nTRACER Solutions of the Two-Dimensional VVER Benchmark Problems

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1. Introduction

nTRACER [1] has recently equipped with a calculation capability to deal with hexagonal geometries with the hexagonal ray tracing module and the hexagonal CMFD acceleration [2]. The calculation accuracy of nTRACER for hexagonal geometries was verified in reference 2 for benchmark problems with C5G7 benchmark cross-sections. As a practical reactor core simulator, however, nTRACER needs to perform further verifications, which consist of real materials of the reactor core. VVER benchmark is a good problem for this evaluation of nTRACER, because it consists of hexagonal assemblies under PWR conditions, and the SNURPL multi-group library, which was verified to have a low error in homogenization [3], is available to be used for nTRACER calculation. In this paper, current improvements in nTRACER are briefly introduced. nTRACER solutions for fuel pin, fuel assembly, and core problems of VVER-440 and VVER-1000, then, are presented. The continuous McCARD [4] solution was selected as a reference solution.

2. Improvements

2.1. Super-pin based CMFD Acceleration

nTRACER uses *elongated model* for hexagonal geometries, in which boundary pin cells are elongated into pentagons and residual regions between pin cells and assembly boundaries are defined as trapezoidal gap cells. Although this model has a merit in explicit modeling of the assembly duct, it requires to resolve area imbalance among CMFD pins. In VVER-1000 fuel assembly, for example, the area of gap pin is equal to 0.06 cm^2 while that of fuel pin is equal to 1.41 cm^2. Large area imbalance among pins induces slow convergence in CMFD calculations.

Fig. 1 shows super-pin, which is defined as a merge between boundary pin cell and its neighboring gap cells. While the previous nTRACER used MOC pin in CMFD calculation, the current nTRACER uses super-pin, in which fluxes among each cell resulted from MOC calculation are merged into.

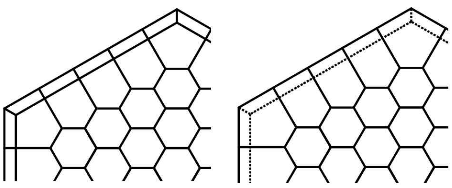

Figure 1. Comparison of MOC pin and super-pin for CMFD

The verification results of super-pin based CMFD acceleration for C5G7 H benchmark problems are summarized in Table 1. The whole calculation time reduced at most 49.2 % for the C5G7 H fuel assembly problem, and the number of outer iterations reduced at most 4 for the C5G7 H 2D core problem.

Table 1. Comparison of calculation results between CMFD accelerations

C5G7 H benchmark	Calculation time (s)		# of outer iterations	
	Previous	Super-pin	Previous	Super-pin
Fuel assembly	25.93	13.17	11	8
2D core	30.61	16.44	12	8
3D core	261.67	195.41	6	5

2.2. nTRACER model for the 'vygorodka'

'Vygorodka' is a kind of shroud in the VVER-440, which is a thin steel reflector wrapping outer-most fuel assemblies. Fig. 2 shows the exact model and the approximated model for the 'vygorodka'. Because of its gap pin structure as shown in Fig. 1, nTRACER adopted the approximated model, and assigned a material to the corner of 'vygorodka' as a mixture of moderator and steel with volume-weighted average.

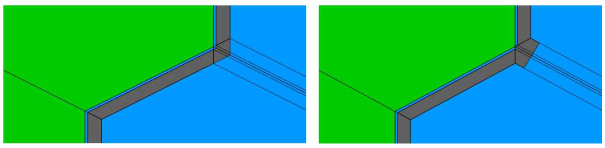

Figure 2. Exact model and approximated model for the 'vygorodka'

3. Calculations and Results for the VVER-1000

KAERI (Korea Atomic Energy Research Institute) suggested VVER-1000 reactor benchmark problems [5] with cases, which are arranged according to the size of problem, control rod insertion, fuel enrichment, boron concentration, and temperature. This paper deals with cases of A01, A02 FS20, and A04, which respectively represent fuel pin, fuel assembly, and 2D core problems.

The ray options of 0.05 cm ray spacing, 24 azimuthal angles within the angle of π, and 4 polar angles within the angle of π/2 were used in solving benchmark problems. Ray tracing calculation of nTRACER was accelerated by super-pin based CMFD. The SNURPL multi-group library based on ENDF/B-VII.0 was used in the core calculation with transport corrected scattering. The calculation options of McCARD solutions were determined according to the size of problem. 'Δρ' indicates the reactivity difference between nTRACER and McCARD in following tables.

Table 2. Calculation options of McCARD solutions

Calculation option	Fuel pin	Fuel assembly	Core
# of inactive cycles	50	100	100
# of active cycles	200	400	400
# of particles per cycle	1,000,000	5,000,000	20,000,000
Std. Dev. of k-eff	< 5 pcm		

3.1 Fuel Pin and Fuel Assembly Problems

Resulted reactivity differences for fuel pin problems are summarized in Table 3. The maximum reactivity difference was -93 pcm for A01 V13 case, which is a fuel pin problem with 2000 ppm of boron and 300 K temperature for all materials (fuel, cladding, and moderator).

