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Benchmark Matrix for Verification and Validation of DeCART2D Code

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1. Introduction

The DeCART2D[1] code has been developed in KAERI for the PWR (Pressurized Water Reactor) core design including SMART (System-integrated Modular Advanced ReacTor). The DeCART2D solves the Boltzmann transport equation by Method of Characteristic (MOC) so that it contributes in generating assembly-wise homogenized group condensed cross section to be used in the MASTER code[2].

In this work, a benchmark suite for the DeCART2D code is made to verify and validate its calculation performance especially as a part of SMART design code system. The benchmark suite consists of 6 bodies as follows:

- Single pin cell problems
- 3x3 multi pin cell problems
- Assembly problems w/o burnable absorber (BA)
- Assembly problems w/ BA
- Rod worth problems
- Burnup problems

All the problem specifications in the benchmark matrix are based on the 17x17 SMART fuel assembly (FA) design and provided in various operating conditions. The 47/18 neutron/gamma energy group XS library based on the ENDF/B-VII.1 is used with 0.02 cm ray spacing, 8 azimuthal angles in 90° domain and 2 polar angles for ray discretization. The results of calculations are compared with the Monte Carlo codes such as McCARD[3] and MCNP[4]. In the subsequent section, the detailed characteristics of each body of a benchmark suite will be provided.

2. Problem Sets for Benchmark Suite

2.1 Single Pin Cell Problems

The configuration of the single fuel pin loaded with UO_2 is given in Figure 1. To check the calculation capability with respect to enrichment variation, 3wt% and 5wt% enriched UO_2 are selected in the test problems. Zircaloy-2 is used as a cladding material.

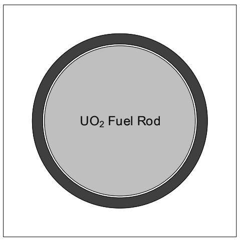

Fig. 1. Basic geometry of fuel pin cell for a benchmark suite.

The operation conditions for benchmark cases are selected depending on fuel and moderator temperatures and soluble boron concentrations. The IDs and their specifications are summarized in Table I.

2.2 3x3 Multi Pin Cell Problems

The array of multi pin cell problems is the 3x3 matrix. The problems are composed of 8 normal UO_2 fuel rods and either a central 8 wt% gadolinia-bearing 1.8 wt% enriched UO_2 fuel rod (GDBA rod) or hollowing guide tube (GT) filled with moderator. The IDs and their specifications are summarized in Table II.

2.3 Assembly Problems w/o BA

An assembly is made up of a 17x17 array of 264 UO_2 fuel rods, 24 guide tubes for control rods and a central instrument tube. In the benchmark suite, the reflective boundary condition for the radial direction and infinite condition for the axial direction are assumed because it is the boundary condition adopted in generating assembly-wise few group constants. The detailed specification is given in Table III.

2.4 Assembly Problems w/ BA

The assembly problems containing 12 and 24 GDBA rods and 16 WABA rods are selected as benchmark problems. The overall assembly design is the same but the location of each BA is different. The GDBA rods are located at fuel rod positions, while the WABA rods are located in guide tube positions. See Table IV for the details.

2.5 Rod Worth Problems

The control rod inserted assembly problems with no BA rod, 12 and 24 GDBA rods are selected for benchmark problems for rod worth calculation. Ag-In-Cd is adopted for the control rod absorber. See Table V for the details.

2.6 Burnup Problems

12 cases are selected from BOL (Beginning Of Life) problems given in Tables I through V. The results are compared to that of McCARD which has capability of burnup calculation. Refer Table VI to see which cases are chosen from the BOL problems.

Table I : Benchmark IDs for Single Pin Cell Problems

ID	U-235 wt%	Temperature (K)			PPM	BA	CR	ID	U-235 wt%	Temperature (K)			PPM	BA	CR
		Fuel	Clad	Mod						Fuel	Clad	Mod			
1	3	300	300	300	0	x	x	10	5	600	600	600	1000	x	x
2	5	300	300	300	0	x	x	11	3	900	600	600	1000	x	x
3	3	600	600	600	0	x	x	12	5	900	600	600	1000	x	x
4	5	600	600	600	0	x	x	13	3	300	300	300	2000	x	x
5	3	900	600	600	0	x	x	14	5	300	300	300	2000	x	x
6	5	900	600	600	0	x	x	15	3	600	600	600	2000	x	x
7	3	300	300	300	1000	x	x	16	5	600	600	600	2000	x	x
8	5	300	300	300	1000	x	x	17	3	900	600	600	2000	x	x
9	3	600	600	600	1000	x	x	18	5	900	600	600	2000	x	x

