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Application of SHAFE code to the CANDU Reactor through Initial Core Calculation

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1. Introduction

The SHAFE code, which is based on the finite element method (FEM), was developed for arbitrary geometry applications. Its verification was conducted, and various core benchmark problems are solved with the SHAFE code. In this research, the SHAFE code result of the C5G7 problem is first compared with the McCARD multi-group solution and a nodal solution. This comparison is for a verification of the soundness of the SHAFE code under a situation in which the basic lattice shape is hexahedron and an up-scattering phenomenon exists. Although it is certain that the calculation time will be much larger than that of nodal code, the accuracy of the SHAFE code can be verified with this problem. Second, the CANDU initial core problem is solved based on the verification. If the steady-state result of SHAFE code is better than or similar with the result of RFSP, the SHAFE code can be developed as an analyzer for CANDU. By verifying and applying the SHAFE code for the C5G7 problem and CANDU system, the soundness and the utilizability of the SHAFE code for the CANDU system can be proved.

2. C5G7 Benchmark Problem

To solve the C5G7 benchmark problem, a 7-group homogenized cross section is used for the core calculation. The size of the assembly and core, and the boundary condition of the problem are the same with those of original C5G7 benchmark problem [3]. Because the basic lattice shape of the C5G7 problem is same as that of the CANDU core, i.e., a square, the result of this problem can ensure the accuracy of the SHAFE code for core problems with a square lattice shape. In addition, by solving the C5G7 problem, the accuracy of the SHAFE code for problems with an up-scattering cross section can be also proved. The reference values of the multiplication factor and power distribution are obtained using McCARD multi-group calculation with 7-group homogenized cross sections.

Table I. FEM Mesh Data for C5G7 3D Benchmark

Basis Ftn.	Nodes	Elements	Avg. Vol.	Avg. Pitch
Linear	1,866	8,367	52.86cm^3	4.167cm
Quadratic	12,840			

As shown in Table I, the average pitch of the element is relatively large, and the difference between the results of linear and quadratic basis functions can be well revealed.

Table II. K$_{\mathrm{eff}}$ for C5G7 3D Benchmark

McCARD	P_1 FEM		SP_3 FEM	
1.19097	Linear	1.19072 (-25)	Linear	1.19232 (135)
	Quadratic	1.18993 (-104)	Quadratic	1.19160 (63)

In Table II, the standard deviation of McCARD is 3 pcm, and the diffusion solution seems to be below the McCARD solution and the SP_3 solution seems to be over the McCARD solution. It was reported that the typical nodal diffusion and SP_3 solutions are 1.18977 and 1.19127 with no submesh (cubes of side length of 21.42cm).

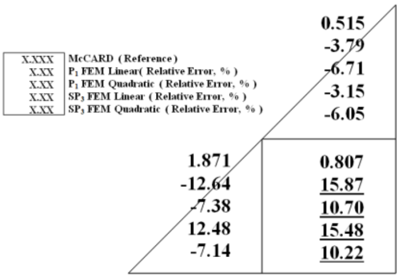


Fig. 1. Power distributions of C5G7 3D benchmark

Table III. Power Errors for C5G7 3D Benchmark

	P_1 FEM		SP_3 FEM	
	Linear	Quadratic	Linear	Quadratic
RMS Err.(%)	14.92	8.38	14.66	9.00
Max. Err.(%)	15.87	10.70	15.48	10.22

Table IV. Calculation Time for C5G7 3D Benchmark

P_1 FEM		SP_3 FEM	
Linear	Quadratic	Linear	Quadratic
150sec	2549sec	501sec	8024sec

As shown in Fig. 1 and Table III, the result of the quadratic function shows a high accuracy improvement for a power estimation, while only a marginal improvement can be found for the multiplication factor. Both the multiplication factor and power error lie on a reasonable interval such that the soundness of SHAFE code is shown indirectly in a specific situation such as the CANDU core. Meanwhile, the speed of the FEM is quite slow, while the time for a nodal solution is near 1 sec.

