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A Neutronics Solution to the OECD/NEA/NSC PBMR-400 Stand Alone Steady State Benchmark Problem by using the Hex-Z Solver of the MASTER Code

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1. Introduction

Recently, the OECD/NEA/NSC PBMR-400 coupled neutronics/thermal hydraulics transient benchmark problem was proposed. [1] The benchmark problem was derived from the design data of the PBMR-400 nuclear power plant. The benchmark problem consists of two phases. Phase I is a steady state which consists of three exercises. Phase II is the transient state initiated from phase I. Exercise 1 and exercise 2 of phase I are stand alone steady state problems for the neutronics and thermal hydraulics, respectively. Exercise 3 is a couple neutronics/thermal hydraulics steady state problem, which is the initial condition for the phase II problems.

In this paper, we present a solution to the exercise 1 of phase I of the benchmark problem by using the MASTER code.[2] Although the original problem is defined as an R-Z 2D problem, we transformed it into an approximate 3D problem which consists of many hexagonal prisms. The approximate 3D problem was then solved by using the Hex-Z solver of the MASTER code. To investigate the effect of the geometrical approximation, the solution of the MASTER code was compared with a reference finite difference method (FDM) solution for the original problem.

2. Methods and Results

2.1 Description of the Problem

Figure 1 shows the geometry and the material compositions of the original benchmark problem. Fuel region, graphite region, control rod region, metal region, and void region are marked in red, yellow, brown, gray, and blue, respectively. Constant macroscopic cross-sections are given for each material composition. The problem shown in Figure 1 was transformed into an approximate 3D problem which consists of many hexagonal prisms. Figure 2 shows the radial distribution of the hexagonal prisms in the approximate 3D problem. In the transformation, it is impossible to preserve all the effective radii of the core-reflector and outer boundaries since we have only one degree of freedom, the pitch of the hexagon. We preserved the core volume and we minimized the errors of the radii of the boundaries. We obtained the 13.4470 as the pitch of the hexagon and the corresponding effective radii are also shown in Figure 2. The same axial mesh structure as that in Figure 1 was used for the approximate 3D model. As shown in Figure 1, a set of cross-sections is assigned to each node in the original problem. The cross-sections for each Hex-Z node were determined by a volume weighted average of the cross-sections for the original nodes with which the Hex-Z node overlaps. No mixing was allowed between the fuel and the moderator.

z ↓ -200	r→ 0	10 10	41 31	73.6 32.6	80.55 6.95	92.05 11.5	100 7.95	117 17	134 17	151 17	168 17	185 17	193 7.95	204.5 11.5	211.4 6.95	225 13.6	243.6 18.6	260.6 17	275 14.4	287.5 12.5	292.5 5
-150	50	133	133	133	133	155	116	113	113	113	113	113	135	164	144	144	152	152	152	189	190
-100	50	133	133	133	133	155	116	113	113	113	113	113	135	164	144	144	152	152	152	189	190
-50	50	133	133	133	133	155	116	112	112	112	112	112	135	164	144	144	152	152	152	189	190
0	50	133	133	133	133	155	116	111	111	111	111	111	135	165	144	144	152	152	152	189	190
50	50	134	134	134	125	156	117	1	23	45	67	89	136	166	145	145	153	153	153	189	190
100	50	134	134	134	125	156	117	2	24	46	68	90	136	167	145	145	153	153	153	189	190
150	50	134	134	134	126	157	118	3	25	47	69	91	137	168	146	146	153	153	153	189	190
200	50	134	134	134	126	157	118	4	26	48	70	92	137	169	146	146	153	153	153	189	190
250	50	134	134	134	126	157	118	5	27	49	71	93	137	170	146	146	153	153	153	189	190
300	50	134	134	134	127	158	119	6	28	50	72	94	138	171	147	147	153	153	153	189	190
350	50	134	134	134	127	158	119	7	29	51	73	95	138	172	147	147	153	153	153	189	190
400	50	134	134	134	127	158	119	8	30	52	74	96	138	173	147	147	153	153	153	189	190
450	50	134	134	134	127	158	119	9	31	53	75	97	138	174	147	147	153	153	153	189	190
500	50	134	134	134	128	159	120	10	32	54	76	98	139	175	148	148	153	153	153	189	190
550	50	134	134	134	128	159	120	11	33	55	77	99	139	176	148	148	153	153	153	189	190
600	50	134	134	134	128	159	120	12	34	56	78	100	139	177	148	148	153	153	153	189	190
650	50	134	134	134	128	159	120	13	35	57	79	101	139	178	148	148	153	153	153	189	190
700	50	134	134	134	129	160	121	14	36	58	80	102	140	179	149	149	153	153	153	189	190
750	50	134	134	134	129	160	121	15	37	59	81	103	140	180	149	149	153	153	153	189	190
800	50	134	134	134	129	160	121	16	38	60	82	104	140	181	149	149	153	153	153	189	190
850	50	134	134	134	129	160	121	17	39	61	83	105	140	182	149	149	153	153	153	189	190
900	50	134	134	134	130	161	122	18	40	62	84	106	141	183	150	150	153	153	153	189	190
950	50	134	134	134	130	161	122	19	41	63	85	107	141	184	150	150	153	153	153	189	190
1000	50	134	134	134	130	161	122	20	42	64	86	108	141	185	150	150	153	153	153	189	190
1050	50	134	134	134	131	162	123	21	43	65	87	109	142	186	151	151	153	153	153	189	190
1100	50	134	134	134	131	162	123	22	44	66	88	110	142	187	151	151	153	153	153	189	190
1150	50	132	132	132	132	163	124	114	114	114	114	114	143	188	151	151	154	154	154	189	190
1200	50	132	132	132	132	163	124	115	115	115	115	115	143	188	151	151	154	154	154	189	190
1250	50	132	132	132	132	163	124	115	115	115	115	115	143	188	151	151	154	154	154	189	190