Table II : Benchmark IDs for 3x3 Multi Pin Cell Problems

ID	U-235 wt%	Temperature (K)			PPM	Central pin type	ID	U-235 wt%	Temperature (K)			PPM	Central pin type
		Fuel	Clad	Mod					Fuel	Clad	Mod		
1	3	300	300	300	0		19	3	300	300	300	0	
2	5	300	300	300	0		20	5	300	300	300	0	
3	3	600	600	600	0		21	3	600	600	600	0	
4	5	600	600	600	0		22	5	600	600	600	0	
5	3	900	600	600	0		23	3	900	600	600	0	
6	5	900	600	600	0		24	5	900	600	600	0	
7	3	300	300	300	1000		25	3	300	300	300	1000	
8	5	300	300	300	1000		26	5	300	300	300	1000	
9	3	600	600	600	1000		27	3	600	600	600	1000	
10	5	600	600	600	1000	GDBA	28	5	600	600	600	1000	Hollowing GT
11	3	900	600	600	1000		29	3	900	600	600	1000	
12	5	900	600	600	1000		30	5	900	600	600	1000	
13	3	300	300	300	2000		31	3	300	300	300	2000	
14	5	300	300	300	2000		32	5	300	300	300	2000	
15	3	600	600	600	2000		33	3	600	600	600	2000	
16	5	600	600	600	2000		34	5	600	600	600	2000	
17	3	900	600	600	2000		35	3	900	600	600	2000	
18	5	900	600	600	2000		36	5	900	600	600	2000	

Table III : Benchmark IDs for Fuel Assembly w/o BA

ID	U-235 wt%	Temperature (K)			PPM	BA	CR	ID	U-235 wt%	Temperature (K)			PPM	BA	CR
		Fuel	Clad	Mod						Fuel	Clad	Mod			
1	3	300	300	300	0	x	x	10	5	600	600	600	1000	x	x
2	5	300	300	300	0	x	x	11	3	900	600	600	1000	x	x
3	3	600	600	600	0	x	x	12	5	900	600	600	1000	x	x
4	5	600	600	600	0	x	x	13	3	300	300	300	2000	x	x
5	3	900	600	600	0	x	x	14	5	300	300	300	2000	x	x
6	5	900	600	600	0	x	x	15	3	600	600	600	2000	x	x
7	3	300	300	300	1000	x	x	16	5	600	600	600	2000	x	x
8	5	300	300	300	1000	x	x	17	3	900	600	600	2000	x	x
9	3	600	600	600	1000	x	x	18	5	900	600	600	2000	x	x

Table IV : Benchmark IDs for Fuel Assembly w/ BA

ID	U-235 wt%	Temperature (K)			PPM	BA	CR	ID	U-235 wt%	Temperature (K)			PPM	BA	CR
		Fuel	Clad	Mod						Fuel	Clad	Mod			
1	3	300	300	300	1000	12GDBA	x	10	5	600	600	600	1000	24GDBA	x
2	5	300	300	300	1000	12GDBA	x	11	3	900	600	600	1000	24GDBA	x
3	3	600	600	600	1000	12GDBA	x	12	5	900	600	600	1000	24GDBA	x
4	5	600	600	600	1000	12GDBA	x	13	3	300	300	300	1000	16WABA	x
5	3	900	600	600	1000	12GDBA	x	14	5	300	300	300	1000	16WABA	x
6	5	900	600	600	1000	12GDBA	x	15	3	600	600	600	1000	16WABA	x
7	3	300	300	300	1000	24GDBA	x	16	5	600	600	600	1000	16WABA	x
8	5	300	300	300	1000	24GDBA	x	17	3	900	600	600	1000	16WABA	x
9	3	600	600	600	1000	24GDBA	x	18	5	900	600	600	1000	16WABA	x

Table V : Benchmark IDs for 17x17 Fuel Assembly Problems with Control Rods

ID	U-235 wt%	Temperature (K)			PPM	BA	CR	ID	U-235 wt%	Temperature (K)			PPM	BA	CR
		Fuel	Clad	Mod						Fuel	Clad	Mod			
1	3	300	300	300	1000	x	24	10	5	600	600	600	1000	12GD8	24
2	5	300	300	300	1000	x	24	11	3	900	600	600	1000	12GD8	24
3	3	600	600	600	1000	x	24	12	5	900	600	600	1000	12GD8	24
4	5	600	600	600	1000	x	24	13	3	300	300	300	1000	24GD8	24
5	3	900	600	600	1000	x	24	14	5	300	300	300	1000	24GD8	24
6	5	900	600	600	1000	x	24	15	3	600	600	600	1000	24GD8	24
7	3	300	300	300	1000	12GD8	24	16	5	600	600	600	1000	24GD8	24
8	5	300	300	300	1000	12GD8	24	17	3	900	600	600	1000	24GD8	24
9	3	600	600	600	1000	12GD8	24	18	5	900	600	600	1000	24GD8	24