3. CANDU Initial Core Calculation

Based on the result of a C5G7 benchmark problem, the initial core of a CANDU reactor was prepared for a test on the utilizability of the SHAFE code for a CANDU system.

Table V. Cross Sections of WS1 at Zero Burnup

	Composition			
	Fuel		Reflector	
	Group 1	Group 2	Group 1	Group 2
D_g	1.36554	8.81410×10^{-1}	1.26274	8.26322×10^{-1}
Σ_{rg}	1.03340×10^{-2}	3.54314×10^{-3}	1.55279×10^{-2}	2.11520×10^{-4}
$\nu\Sigma_{fg}$	8.78882×10^{-4}	4.26202×10^{-3}	-	-
χ_g	1.00000	-	-	-
h_{factor}	4.33055×10^{-2}	2.29720×10^{-1}	-	-
$\Sigma_{s,g\rightarrow g+1}$	8.72258×10^{-3}	-	1.55170×10^{-2}	-
$\Sigma_{s,g\rightarrow g-1}$	-	6.54433×10^{-5}	-	2.67738×10^{-5}

The cross sections are generated using WIMS-IST with the dimensions of Wolsong Unit 1, initial fuel [2]. The 2-group cross sections at a zero burnup for fuel and reflector are listed in Table V. For the calculation of the McCARD and FEM solution, the reference geometry should be determined. The $42\times34\times22$ configuration is usually used in RFSP [1]. Thus another calculation is also conducted with a geometry equivalent to the RFSP.

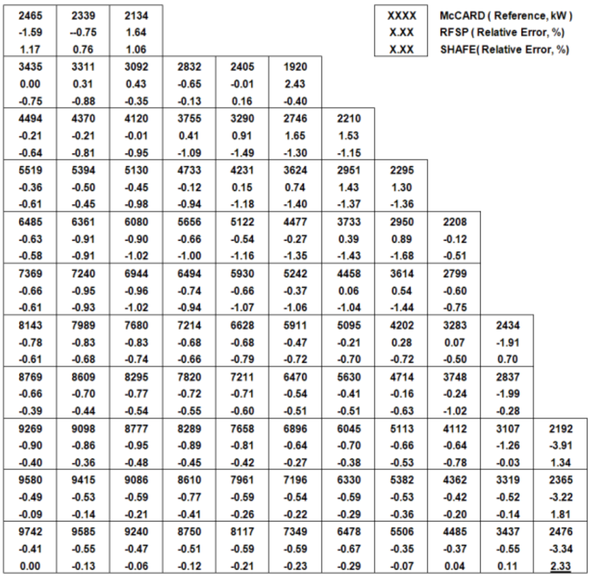
Table VI. FEM Mesh Data for CANDU Initial Core Problem

Nodes	Elements	Avg. Vol.	Avg. Pitch
45,952	264,553	952.80cm^3	10.92cm

Table VII. K$_{eff}$ for C5G7 Benchmark with Various Codes

McCARD	RFSP	SCAN	SHAFE
1.08937	1.08982 (45)	1.08981 (44)	1.08925 (-12)

It turned out that the result of a linear basis function is sufficiently converged one for this problem, such that the quadratic basis function is not necessary. In addition, because of a small transport effect of CANDU core, the SP$_3$ calculation is not listed. As shown in Table VII, the result of the SHAFE code is much closer to the McCARD solution than RSFP and SCAN solutions. The standard deviation of McCARD is 3 pcm.



