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Improvement of Axial Reflector Cross Section Generation Model for PWR Core Analysis

Cheon Bo Shim*, Kyung Hoon Lee, and Jin Young Cho
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Korea
**Corresponding author: scvstyle@kaeri.re.kr*

1. Introduction

Two-step procedure has been regarded as the most practical approach for reactor core designs because it offers core design parameters quite rapidly within acceptable range. Thus this approach is adopted for SMART (System-integrated Modular Advanced ReacTor) core design in KAERI with the DeCART2D1.1[1]/ MASTER4.0[2] (hereafter noted as DeCART2D/ MASTER) code system. Within the framework of the two-step procedure based SMART core design, various researches have been studied to improve the core design reliability and efficiency. One of them is improvement of reflector cross section (XS) generation models.

In conventional core design procedures, homogenized reflector XS has been generated by fuel assembly (FA)/reflector two-node model because it is sufficient to render reasonable reflector XS to generate proper core design parameters in diffusion nodal codes. In the SMART core design, however, this approach would not be valid because the neutron leakage effect is more significant in SMART whose size is smaller compared to conventional large reactors. Thus preparation of accurate reflector XS might be necessary. In this regard, SMART reflector XS are generated as follows:

- Radial reflector XS is generated from the two-dimensional (2D) core model
- Axial reflector XS is generated from the one-dimensional (1D) simplified core model

This paper covers the study for improvement of axial reflector XS generation model. In the next section, the improved 1D core model is represented in detail. Reflector XS generated by the improved model is compared to that of the conventional model in the third section. Nuclear design parameters generated by these two XS sets are also covered in that section. Significant of this study is discussed in the last section.

2. Axial Reflector XS Generation Model

In order to obtain effective reflector XS data, composition of materials contained in the reflector region as well as neutron flux distribution on space and energy should be well considered. And discontinuity factor (DF) at the interface between FA and reflector is also necessary. However, the conventional simplified two-node model described in Fig. 1 is not proper to attain actual neutron flux distribution and DF because active core region is assumed as one FA node. Moreover, fuel rods and reflector regions are assumed to be parallel in this model for axial reflector XS generation although fuel rods in fact lies at right angles to the interface of FA and axial reflectors.

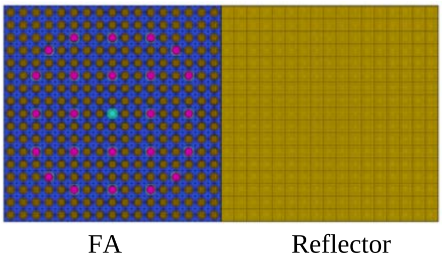

Fig. 1. Conventional FA/reflector two-node model for reflector XS generation

Compared to conventional lattice transport codes, DeCART2D has a capability to simulate 1D core models whose configuration consists of a 1D assembly array. Thus a new core model described in Fig. 2 is introduced for SMART axial reflector XS generation to avoid the problem of the conventional model. In this model, the active core region consists of repeated arrangement of fuel and moderator, and it is modeled infinitely on the radial direction applying the zero albedo condition. Thus, we called it 'Simplified 1D Model'. In this 1D core model, fuel rods are modeled to be orthogonal to reflector regions like as actual core configurations, so neutron flux distribution and DFs can be estimated more realistically.

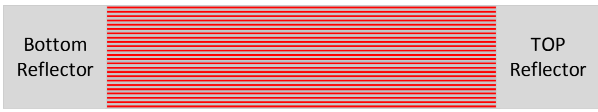

Fig. 2. Simplified 1D core model for SMART axial reflector XS generation

The active core region in the 1D core model is determined as described in Fig. 3.

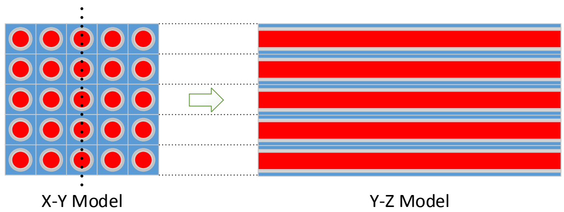

Fig. 3. How to model the active core region in the 1D core model

There are UO_2 fuel pins with different enrichment, BA pins, and guide tubes in the SMART active core region. In the 1D core model, it is simplified that there is only one type of UO_2 fuel pin whose enrichment is determined by average of total UO_2 enrichment and other pins are neglected. This assumption is come from that neutron flux distribution on axial direction has weak dependency on the radial composition of the active core region.

Axial reflector node size is recommended to be 30.0 cm in MASTER modeling. Since assembly pitch is used as homogenized node size in DeCART2D, virtual assembly pitch close to 30.0 cm should be introduced instead of using the nominal data. Also, it is necessary to maintain the pin pitch as the design value. With these constraints, the virtual assembly pitch is determined and the simplified 1D core model is then constructed.