Figure 1. The geometry and the material compositions of the original benchmark problem.

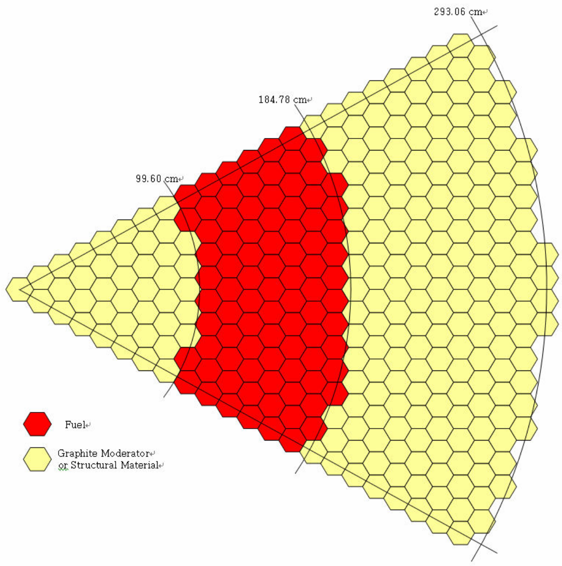

Figure 2. Top view of the approximate 3D model

2.2 Results and Discussions

A fine mesh R-Z 2D FDM solution for the original problem was taken as a reference solution. Figure 3 shows the reference power density distribution and the error of that obtained by azimuthally averaging the 3D MASTER results. The nodes at the core periphery have relatively large errors, which is ascribed to the approximation of the core/reflector boundary with a zigzag one. A very large negative relative error at the top of the outer periphery of the core is observed though it is not so serious since the power density itself is very small. The large negative error is ascribed to a thermal flux depression near the control rod region. The narrow and strong absorber compositions in the control rod region of the original problem were diluted by the nearby graphite moderator compositions to form a wide and weak absorber region in the approximate 3D model, which caused a wide thermal flux depression near the control rod region.

Table 1 compares the global parameters of the solutions. The error of the effective multiplication factor is 182pcm, which is acceptable in practical applications. The relative errors of the other parameters are very small except for the leakage from the calculation domain. However, it matters little because the leakage itself is very small.

Figure 4. shows the axially averaged relative power density. The solid line is the reference solution obtained from the R-Z 2D FDM solution. The dots are the axially averaged relative power density at each hexagon in the approximate 3D model. The power densities are different even at the hexagons of which the distances from the center of the reactor are the same depending on their azimuthal position. We see a large azimuthal dependency of the power density especially at the outer periphery of the core, which was additionally introduced by the zigzag core/reflector boundary in the approximate 3D model. The errors caused by the azimuthal dependency can be canceled out by azimuthally averaging the results in the 2D problems but they are inevitable in the 3D problems.