3. BOL Benchmark Calculations

3.1 Single Pin Problems

The benchmark problems given in Table I are solved by using DeCART2D and the results are compared with the references obtained by MCNP and McCARD. The errors between two codes are given in Figure 2. It shows that the maximum error in eigenvalues is 69 pcm in case of MCNP, while it is -87 for McCARD. Since the error is calculated in a way of subtracting the result of Monte Carlo code from that of DeCART2D, the minus sign indicates the results obtained by DeCART2D is smaller than the reference solution.

3.2 3x3 Multi Pin Problems

The errors in eigenvalues for the problems provided in Table II are presented in Figure 2. It shows that the maximum difference between DeCART2D and MCNP is -426 pcm when GDBA is located at center, while it is 141 pcm for the case when hollow GT is replaced it. In case of McCARD, the maximum difference with DeCART2D is -367 pcm for GDBA case, while -93 pcm is the largest error for the hollow GT case.

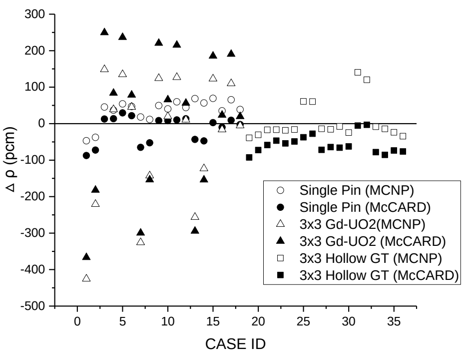

Fig. 2. Differences in eigenvalues between the results obtained from DeCART2D and MCNP/McCARD for benchmark problems given in Tables I and II.

Figure 3 shows the largest power errors at each pin positions extracted from whole cases. Due to 45 degree symmetry, only 1/8 array is illustrated in the Figure 3. The largest error in power is -0.56% in case of MCNP, while it is -0.80% for McCARD.

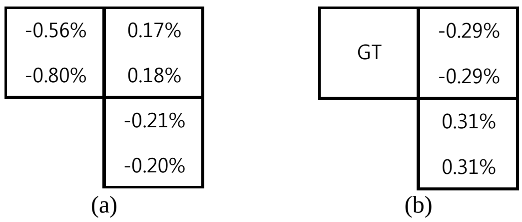

Fig. 3. Maximum errors appeared in power distributions for 1/8 multi pin array with (a) GDBA in central pin location and (b) hollowing GT case. The first line is the difference between DeCART2D and MCNP, while the second one is for DeCART2D and McCARD.

3.3 Assembly Problems

The eigenvalue errors for the problems given in Tables III and IV are given in Figure 4. It shows the maximum error in eigenvalues between DeCART2D and MCNP for the assembly problem is -379 pcm, while it is -415 pcm for McCARD. In either case, the maximum error appears when BA is considered.

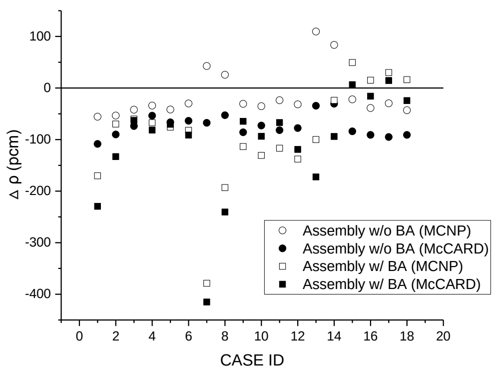

Fig. 4. Differences in eigenvalues between the results obtained from DeCART2D and MCNP/McCARD for benchmark problems given in Tables III and IV.

Figure 5 shows the maximum power errors at each pin position regardless of existence of BA. The maximum pin power error between DeCART2D and MCNP is -0.72%, while it is -0.56% for McCARD.