3. Numerical Result

In this section, three types of data are compared, which are obtained by the conventional two-node model and improved simplified 1D core model. The first one is comparison of DeCART2D homogenized group constant (HGC) data to be used for MASTER reflector XS generation. Then MASTER reflector XS data are compared. Using the generated reflector XS, MASTER can perform core calculation and the main nuclear design parameters such as critical boron concentration (CBC) and peaking factors can be evaluated. These parameters are compared last.

In the DeCART2D/MASTER two-step procedure, DeCART2D generates HGC for each assembly. The HGC data related to the reflector XS are as follows:

- Diffusion coefficient, macroscopic absorption and scattering XSs
- Density and microscopic transport, absorption, and scattering XSs of H-1, O-16, and B-10
- DFs at the interface between reflector and fuel nodes

Table I and Table II show some of HGC data for the bottom and top reflectors generated by the two models where f^{refl} and f^{refl} are DFs obtained in the reflector and fuel node by one-node nodal calculation in DeCART2D. It is noted that D_1 has more than 7% relative difference in the two models and most $N\sigma_{tr1}$ data have similar relative difference. The most significant difference between the two models is the DF. The spatial composition of the two-node model has large heterogeneity on the axial direction because fuel rods are modeled to be parallel on the axial reflector. On the other hand, the 1D core model considers the actual orthogonality of fuel rods and reflector regions. Thus large difference in DF occurs.

Table I: HGC for the Bottom Reflector

	Two-Node	1D Core	Diff. (%)
D_1	1.34365E+00	1.25340E+00	7.2
Σ_{a2}	3.88039E-02	3.96616E-02	2.2
Σ_{12}	2.63402E-02	2.61075E-02	0.9
$N^H \sigma_{tr1}^H$	7.85098E-02	8.37945E-02	6.3
$N^H \sigma_{a2}^H$	5.38001E-03	5.15031E-03	4.5
$N^H \sigma_{12}^H$	2.55748E-02	2.53269E-02	1.0
$N^B \sigma_{tr1}^B$	6.67781E-05	6.91448E-05	3.4
$N^B \sigma_{a2}^B$	5.13236E-03	4.91315E-03	4.5
$N^O \sigma_{tr1}^O$	3.03554E-02	3.18351E-02	4.6
f_1^{refl}	9.18893E-01	9.72165E-01	5.5
f_2^{refl}	1.01306E+00	9.92066E-01	2.1
f_1^{fuel}	7.00560E-01	9.90083E-01	29.2
f_2^{fuel}	9.77553E-01	9.92159E-01	1.5

Table II: HGC for the Top Reflector

	Two-Node	1D Core	Diff. (%)
D_1	2.04583E+00	1.90250E+00	7.5
Σ_{a2}	2.51521E-02	2.49347E-02	0.9
Σ_{12}	2.99676E-02	3.01427E-02	0.6
$N^H \sigma_{tr1}^H$	8.54846E-02	9.24158E-02	7.5
$N^H \sigma_{a2}^H$	6.01429E-03	5.96235E-03	0.9
$N^H \sigma_{12}^H$	2.94845E-02	2.96620E-02	0.6
$N^B \sigma_{tr1}^B$	7.34724E-05	7.74133E-05	5.1
$N^B \sigma_{a2}^B$	5.73764E-03	5.68802E-03	0.9
$N^O \sigma_{tr1}^O$	3.32512E-02	3.53183E-02	5.9
f_1^{refl}	1.06304E+00	1.11949E+00	5.0
f_2^{refl}	8.93978E-01	7.51683E-01	18.9
f_1^{fuel}	6.85121E-01	9.94082E-01	31.1
f_2^{fuel}	9.74227E-01	9.78779E-01	0.5

In order to convert the DeCART2D HGC data to MASTER XS library format for reflectors, the PROMARX(PROcessor for Master Reflector Xs library) code has been developed and used in SMART core design. PROMARX works by the following sequence.

- Calculate node-wise macroscopic transport XS by using diffusion coefficients given in HGC files.
- Calculate effective DF $(= f^{refl} / f^{fuel})$.
- Calculate effective H_2O number density.
- Calculate XS for H_2O and structure.
- Correct XS using effective DF.
- Correct down-scattering XS to consider up-scattering effect.

Table III and Table IV show the bottom and top reflector XS data to be written in MASTER XS library. Most XS data obtained from the two-node and 1D core models have large difference. It would be mostly come from the difference of the DF.

