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CANDU Core Calculation with HELIOS/RFSP

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Abstract

A Canadian Deuterium Uranium (CANDU) reactor core calculation was performed using lattice parameters generated by HELIOS. The HELIOS-based lattice parameters were processed by TABGEN in a form suitable for the core analysis code RFSP. The core calculation was performed and the results were compared to those of the reference calculation which uses POWDERPUFS-V (PPV) for the lattice parameter generation. The characteristics of the core calculated based on the PPV and HELIOS lattice parameters match within 0.4%Δk and 7% for the excess reactivity and the channel power distribution, respectively.

I. Introduction

The code system used for the design of currently operating CANDU reactors consists of the cell code PPV[1] and the finite difference diffusion code RFSP[2]. But the application of PPV is limited to the natural uranium fuel because of the empirical correlations used. Currently the advanced CANDU fuel design study is being carried out using the enriched uranium, spent PWR fuel or Mixed Oxide (MOX) fuel. For the purpose of research and development of the advanced CANDU fuels, it is necessary to adopt a lattice code that has the general application in the isotopics and geometry modeling. Recently, HELIOS[3] has been introduced for the CANDU physics calculation because it has an extensive cross section library and the flexible geometry modeling capability.

In order to use the lattice parameters generated by HELIOS for the CANDU core analysis, a processing code TABGEN[4] has been modified to produce the lattice parameters in a form suitable for the core analysis code RFSP. The cross section library used in this study is a 34-group working library[5] generated for a heavy water system. The performance of the HELIOS-based lattice parameters have been assessed by comparing the results of the CANDU core calculation to those obtained by the PPV-based lattice parameters.

II. Code Description

PPV was developed by Atomic Energy of Canada Limited (AECL) for the design of CANDU reactor prototypes and widely used for the power reactor design since it is fast and reasonably accurate. But it is licensed only for the natural uranium fuel design and analysis.

HELIOS is a transport code which has a diverse geometry modeling capability. The lattice geometry is constructed by a stand-alone code AURORA and the results of HELIOS calculation are processed by ZENITH.

RFSP is a 3-dimensional finite difference diffusion program used for CANDU core design and analysis. It calculates the time-average flux and irradiation distributions and simulates the refueling operation.

III. Lattice Parameter Generation

For the CANDU core calculation, three cross section types are required: the fuel channel lattice parameters, reflector cross sections, and the incremental cross sections of the reactivity devices. In this study, the fuel channel and the reflector data have been produced by TABGEN based on the HELIOS calculation. But the incremental cross sections, which requires a series of supercell calculations, have not been generated in this study.

Fuel Channel Data

The TABGEN is typically used for the general tabulation of cross section data. However, it does not produce the lattice parameters in the format suitable for the RFSP. Therefore TABGEN has been updated to process the two-group cross section data such as fast/thermal transport cross sections, fast/thermal absorption cross sections, fast-to-thermal effective scattering cross section, effective fission yield cross section, F-factor, and H-factor. The formulations used to condense the multi-group cross section data are given in Eqs.(1)-(3).

$$\Sigma_X = \frac{\int\int \Sigma_X(r,E)\,\phi(r,E)\,V(r)drdE}{\int\int \phi(r,E)\,V(r)drdE} \qquad (1)$$

$$F = \frac{\int_{th} dE \int_{fuel} dr\ \phi(r,E)}{\int_{th} dE \int_{cell} dr\ \phi(r,E)} \qquad (2)$$

$$H = 1.602177 \times 10^{-5} V_{cell} E_f \frac{\int_{th}^{fast} dE \int_{cell} dr\ \phi(r,E) V(r)}{\int_{th} dE \int_{cell} \phi(r,E) V(r)} \quad (3)$$

where X = absorption, transport, nu*fission, and fission cross sections and
E_f = average energy release per fission excluding neutrinos.

Reflector Data

The reflector data is obtained from the moderator region of the fuel channel lattice. In principle, there is no depletion in the moderator material but the cross sections are simply averaged over the burnup interval in order to consider the effect of the spectral shift to the cross sections. The reflector data includes the fast and thermal transport cross sections, thermal absorption cross section, and fast-to-thermal effective scattering cross section of the moderator region. The collapsing procedure of the multi-group reflector cross section is the same as that of the fuel channel cross section, Eq.(1).

IV. Core Calculation

Core Model

For the comparison of the CANDU core calculation by HELIOS/RFSP against that by the design code system PPV/RFSP, the time-average model of the natural uranium CANDU core has been prepared. At first, a critical core was found by adjusting the discharge burnup using PPV/RFSP. Secondly, the reactivity devices were removed from the core while the time-average burnup distribution was kept the same. Because the incremental cross sections of the reactivity devices were not available yet, the core calculation would compare the fuel channel lattice and the reflector data only.

Results

The results of the core calculations are summarized in Table 1 with the results of WIMS/RFSP calculation. The k_{eff} of the HELIOS/RFSP calculation agrees with that of PPV/RFSP within 0.4%Δk. The channel power distribution of the PPV/RFSP calculation is shown in Fig.1 together with the difference of the channel power obtained by the HELIOS/RFSP and WIMS/RFSP. As shown in Fig.1, the channel powers agree with the maximum difference of 7%. It should be noted that the channel powers of the inner core region are over the operation limit because the reactivity devices are not considered in this study.

