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Assessment of the HELIOS Code for the OPR-1000 Assembly with an Annular Fuel

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1. Introduction

Recently, the application of an annular fuel concept to a PWR fuel design has drawn attention due to its potential advantages in lowering the fuel temperature. Typical Westinghouse assembly with annular fuel rods was investigated by MIT [1] and a similar study for the OPR-1000 fuel assembly was also performed by KAERI [2]. In that, a conceptual design of a 12×12 annular fuel assembly was proposed and its neutronic characteristics were studied. At present, core modeling with the 12×12 annular fuel assembly is being conducted in parallel by KAERI and MIT by utilizing respective analysis codes and methods.

The standard reactor physics analysis procedure with the HELIOS/MASTER code package developed by KAERI is adopted for the core assessment. In this procedure, group constants are generated through the 2-dimensional transport lattice code HELIOS [3], and the core physics analysis is performed by the 3-dimensional nodal diffusion code MASTER [4]. Early study by MIT [1] shows a special treatment of a pin cell is required for the annular fuel assembly calculation to reduce the associated errors.

In this study, HELIOS model is assessed and validated by comparing key parameters with the Monte Carlo code, McCARD [5] results as a reference.

2. Methods and Results

2.1 Description of Solid and Annular Fuel Designs

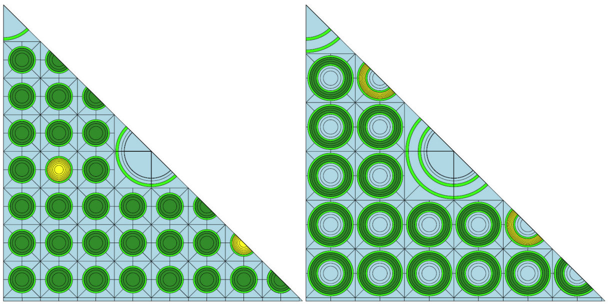

(a) Solid (b) Annular

Fig. 1. The HELIOS models for the OPR-1000 fuel assembly.

As shown in Fig. 1(a), the reference OPR-1000 fuel assembly has a 16×16 array with 236 solid fuel rods, 4 guide tubes for B_4C control rods and a central guide tube for instrumentation. On the other hand, the annular fuel assembly shown in Fig. 1(b) consists of a 12×12 array of 124 annular fuel rods, 4 control rod guide tubes and a central instrumentation tube. The annular fuel design is fully compatible with the solid fuel design in terms of structure, fuel to moderator ratio, amount of fissile material and coolant flow area. Besides, the guide tubes are of annular shape and their positions are compatible with the conventional design to match the control rod driving mechanism. The outer tube was sized to reduce the large flow area around the original tube, reducing the bypass flow as compared to the original design.

2.2 Benchmark Problems

In order to evaluate the validity of the HELIOS code, two benchmark problems are selected for the solid and annular fuel design, respectively. One is poison free; the other contains the gadolinia burnable absorber. In these benchmarks, the soluble boron in the moderator is not considered. For all cases, the fuel rod is loaded with 4.5 w/o enriched UO_2 fuel of 95 % theoretical density (10.4 g/cm^3). The gadolinia-bearing fuel rod is loaded with 6.0 w/o gadolinia (Gd_2O_3) admixed in natural UO_2 fuel. Reflective boundary condition for the radial direction and infinite condition for the axial direction are assumed.

For the solid fuel, the clad and coolant temperature is 600 K and the fuel temperature is assumed to be 900 K. For the annular fuel, the fuel temperature is changed from 900 K to 600 K to reflect lower temperatures of annular fuel. Specific power is increased from 36.574 W/gU to 42.748 W/gU because the fuel volume per assembly is decreased for the annular fuel design.

The geometric dimensions are given in Table 1. Note that thermal expansions for the structures are ignored in all calculations.

Table 1. Geometric data for benchmark problems (unit: cm)

	Solid (16×16)	Annular (12×12)
Assembly Pitch	20.78	20.78
Pin Pitch	1.285	1.713
Inner Clad Inner Radius	-	0.4400
Inner Clad Outer Radius	-	0.4970
Pellet Inner Radius	-	0.5040
Pellet Outer Radius	0.4095	0.7260
Outer Clad Inner Radius	0.4180	0.7330
Outer Clad Outer Radius	0.4750	0.7950
Guide Tube Inner Radius	1.1450	1.1450
Guide Tube Outer Radius	1.2450	1.2450
Outer Tube Inner Radius	-	1.5750
Outer Tube Outer Radius	-	1.6750

2.3 Calculational Results

The HELIOS calculations were performed with a 47-group library. The McCARD reference calculations by employing continuous-energy library were done with 25,000 particles per cycle and 100 active cycles after 20 inactive cycles. For all calculations, the radial zone of the fuel rod and the burnable absorber rod were divided into 3 and 7 equivalent volume regions, respectively. A predictor-corrector approach was adopted for all burnup calculations.