Table 3. Reactivity differences between nTRACER and McCARD for VVER-1000 A01 cases

A01	k-eff		A01	k-eff	
Case	McCARD	Δρ (pcm)	Case	McCARD	Δρ (pcm)
V01	1.27689	-14	V10	1.19508	-7
V02	1.38618	-3	V11	1.06692	-49
V03	1.21006	23	V12	1.18457	-50
V04	1.30532	17	V13	0.93063	-93
V05	1.19927	-32	V14	1.08017	-78
V06	1.29390	-44	V15	0.97250	-23
V07	1.07376	-58	V16	1.10426	-26
V08	1.21190	-34	V17	0.96389	-62
V09	1.07655	-8	V18	1.09471	-72

The comparison results of nTRACER with McCARD for fuel assembly problems are summarized in Table 4. The maximum reactivity difference was -124 pcm for A02 FS20 V07 case, which is a fuel assembly problem with 1000 ppm of boron and 300 K temperature for all materials. The maximum and RMS pin power error did not exceed 0.34 % and 0.12 % all for A02 FS20 cases, respectively.

Table 4. Comparison of calculation results between nTRACER and McCARD for VVER-1000 A02 FS20 cases

A02 FS20	k-eff		Radial pin power error (%)	
Case	McCARD	Δρ (pcm)	Max.	RMS
V01	1.24910	-85	0.34	0.12
V02	1.19957	-21	0.28	0.08
V03	1.18975	-63	0.24	0.06
V04	1.02908	-112	0.32	0.11
V05	1.05149	-38	0.21	0.07
V06	1.04285	-70	0.21	0.07
V07	0.87961	-124	0.31	0.11
V08	0.93926	-50	0.23	0.07
V09	0.93151	-70	0.34	0.12

3.2 Simplified 3D Fuel Assembly Problem

The evaluation for the simple 3D fuel assembly problem was performed to verify the reasonability of nTRACER calculation with T/H feedback. Comparing to A05 cases in reference 6, the fuel region of this problem is filled with the fuel assembly of A02 FS20 neglecting any spacer grid as shown in Fig. 3. The fuel region is divided with 10 planes and the top reflector is divided with 2 planes in nTRACER calculation. The power of fuel assembly, the outlet pressure of coolant, and the mass flow rate of coolant per fuel assembly are equal to 18.405 MW, 15.7 MPa, 107.61 kg/s, respectively [6].

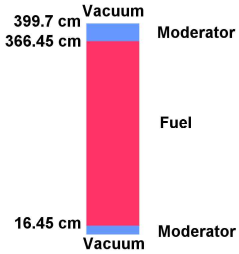

Figure 3. Axial configuration of simple 3D fuel assembly problem

After reflecting the T/H feedback effect by assembly-wise closed lumped channel model, the axial pin power became skewed to the bottom due to the relatively low coolant temperature at the lower part of the core. Fig. 4 and Fig. 5 show reasonable axial power shape and temperature distributions from nTRACER calculation for the simple 3D fuel assembly problem.

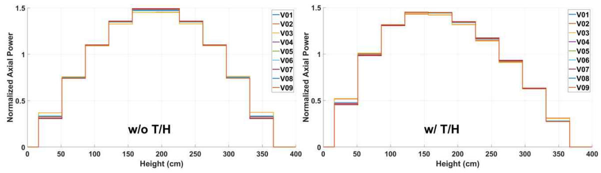

Figure 4. Axial power shape for the simple 3D fuel assembly problem

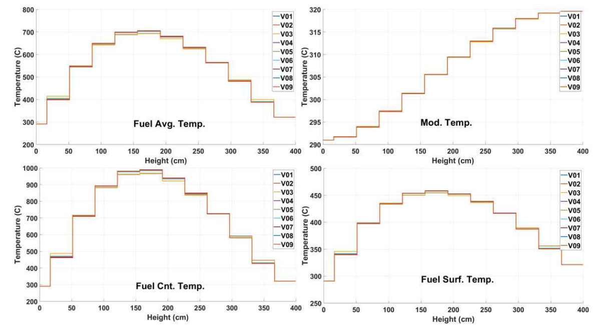

Figure 5. Axial temperature distributions for the simple 3D fuel assembly problem

3.3 2D Core Problem

The comparison results of nTRACER with McCARD for 2D core problems are summarized in Table 5. The maximum reactivity difference was -84 pcm for A04 V04 case, which is a core problem with 1000 ppm of boron and 300 K temperature for all materials. Except A04 V01 case with none of boron and 300 K temperature for all materials, the maximum and RMS relative pin power error did not exceed 2.65 % and 0.81 % for all A04 cases, respectively. Fig. 6 and Fig. 7 respectively show relative pin power error distribution for A04 V01 case and A04 V05 case.