3. Conclusion

In this paper, we presented a solution to exercise 1 of phase I of the OECD/NEA PBMR-400 benchmark problem using Hex-Z solver of the MASTER code. We obtained very accurate results at the internal of the core. However, we observed large errors at the core periphery caused by a geometrical modeling error. The azimuthally averaged results for this problem have an insufficient accuracy but they are acceptable though.

Acknowledgement

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REFERENCES

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2. Jin Young Cho et.al., MASTER 3.0 USER'S MANUAL, KAERI/UM-8/2004 (2004).

2.53 -3.8	2.00 -4.5	1.72 -6.1	1.51 -7.2	1.35 -9.6
4.24 -2.7	3.31 -2.7	2.81 -4.2	2.42 -5.4	2.16 -8.0
6.23 -1.6	4.98 -1.7	4.34 -2.6	3.90 -3.2	3.65 -5.1
8.26 -0.6	6.81 -0.8	6.19 -1.3	5.96 -1.0	6.37 -1.3
9.84 0.1	8.32 -0.4	7.72 -0.6	7.62 -0.3	8.34 -0.5
10.67 0.6	9.18 -0.2	8.58 -0.3	8.50 -0.1	9.23 0.0
10.77 1.0	9.41 -0.1	8.82 -0.2	8.73 0.0	9.37 0.3
10.30 1.3	9.12 -0.1	8.59 -0.1	8.48 0.1	9.00 0.5
9.49 1.5	8.51 -0.1	8.03 0.0	7.91 0.1	8.30 0.8
8.51 1.8	7.70 -0.1	7.28 0.0	7.17 0.1	7.45 0.9
7.46 1.9	6.82 -0.1	6.46 0.0	6.34 0.1	6.54 1.1
6.44 2.1	5.93 -0.1	5.62 0.1	5.52 0.1	5.65 1.2
5.49 2.2	5.09 -0.1	4.84 0.1	4.74 0.1	4.83 1.3
4.65 2.4	4.33 -0.1	4.12 0.1	4.03 0.1	4.09 1.4
3.91 2.5	3.66 0.0	3.48 0.2	3.41 0.1	3.44 1.5
3.27 2.6	3.07 0.0	2.92 0.2	2.86 0.2	2.87 1.6
2.71 2.8	2.56 0.1	2.44 0.3	2.38 0.2	2.39 1.7
2.24 2.9	2.12 0.2	2.02 0.4	1.98 0.3	1.97 1.9
1.83 3.1	1.74 0.3	1.66 0.5	1.62 0.5	1.62 2.0
1.48 3.3	1.40 0.4	1.34 0.7	1.31 0.6	1.30 2.2
1.17 3.4	1.11 0.5	1.06 0.8	1.03 0.8	1.02 2.5
0.94 4.1	0.93 1.1	0.90 1.4	0.86 1.3	0.81 3.2

x.xx Reference Power Density (W/cm^3)
x.x MASTER Power Density Error (%)

Figure 3. Comparison of Power Distribution

Table 1. Comparison of the global parameters

	Reference	MASTER
k_{eff}	0.99938	1.00120
Max. Powe Density (W/cm^3)	10.77	10.87
Max. Fast Flux (n/cm^2·s)	2.109e+14	2.084e+14
Max. Thermal Flux (n/cm^2·s)	3.296e+14	3.284e+14
Leakage from Core (% per loss)	14.91	14.90
Leakage from Cal. Domain (%)	0.2571	0.4984

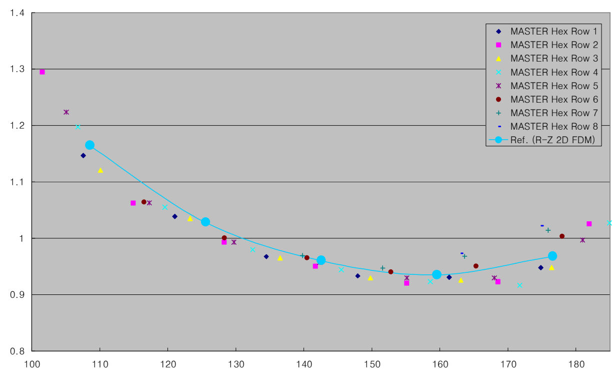

Figure 4. Azimuthal Dependency of MASTER Solution