The calculation results of HELIOS and McCARD for the solid fuel design are shown in Fig. 2. As expected, the results of HELIOS are very consistent with those of McCARD to within the maximum of errors of 590 pcm.

For the annular fuel design, the calculation results of HELIOS and McCARD are shown in Fig. 3. It is shown that HELIOS overestimates the eigenvalue in all burnup steps. However, the maximum of errors of 740 pcm is similar to those of the solid fuel.

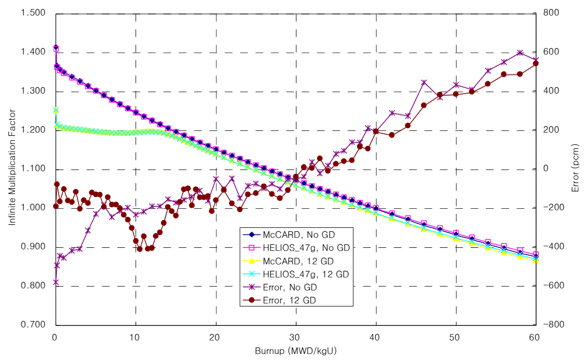


Fig. 2. The multiplication factor for the solid fuel design.

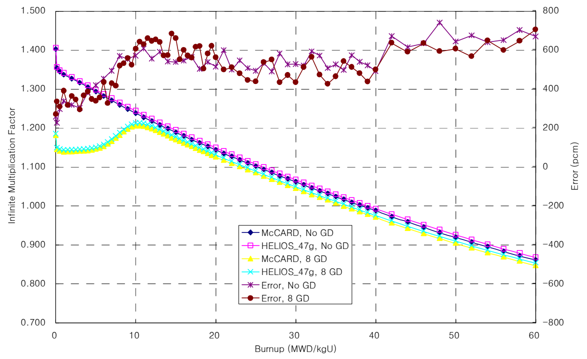
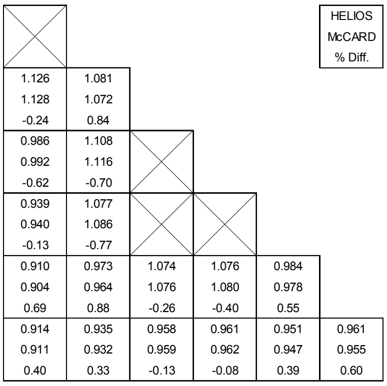


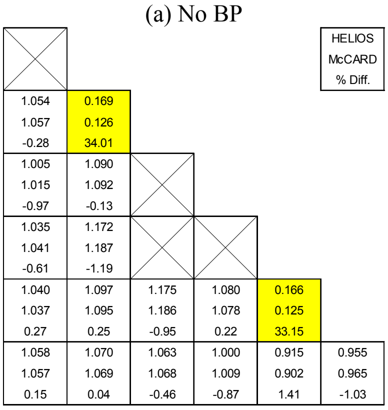
Fig. 3. The multiplication factor for the annular fuel design.

Fig. 4 shows a comparison of the pin power distributions for the annular fuel assembly at a burnup of 0 MWD/kgU. For no BP case as shown in Fig. 4(a), the neutron fission powers of HELIOS agree very well with those of McCARD within the RMS error of 0.54 % and the maximum relative error is 0.88 %. For the case with BP as shown in Fig. 4(b), the gamma-smearing powers of HELIOS agree well with those of McCARD within the RMS error of 1.61 %. However, the relative errors of about 30 % in BP positions are estimated owing to relatively lower power density.



☒					HELIOS McCARD % Diff.
1.126 1.128 -0.24	1.081 1.072 0.84				
0.986 0.992 -0.62	1.108 1.116 -0.70	☒			
0.939 0.940 -0.13	1.077 1.086 -0.77	☒	☒		
0.910 0.904 0.69	0.973 0.964 0.88	1.074 1.076 -0.26	1.076 1.080 -0.40	0.984 0.978 0.55	
0.914 0.911 0.40	0.935 0.932 0.33	0.958 0.959 -0.13	0.961 0.962 -0.08	0.951 0.947 0.39	0.961 0.955 0.60

(a) No BP



☒					HELIOS McCARD % Diff.
1.054 1.057 -0.28	0.169 0.126 34.01				
1.005 1.015 -0.97	1.090 1.092 -0.13	☒			
1.035 1.041 -0.61	1.172 1.187 -1.19	☒	☒		
1.040 1.037 0.27	1.097 1.095 0.25	1.175 1.186 -0.95	1.080 1.078 0.22	0.166 0.125 33.15	
1.058 1.057 0.15	1.070 1.069 0.04	1.063 1.068 -0.46	1.000 1.009 -0.87	0.915 0.902 1.41	0.955 0.965 -1.03

(b) With BP

Fig. 4. The pin power distributions for the annular fuel design.

3. Conclusions

We evaluated the validity of the HELIOS results for an annular fuel. The differences between HELIOS and McCARD for the annular fuel are similar to those for a solid fuel. In conclusion, the HELIOS code can be applied to a physics analysis for an annular fuel.

ACKNOWLEDGEMENT

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