V. Conclusion

In this study, the TABGEN has been modified to provide the lattice parameters for the CANDU core analysis code RFSP. In general, the results of the HELIOS/RFSP calculation are in good agreement with those of the reference calculation. But, compared to the results of the WIMS/RFSP calculation, the results of HELIOS/RFSP calculation were further away from the accepted reference values. Therefore, more studies are required to assess the potential of HELIOS as a CANDU physics analysis code.

References

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4. A.A. Ferri, "TABGEN Extensions for DUPIC Core Analysis," T1/44.96.00, 1996.
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Table 1. Comparison of Core Characteristics Parameters

	PPV/RFSP (reference)	HELIOS/RFSP (difference)	WIMS/RFSP (difference)
k_{eff}	1.01979 -	1.02422 (0.4% Δk)	1.01814 (-0.2% Δk)
Maximum Channel Power (kW)	8576.13 -	8481.52 (-1.1%)	8477.72 (-1.1%)
Maximum Bundle Power (kW)	1302.15 -	1309.98 (0.6%)	1280.57 (-1.7%)

- PPV (Reference)
- % Difference with HELIOS
- % Difference with WIMS

	12	13	14	15	16	17	18	19	20	21	22
A	3639 7 4	3507 7 5	3377 7 4								
B	4809 7 3	4673 7 3	4417 7 4	4086 7 4	3561 7 4	3022 7 5					
C	5971 6 2	5835 6 2	5561 6 2	5152 7 3	4607 7 3	3956 7 4	3332 7 4				
D	6956 5 1	6829 5 1	6567 5 1	6163 5 2	5616 6 2	4934 6 3	4153 7 4	3398 6 4			
E	7661 3 0	7559 3 0	7332 4 1	6965 4 1	6444 5 1	5773 5 2	4967 6 2	4075 6 4	3214 5 4		
F	8038 2 0	7982 2 0	7811 2 0	7586 3 0	7111 4 1	6473 4 1	5680 5 2	4773 5 3	3837 5 4		
G	8247 0 0	8295 1 0	8172 1 0	7890 2 0	7458 2 0	6961 3 0	6209 4 1	5319 4 2	4303 5 3	3352 4 4	
H	8410 -1 -1	8496 0 0	8405 0 0	8142 1 0	7732 1 0	7269 2 0	6560 3 0	5707 3 1	4702 4 2	3687 4 3	
J	8476 -2 -1	8576 -1 -1	8498 0 0	8242 0 0	7828 0 0	7290 1 0	6705 2 0	5909 2 0	4939 3 1	3872 4 3	2866 3 3
K	8452 -3 -1	8557 -2 -1	8485 -1 -1	8228 0 0	7804 0 0	7251 0 0	6698 0 0	5970 1 0	5055 2 1	4013 3 2	2959 3 3
L	8297 -3 -2	8403 -2 -1	8333 -2 -1	8071 -1 -1	7623 -1 -1	7001 -1 -1	6460 0 0	5860 0 0	5016 1 0	4022 2 1	3000 3 3
M	8020 -4 -2	8129 -3 -2	8065 -2 -1	7804 -2 -1	7350 -2 -1	6719 -2 -1	6195 -1 -1	5649 0 0	4859 1 0	3911 2 1	2926 2 2
N	7605 -5 -2	7732 -4 -2	7685 -3 -1	7438 -3 -1	6996 -3 -1	6380 -3 -1	5870 -2 -1	5346 0 0	4593 0 0	3686 1 1	2743 1 2
O	7056 -5 -2	7251 -4 -2	7232 -4 -2	7006 -3 -1	6584 -3 -1	5993 -3 -1	5491 -3 -1	4975 -1 0	4250 0 0	3388 1 1	2534 0 2
P	6514 -6 -2	6716 -5 -2	6714 -4 -2	6507 -4 -1	6113 -3 -1	5612 -4 -1	5043 -3 -1	4523 -1 0	3824 0 0	3064 0 1	
Q	5960 -6 -2	6152 -5 -2	6154 -4 -2	5963 -4 -1	5583 -4 -1	5090 -4 -1	4521 -3 -1	4001 -2 0	3332 0 1	2664 0 1	
R	5391 -6 -2	5564 -5 -2	5564 -4 -1	5440 -4 -1	5059 -3 -1	4500 -4 -1	3930 -3 -1	3416 -2 0	2835 -1 1		
S	4861 -6 -2	5011 -4 -2	4990 -4 -1	4788 -3 -1	4398 -3 -1	3843 -4 -1	3283 -3 0	2791 -2 0	2271 -2 1		
T	4187 -5 -2	4307 -4 -1	4266 -3 -1	4051 -3 -1	3662 -3 0	3103 -4 0	2574 -4 0	2213 -3 1			
U	3443 -5 -1	3536 -4 -1	3481 -3 0	3269 -3 0	2898 -3 0	2386 -3 0	1968 -4 0				
V	2643 -4 0	2731 -3 0	2680 -2 0	2519 -2 0	2178 -3 1	1755 -4 1					
W	1925 -4 0	1990 -3 1	2001 -3 1								

Fig.1. Comparison of Channel Power Distributions