2D HZP BOC Fuel Pin, Fuel Lattice and 3x3 Assembly of VERA Benchmark Calculations by DeCART2D Code

Saud Abdulmohsen Al-Shikh [a*], Alaa Hadi Al-Nahdi [a], C. B. Shim [b], K. H. Lee [b], and B. S. Koo [b],
[a]King Abdullah City for Atomic and Renewable Energy, Al Olaya, Riyadh 12244, Saudi Arabia
[b] *Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu Daejeon 34057, Korea*
[*]*Corresponding author: s.shikh@energy.gov.sa*

1. Introduction

The DeCART2D (Deterministic Core Analysis based on Ray Tracing) code [1] 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).

For the Verification and Validation (V&V) of the DeCART2D code, the Benchmark of Evaluation and Validation of Reactor Simulations (VERA) [2] core is modeled by the 3-step code sequence.

In this study, the calculation result of Cycle 1 Hot Zero Power (HZP) is compared to the HZP data of VERA for fuel Pin, fuel Lattice and 3x3 Assembly.

2. Benchmark Specification

The VERA Core Physics Benchmark Progression Problems. Each of the problems in this specification is based on actual fuel and core geometries used in the Watts Bar Nuclear 1 (WBN1) initial core loading. The fuel is a Westinghouse 17x17 design utilizing discrete Pyrex burnable poisons and hybrid AIC/B_4C rod cluster control assemblies (RCCAs). In this study, fuel Pin, fuel Lattice and 3x3 Assembly were selected from the benchmark which are they problem 1, 2 and 4-2D respectively. Fig. 1 shows the configuration of fuel pin, fuel lattice and 3x3 assembly problem. The detailed specifications of each problem are briefly described in reference 2.

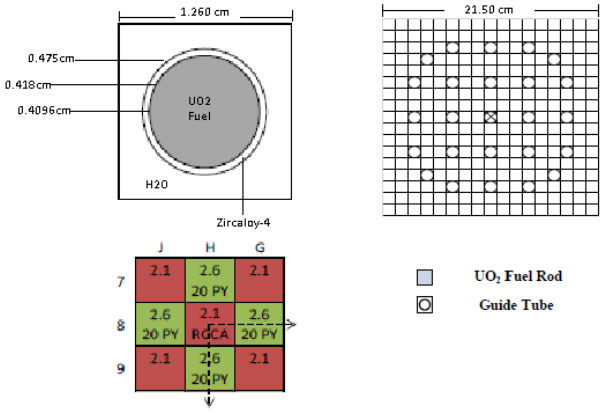

Fig. 1. Configration of Fuel Pin, Fuel Lattice and 3x3 Assembly Problem

3. Methods and Results

The study done using DeCART2D code to generate the multiplication factor (K-effective) and pin power (only for problem 2) than to be compared with VERA benchmark result. After that, the root mean square (RMS) calculated for each problem individually.

$$RMS = \sqrt{\frac{x_1^2+x_2^2+\cdots+x_i^2}{N}}$$

2.1 DeCART2D Modeling for Fuel Pin

There are 5 different cases for VERA in Fuel pin problem. Each case calculated using DeCART2D code. The problem consists of a single Westinghouse 17x17-type fuel rod cell at beginning-of-cycle (BOC). The first (Case A) represents typical zero power isothermal conditions which are representative of power reactor startup physics testing. Calculations B, C, and D are for the same rod geometry but with a range of fuel temperatures that are common under full power operating conditions. Problem 1E is an IFBA (Integral Fuel Burnable Absorber). All results for pin cell problems show a good agreement except for 1E. The problem 1E is the fuel pin cell with IFBA. Because the coating layer (0.001 cm) of IFBA is very thin. If the default ray spacing (0.02 cm) is used, IFBA cannot be dealt with properly. To confirm this, a sensitivity analysis done as shown in Table I. As a result, fewer errors can be seen when using smaller ray spacing as shown in Fig. 2. In conclusion, it can be determined that using the ray spacing of 0.002 cm is optimal in terms of calculation time and accuracy. Table II shows the result of DeCART2D code compared to VERA benchmark result with RMS of all the cases in this problem.

Table I: Result of sensitivity analysis on ray spacing for a Problem #1 part E: 2D HZP BOC Fuel Pin

Problem 1	K-effective result		ΔK (pcm)	Error (%)	Ray Spacing (cm)
	Reference	DeCART2D			
1E-1	0.771691	0.766891	480	0.625904	0.02
1E-2	0.771691	0.768608	308.3	0.401115	0.01
1E-3	0.771691	0.770212	147.9	0.192025	0.005
1E-4	0.771691	0.772030	33.9	0.04391	0.002
1E-5	0.771691	0.771130	56.1	0.07275	0.001