Table 5. Comparison of calculation results between nTRACER and McCARD for VVER-1000 A04 cases

A04 Case	k-eff		Radial pin power error (%)	
	McCARD	Δρ (pcm)	Max.	RMS
V01	1.28365	-53	4.24	1.20
V02	1.22097	-12	1.38	0.26
V03	1.21116	-57	1.42	0.28
V04	1.08154	-84	2.65	0.81
V05	1.08246	-28	1.30	0.28
V06	1.07377	-65	1.37	0.29
V07	0.94263	-83	1.98	0.72
V08	0.97712	-32	1.19	0.28
V09	0.96935	-65	1.25	0.32

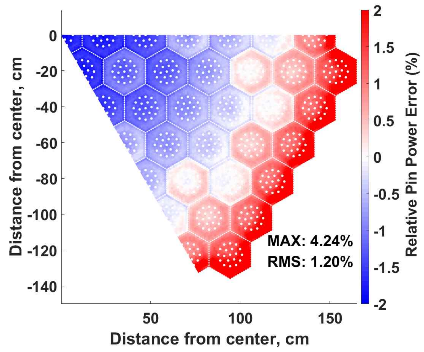

Figure 6. Relative pin power error distribution for the A04 V01 case

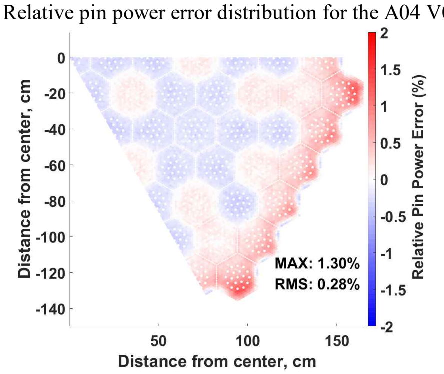

Figure 7. Relative pin power error distribution for the A04 V05 case

4. Calculations and Results for the VVER-440

The VVER-440 benchmark problem, which has a name of ‘Full-Core’ [7], is a 2D calculation benchmark, proposed at the AER symposium several years ago. This benchmark describes explicit radial reflector, but the core basket and the steel tube were neglected in this paper. nTRACER and McCARD performed benchmark calculations using the same calculation condition with the previous part.

4.1 Fuel Pin and Fuel Assembly Problems

The comparison results of nTRACER with McCARD for VVER-440 fuel pin problems are summarized in Table 6. Except the fuel pin problem with gadolinia, which has an extremely low k-eff value, the maximum reactivity difference was -125 pcm for the fuel pin problem with 1.6 w/o enrichment.

Table 6. Comparison of calculation results between nTRACER and McCARD for VVER-440 fuel pin problems

Fuel Pin	k-eff	
	McCARD	Δρ (pcm)
1.6 w/o	1.07170	-125
2.4 w/o	1.19162	-110
3.6 w/o	1.28936	-111
4.0 w/o	1.31116	-111
4.4 w/o	1.32958	-106
4.4 w/o + Gd	0.39584	-1218

The comparison results of nTRACER with McCARD for VVER-440 fuel assembly problems are summarized in Table 7. The maximum reactivity difference was -134 pcm for the fuel assembly problem with 1.6 w/o enrichment. The maximum and the RMS pin power error did not exceed 0.37 % and 0.11 %, respectively.

Table 7. Comparison of calculation results between nTRACER and McCARD for VVER-440 fuel assembly problems

Fuel assembly	k-eff		Radial pin power error (%)	
	McCARD	Δρ (pcm)	Max.	RMS
1.6 w/o	1.06701	-134	0.18	0.05
2.4 w/o	1.19471	-121	0.22	0.06
4.25 w/o	1.19734	-17	0.37	0.11

4.2 2D Core Problem

The resulted k-eff value of McCARD was 1.08834, and the reactivity error of nTRACER with McCARD was -116 pcm for the VVER-440 2D core problem. Fig. 8 shows relative pin power error distribution. The maximum and the RMS pin power error were 2.02 % and 0.58 %, respectively.

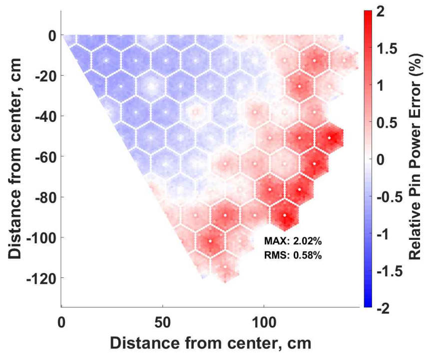

Figure 8. Relative pin power error distribution for the VVER-440 2D core problem

4. Conclusions

In this work, the hexagonal version of nTRACER was applied to solve the VVER-1000 and the VVER-440 benchmark problems. It turned out that the nTRACER solutions match quiet well with continuous McCARD solutions in the aspect of reactivity and power distribution. The maximum reactivity difference was 134 pcm among all benchmark solutions except the VVER-440 fuel pin problem with gadolinia. Except the A04 V01 case, the maximum and RMS relative pin power error did not exceed 2.65 % and 0.81 % for fuel assembly problems and 2D core problems, respectively. Since verifications in this work were limited on 2D problems, it is necessary to perform nTRACER evaluation for 3D core of VVER benchmark problem with explicit axial configuration in the future.

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