2465 -1.59 1.17	2339 --0.75 0.76	2134 1.64 1.06								
3435 0.00 -0.75	3311 0.31 -0.88	3092 0.43 -0.35	2832 -0.65 -0.13	2405 -0.01 0.16	1920 2.43 -0.40					
4494 -0.21 -0.64	4370 -0.21 -0.81	4120 -0.01 -0.95	3755 0.41 -1.09	3290 0.91 -1.49	2746 1.65 -1.30	2210 1.53 -1.15				
5519 -0.36 -0.61	5394 -0.50 -0.45	5130 -0.45 -0.98	4733 -0.12 -0.94	4231 0.15 -1.18	3624 0.74 -1.40	2951 1.43 -1.37	2295 1.30 -1.36			
6485 -0.63 -0.58	6361 -0.91 -0.91	6080 -0.90 -1.02	5656 -0.66 -1.00	5122 -0.54 -1.16	4477 -0.27 -1.35	3733 0.39 -1.43	2950 0.89 -1.68	2208 -0.12 -0.51		
7369 -0.66 -0.61	7240 -0.95 -0.93	6944 -0.96 -1.02	6494 -0.74 -0.94	5930 -0.66 -1.07	5242 -0.37 -1.06	4458 0.06 -1.04	3614 0.54 -1.44	2799 -0.60 -0.75		
8143 -0.78 -0.61	7989 -0.83 -0.68	7680 -0.83 -0.74	7214 -0.68 -0.66	6628 -0.68 -0.79	5911 -0.47 -0.72	5095 -0.21 -0.70	4202 0.28 -0.72	3283 0.07 -0.50	2434 -1.91 0.70	
8769 -0.66 -0.39	8609 -0.70 -0.44	8295 -0.77 -0.54	7820 -0.72 -0.55	7211 -0.71 -0.60	6470 -0.54 -0.51	5630 -0.41 -0.51	4714 -0.16 -0.63	3748 -0.24 -1.02	2837 -1.99 -0.28	
9269 -0.90 -0.40	9098 -0.86 -0.36	8777 -0.95 -0.48	8289 -0.89 -0.45	7658 -0.81 -0.42	6896 -0.64 -0.27	6045 -0.70 -0.38	5113 -0.66 -0.53	4112 -0.64 -0.78	3107 -1.26 -0.03	2192 -3.91 1.34
9580 -0.49 -0.09	9415 -0.53 -0.14	9086 -0.59 -0.21	8610 -0.77 -0.41	7961 -0.59 -0.26	7196 -0.54 -0.22	6330 -0.59 -0.29	5382 -0.53 -0.36	4362 -0.42 -0.20	3319 -0.52 -0.14	2365 -3.22 1.81
9742 -0.41 0.00	9585 -0.55 -0.13	9240 -0.47 -0.06	8750 -0.51 -0.12	8117 -0.59 -0.21	7349 -0.59 -0.23	6478 -0.67 -0.29	5506 -0.35 -0.07	4485 -0.37 0.04	3437 -0.55 0.11	2476 -3.34 2.33

XXXX	McCARD (Reference, kW)
X.XX	RFSP (Relative Error, %)
X.XX	SHAFE(Relative Error, %)

Fig. 2. Power distribution of CANDU initial core problem

Table VIII. Power Errors for CANDU Initial Core Problem

	RFSP	SCAN	SHAFE
RMS Err.(%)	0.79	0.77	0.52
Max. Err.(%)	4.70	4.94	2.33
Ch. I.D.	L-1	M-1	L-22

This is an initial core problem so that the h factors for all channels are same. This means that the fission powers of McCARD and FEM are equivalent to the powers of RFSP and SCAN. In addition to the multiplication factor accuracy, the power estimation of FEM is also better than those of RFSP and SCAN. The k$_{eff}$ error is only 12 pcm. Also the RMS error is much lower than those of RFSP and SCAN as nearly half of 1%. The max. power errors appear at the periphery channels of the core and reflector for all 3 codes.

4. Conclusions

By solving the C5G7 benchmark, the effectiveness of the SHAFE code for CANDU system is investigated and verified, especially for the treatment of a rectangular geometry and up-scattering. Based on this result, the initial core of the CANDU reactor is solved using various core calculation modules such as RFSP, SCAN, and SHAFE. Among these codes, the results of both the multiplication factor and power of the SHAFE code agree well with results of McCARD, compared with the results of RFSP and SCAN. This consequence indicates that the FEM-based module can give a more accurate result for a CANDU system. In addition, the FEM-based code can always use the original geometry such that a variation of the modeling for different mesh can be avoided. Although the calculation time is much longer than the nodal method, by considering the fact that it is a code under development, it can be said that it is not a serious problem. In this research, the strong utilizability of the FEM-based SHAFE code for the CANDU system is well revealed.

5. Acknowledgement

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