	0.996891
Deviation (pcm)		
C-M	D-M	D-C
10	312	302

M: Measured data from WBN1

Table III shows the RCCA bank worth results measured and computed data and Table IV shows differences between measured and computed RCCA bank worth. The maximum difference is 10.55 % at Bank SA since Bank SA is located peripheral assemblies.

Table III: VERA benchmark problem measured and calculated RCCA bank worth results

RCCA bank worth (pcm)			
Bank	M	C	D
A	843	898	858
B	879	875	903
C	951	984	951
D	1342	1386	1371
SA	435	447	481
SB	1056	1066	1055
SC	480	499	511
SD	480	499	511
Total	6466	6654	6640.5

Table IV: Differences between measured and computed RCCA bank worth

RCCA bank worth deviation (%)			
Bank	(C-M)/M	(D-M)/M	(D-C)/M
A	6.52	1.73	-0.05
B	-0.46	2.67	0.03
C	3.47	-0.05	-0.04
D	3.28	2.16	-0.01
SA	2.76	10.55	0.08
SB	0.95	-0.08	-0.01
SC	3.96	6.54	0.03
SD	3.96	6.54	0.03
Total	2.91	2.70	0.00

The DBW is calculated at ARO conditions using the ARO critical boron concentration (1291 ppm) and the dilution boron concentration (1170 ppm). Table V shows the DBW results measured and computed data.

Table V: VERA benchmark problem measured and calculated DBW results

Differential Boron Worth (pcm/ppm)		
M	C	D
-10.77	-10.21	-10.09
Deviation (pcm/ppm)		
C-M	D-M	D-C
0.56	0.68	0.12

The ITC is calculated over the range of 560K to 570K at ARO conditions. Table VI shows the ITC results measured and computed data.

Table VI: VERA benchmark problem measured and calculated ITC results

Differential Boron Worth (pcm/℃)		
M	C	D
-3.91	-5.72	-5.91
Difference (pcm/℃)		
C-M	D-M	D-C
-1.82	-2.00	-0.19

Fig 5 and Fig 6 show the Bank D differential and integral worth computed by CE KENO-VI and DeCART2D/MASTER, respectively. These values are calculated using Bank D insertion increments of 10 % (23 steps) at 565K. The red line in each these figure means the difference between CE KENO-VI and DeCART2D/MASTER results.

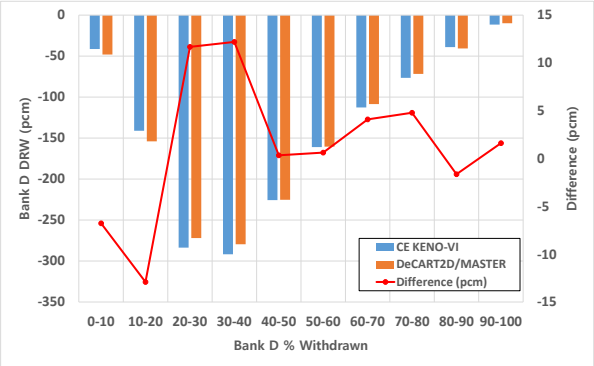

Fig. 5. VERA benchmark problem Bank D Differential Worth

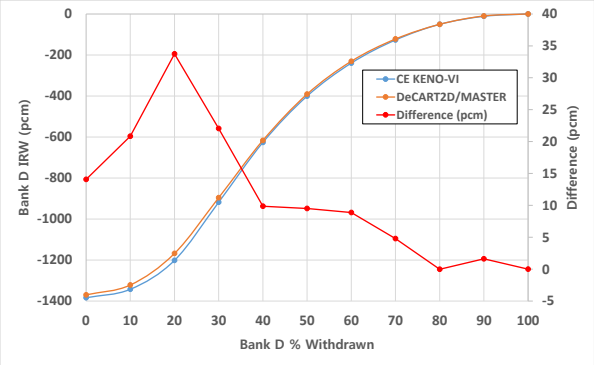

Fig. 6. VERA benchmark problem Bank D Integral Worth Curve

Fig 7 shows the comparison of the radial assembly power distributions for initial critical condition obtained by CE KENO-VI and DeCART2D/MASTER. The maximum difference is 4.9 %.

0.949 0.907 -4.4	0.919 0.880 -4.3	1.018 0.978 -3.9	0.985 0.957 -2.8	1.065 1.046 -1.8	1.048 1.041 -0.6	1.084 1.088 0.4	0.793 0.801 0.9
	0.997 0.955 -4.3	0.908 0.873 -3.9	1.082 1.052 -2.8	1.047 1.032 -1.5	1.162 1.156 -0.5	1.063 1.072 0.9	0.907 0.913 0.7
		1.065 1.032 -3.1	1.041 1.020 -2.0	1.175 1.163 -1.0	1.152 1.156 0.4	1.104 1.118 1.3	0.805 0.819 1.8
			1.162 1.148 -1.1	1.085 1.087 0.2	1.151 1.165 1.2	1.050 1.077 2.6	0.659 0.671 1.8
KENO-VI MASTER %Diff.				1.237 1.252 1.2	0.897 0.925 3.1	0.945 0.975 3.1	
					0.913 0.957 4.9	0.630 0.657 4.4	

Fig. 7. VERA benchmark problem radial power distribution and difference between two code system

3. Conclusions

In the paper, a core follow calculation based on ZPPTs for VERA benchmark core in cycle 1 at HZP isothermal condition was performed using the DeCART2D/MASTER4.0 nuclear design code system developed in KAERI. Three types HGC data were generated using the DeCART2D code. Then, PROLOG and PROMARX converted these HGC for available in MASTER code. Various nuclear parameters such as critical configurations, RCCA bank worth, differential boron worth (DBW), isothermal temperature coefficient (ITC) and radial assembly power distribution were generated by DeCART2D/MASTER4.0 and they are compared to the measured data from WBN1 and CE KENO-VI reference solutions. Although some parameters have relatively large uncertainty compared to measured data and reference solutions, most data have good agreement with the reference measured data. As a result, it can be concluded that DeCART2D/MASTER4.0 has sufficient capabilities for nuclear designs.

ACKNOWLEDGMENT

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REFERENCES

[1] J. Y. Cho, et al., "DeCART2D v1.1 User's Manual," KAERI/UM-40/2016, 2016.
[2] J. Y. Cho, et al., "MASTER v4.0 User's Manual," KAERI/UM-41/2016, 2016.
[3] J. S. Song, et al., "Verification and Uncertainty Evaluation of CASMO-3/MASTER Nuclear Analysis System," KAERI/TR-806/97, 1997.
[4] Andrew T. Godfrey, "VERA Core Physics Benchmark Progression Problem Specification," CASL-U-2012-0131-004, Rev. 04, Aug. 29, 2014.
[5] SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design, ORNL/TM-2005/39, Version 6.1, June 2011. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785.
[6] C. B. Shim, et al., "Improvement of Axial Reflector Cross Section Generation Model for PWR Core Analysis," Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 27-28, 2016.
[7] J. S. Song, et al., "PROLOG1.1 User's Manual," KAERI/UM-4/99, 1999.