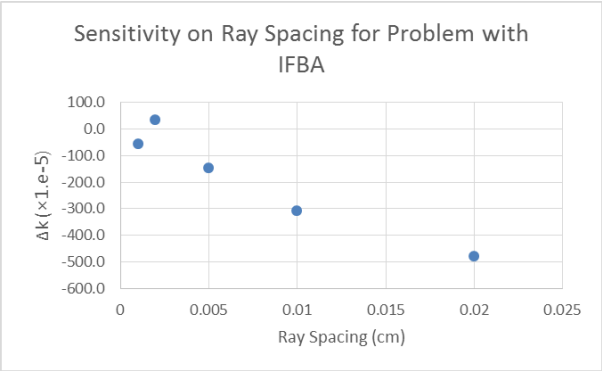

Fig. 2. Sensitivity on Ray Spacing for Problem 1E (IFBA)

Table II: Result of DeCART2D code for a Problem #1: 2D HZP BOC Fuel Pin compared with VERA result

Problem 1	K-effective result		ΔK x1e-5 (pcm)	Error (%)	RMS (%)
	Reference	DeCART2D			
1A	1.187038	1.187062	2.4	0.002022	0.287
1B	1.182149	1.182521	37.2	0.031458	
1C	1.171722	1.172512	79	0.067377	
1D	1.162603	1.164074	147.1	0.126367	
1E	0.771691	0.772030	33.9	0.04391	

2.2 DeCART2D Modeling for Fuel Lattice

The problem consists of a single Westinghouse 17x17- type fuel lattice at beginning-of-cycle (BOC) as depicted in Fig. 1. This study will be divided into several calculations. The first (part A) represents typical zero power isothermal conditions which are representative of power reactor startup physics testing. Other calculations (parts B, C, and D) are for the same geometry but with a range of fuel temperatures that are common under full power operating conditions, consistent with problem 1. Cases 2E to 2P test the capability to accurately model radial heterogeneities created by different burnable poisons and control rod types. In case 2L, 2M and 2N (IFBA-cases) ray spacing of 0.002 cm used. Finally, 2Q test a code's capability to accurately model the reactivity depression and radial power distribution produced by a spacer grid with uniformly distributed mass. This calculation will validate capabilities of DeCART2D code against the reference values for this benchmark problem which were calculated by the SCALE 6.2 Beta code KENO-VI and a continuous energy (CE) Monte Carlo-based transport tool. Error percentage calculated for pin to pin powers for each case between DeCART2d code and the reference values. Fig. 3 shows case 2Q (spacer grid case) Relative Difference for pin power distribution of DeCART2D code compared with CE KENO-VI (Ref.). Table III, shows the result of DeCART2D code compared to VERA benchmark result including the RMS for all fuel lattice cases.

		1.0368	1.0371		1.0353	1.0320	1.0113	0.9774
		1.0348	1.0357		1.0344	1.0318	1.0108	0.9773
		-0.19	-0.13		-0.09	-0.02	-0.05	-0.01
		1.0105	1.0113	1.0375	1.0098	1.0069	1.0258	0.9883	0.9726
		1.0088	1.0093	1.0361	1.0086	1.0055	1.0257	0.9884	0.9724
		-0.17	-0.20	-0.13	-0.12	-0.14	-0.01	0.01	-0.02
			1.0120	1.0389	1.0124	1.0098	1.0273	0.9879	0.9723
			1.0101	1.0377	1.0109	1.0087	1.0274	0.9883	0.9718
			-0.19	-0.12	-0.15	-0.11	0.01	0.04	-0.05
					1.0448	1.0448		1.0109	0.9745
					1.0443	1.0451		1.0109	0.9748
					-0.05	0.03		0.00	0.03
					1.0331	1.0513	1.0357	0.9828	0.9646
					1.032	1.0508	1.0354	0.9841	0.9653
					-0.11	-0.05	-0.03	0.13	0.07
							1.0160	0.9639	0.9548
							1.0176	0.9661	0.9559
							0.16	0.23	0.12
Max Relative Difference (%)				0.310			0.9726	0.9468	0.9457
Minimum Relative Difference (%)				-0.198			0.9748	0.9488	0.9475
RMS				0.131			0.23	0.21	0.19
								0.9369	0.9413
								0.9398	0.9429
								0.31	0.17
					1st line	CE KENO-VI (Ref.)			0.9479
					2nd line	DeCART2D			0.9485
					3rd line	Relative Difference (%)			0.06

Fig. 3. Case 2Q Relative Difference error for pin power distribution of DeCART2D code compared with CE KENO-VI (Ref.)