IT	-0.38% -0.37%	-0.32% -0.34%	GT	-0.38% -0.31%	-0.47% -0.32%	GT	-0.30% -0.39%	0.27% 0.29%
	0.43% 0.27%	0.22% 0.26%	-0.38% -0.38%	0.22% 0.24%	0.26% 0.21%	-0.38% -0.37%	0.33% 0.29%	0.18% 0.25%
		0.25% 0.21%	-0.36% -0.42%	0.30% 0.20%	0.16% 0.18%	-0.38% -0.35%	0.30% 0.22%	0.28% 0.19%
			GT	-0.48% -0.38%	-0.39% -0.33%	GT	-0.34% -0.28%	0.23% 0.22%
				0.16% 0.22%	-0.42% -0.37%	-0.40% -0.44%	0.31% 0.35%	0.29% 0.29%
					GT	-0.34% -0.34%	0.38% 0.32%	0.25% 0.26%
						0.28% 0.29%	0.36% 0.27%	0.31% 0.32%
							0.46% 0.39%	0.33% 0.27%
								0.33% 0.27%

Fig. 5. Maximum pin power errors estimated for 1/8 assembly regardless of existence of BA. The first line is the maximum difference between DeCART2D and MCNP, while the second one is for DeCART2D and McCARD.

3.4 Rod Worth Problems

Rod worth is evaluated by using both the rodded cases given in Table V and the corresponding unrodded results obtained in the previous results. Figure 6 shows the relative errors in rod worth compared to MCNP and McCARD. The maximum errors are found to be -3.04% and -3.85%, respectively.

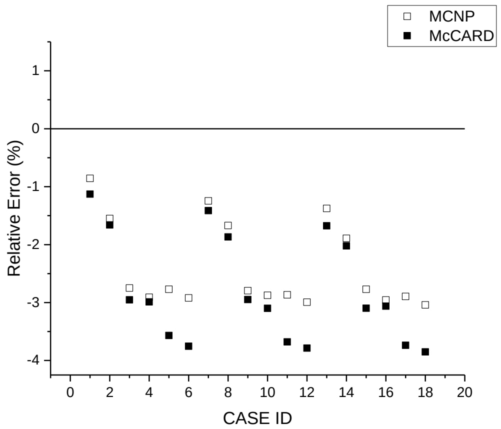

Fig. 6. Relative error in rod worth for each problem given in Table V between DeCART2D and MCNP/McCARD.

4. Burnup Benchmark Calculations

For delivering the capability with respect to burnup calculation, 12 problems are selected from the BOL problems given in Tables I through V. Table VI shows the selected problems in pairs with its corresponding ID of the BOL problems. The results are compared with that of McCARD. Figure 7 shows the eigenvalue errors at each burnup steps for each case.

Table VI : Benchmark IDs for burnup problems and its corresponding BOL cases

ID	Reference case ID	ID	Reference case ID
1	Table I, ID=11	7	Table IV, ID=5
2	Table I, ID=12	8	Table IV, ID=6
3	Table II, ID=11	9	Table IV, ID=11
4	Table II, ID=12	10	Table IV, ID=12
5	Table III, ID=11	11	Table IV, ID=17
6	Table III, ID=12	12	Table IV, ID=18

The maximum error is observed by -1118 pcm appeared in the problem ID 11 at the end of life. The error is found to be burnup dependent so that it is considered that the error is mainly originated from the burnup modeling. The maximum pin power error is observed to be 2.61% over the whole problems and burnup steps.

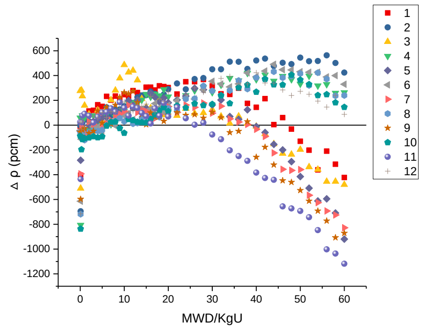

Fig. 7. Eigenvalue errors observed in burnup calculations between DeCART2D and McCARD. See Table VI for identifying the problem IDs.

5. Conclusion

A benchmark suite for the DeCART2D code is developed to verify and validate its calculation performance. The maximum eigenvalue error between DeCART2D and MCNP is appeared to be -426 pcm for the BOL problems, while it is -415pcm when compared to McCARD. The largest errors in pin power are -0.72% when the reference is MCNP, while it is -0.80% for McCARD. The maximum errors in rod worth are estimated as below 4%. In case of burnup problems, the maximum error in eigenvalue is observed as -1118 pcm when compared to McCARD. The largest error in power is shown to be 2.61%.

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