Table III: Result of DeCART2D code for a Problem #2: 2D HZP BOC Fuel Lattice compared with VERA result

Problem 2	K-effective result		ΔK x1e-5 (pcm)	Error (%)	RMS (%)
	Reference	DeCART2D			
2A	1.182175	1.181199	97.6	0.082628	0.029
2B	1.183360	1.182615	74.5	0.062996	
2C	1.173751	1.173412	33.9	0.02889	
2D	1.165591	1.165617	2.6	0.002231	
2E	1.069627	1.069073	55.4	0.051821	
2F	0.976018	0.976005	1.3	0.001332	
2G	0.847695	0.852995	530	0.62134	
2H	0.788221	0.792719	449.8	0.567414	
2I	1.179916	1.178911	100.5	0.085248	
2J	0.975193	0.975265	7.2	0.007383	
2K	1.020063	1.020106	4.3	0.004215	
2L	1.018915	1.017858	105.7	0.103846	
2M	0.938796	0.937922	87.4	0.093185	
2N	0.869615	0.869458	15.7	0.018057	
2O	1.047729	1.046295	143.4	0.137055	
2P	0.927410	0.925632	177.8	0.192085	
2Q	1.171940	1.180652	871.2	0.737897	

2.3 DeCART2D Modeling for 3x3 Assembly

This study consists of nine Westinghouse 17x17-type fuel assemblies arranged in a 3x3 checkerboard pattern directly from the center of the WBN1 initial loading pattern as shown in Fig. 1. The capabilities of DeCART2D demonstrated by this problem are the same as Problem #2 plus the addition of multiple assemblies and poison rod placement. Fig. 4 shows Problem 4-2D octant radial geometry by DeCART2D code. Three study cases in this problem calculated by DeCART2D code. All the results are calculated for a quadrant, but are collapsed to octant geometry. This study also tests the ability to define and place Pyrex, AIC, and B_4C absorbers in the assembly guide tubes. Table IV shows the result of DeCART2D code compared to VERA benchmark result including the rod worth and RMS of the whole study. The Assembly power comparison for each case present in Table V.

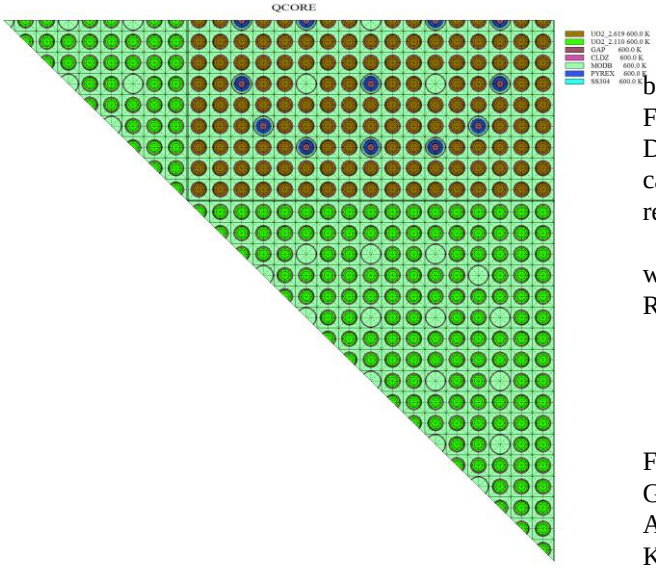

Fig. 4. Problem 4-2D Octant Radial Geometry

Table IV: Result of DeCART2D code for a Problem #4: 2D HZP BOC 3x3 Assembly compared with VERA result

Problem 4		4A-2D Uncontrolled	4B-2D AIC Controlled	4C-2D B4C Controlled
K-effective result	Reference	1.01023	0.98344	0.98029
	DeCART2D	1.01091	0.98273	0.98021
ΔK x1e-5 (pcm)		67.3	70.9	7.5
Rod Worth (pcm)	Reference	-	2697	3024
	DeCART2D	-	2817	3069
Error	(%)	0.0665	0.0721	0.0076
RMS	(%)	0.0044		

Table V: DeCART2D result of Assembly power compared to VERA benchmark result for All the cases in problem 4-2D

4A-2D Assembly Powers			
VERA		DeCART2D	
0.99772		0.99823	
0.92262	1.07795	0.92444	1.07562
4B-2D Assembly Powers			
VERA		DeCART2D	
0.57019		0.58350	
0.92597	1.18148	0.92884	1.17490
4C-2D Assembly Powers			
VERA		DeCART2D	
0.52505		0.53061	
0.92446	1.19428	0.92694	1.19000

3. Conclusions

A study of the VERA core benchmark analysis has been performed by simulating 2D HZP BOC Fuel Pin, Fuel Lattice and 3x3 Assembly for V&V of the DeCART2D code. The multiplication factor for each case in the three problems was compared with VERA reference solution.

Also, pin to pin power calculations were compared with the reference for fuel lattice and 3x3 assembly. RMS was generated for each problem in this study.

ACKNOWLEDGMENT

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIT), in addition to funding from King Abdullah City for Atomic and Renewable Energy, Kingdom of Saudi Arabia, within the SMART PPE Project (No. 2016M2C6A1930038).

REFERENCES

[1] J. Y. Cho, et al., "DeCART2D v1.0 Methodology Manual," KAERI/TR-5283/2013, 2013.
[2] A.T. Godfrey, VERA Core Physics Benchmark Progression Problem Specifications, Rev. 4, Oak Ridge National Laboratory, Oak Ridge (TN), 2014. CASL-U-2012- 0131-004.