Table III: Bottom Reflector XS for MASTER Calculation

	Two-Node	1D Core	Diff. (%)
σ_{a1}^{B}	3.14336E+01	6.03039E+01	47.9
σ_{a2}^{B}	2.19251E+03	3.10736E+03	29.4
σ_{tr1}^{B}	3.87770E+01	4.29358E+01	9.7
σ_{tr2}^{B}	2.11897E+03	2.79765E+03	24.3
σ_{12}^{B}	1.34941E-02	2.51863E-02	46.4
$\sigma_{a1}^{H_2O}$	4.08317E-03	5.11195E-03	20.1
$\sigma_{a2}^{H_2O}$	2.11433E-01	2.09777E-01	0.8
$\sigma_{tr1}^{H_2O}$	5.81390E+00	4.62271E+00	25.8
$\sigma_{tr2}^{H_2O}$	2.98705E+01	2.77232E+01	7.7
$\sigma_{12}^{H_2O}$	7.94923E-01	1.04908E+00	24.2
Σ_{tr1}^{STRM}	1.24329E-03	1.74150E-03	28.6
Σ_{tr2}^{STRM}	2.72984E-02	2.95994E-02	7.8
Σ_{a1}^{STRM}	1.82515E-01	1.47526E-01	23.7
Σ_{a2}^{STRM}	2.35416E-01	2.40431E-01	2.1
Σ_{12}^{STRM}	3.71414E-04	5.17449E-04	28.2

Table IV: Top Reflector XS for MASTER Calculation

	Two-Node	1D Core	Diff. (%)
σ_{a1}^{B}	2.12156E+01	3.69083E+01	42.5
σ_{a2}^{B}	1.92701E+03	2.82778E+03	31.9
σ_{tr1}^{B}	3.51337E+01	3.32850E+01	5.6
σ_{tr2}^{B}	1.42100E+03	1.45661E+03	2.4
σ_{12}^{B}	9.21998E-03	1.56671E-02	41.2
$\sigma_{a1}^{H_2O}$	4.72030E-03	6.12012E-03	22.9
$\sigma_{a2}^{H_2O}$	2.93876E-01	3.48108E-01	15.6
$\sigma_{tr1}^{H_2O}$	8.25821E+00	6.44803E+00	28.1
$\sigma_{tr2}^{H_2O}$	3.14368E+01	2.60502E+01	20.7
$\sigma_{12}^{H_2O}$	8.56051E-01	1.18546E+00	27.8
Σ_{tr1}^{STRM}	3.77785E-04	5.33122E-04	29.1
Σ_{tr2}^{STRM}	1.46012E-02	1.72955E-02	15.6
Σ_{a1}^{STRM}	6.84629E-02	5.33758E-02	28.3
Σ_{a2}^{STRM}	8.61208E-02	7.17949E-02	20.0
Σ_{12}^{STRM}	1.04155E-04	1.42772E-04	27.0

Axial reflector XS has been regarded to have relatively insignificant effect on the core design parameter evaluation because of less neutron leakage on axial direction, which is caused by small power density at axial core boundaries and smooth axial power distribution come from axially homogeneous core configuration. However, it can be large in this case because of huge difference of XS data as shown in Table III and Table IV.

In order to evaluate that how much the distinct reflector XS make difference on core design parameters, depletion calculation for the SMART SDA (Standard Design Approval) initial core is performed by MASTER. Except the axial reflector XS, all data such as the radial and FA group constant and MASTER inputs are same in both calculations. In order to provide the reference solution, DeCART 3D whole core calculation result[1] is compared together. Fig. 4 shows the CBC difference curve, and Fig. 5 and Fig. 6 represent the behavior of the pin peaking factor (Fq) relative error and AO difference. CBC with the two-node axial reflector XS generation model has more than 80 ppm error whereas that of the 1D core model is about 50 ppm at most. Maximum error of Fq is about 6 and 2.5 percent for each model, respectively, and AO prediction is also better in the 1D core model.

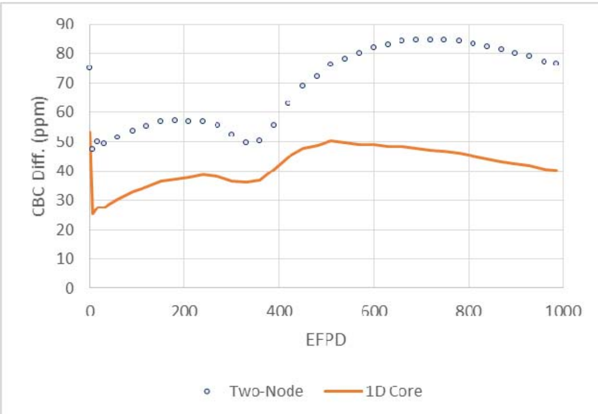

Fig. 4. CBC difference

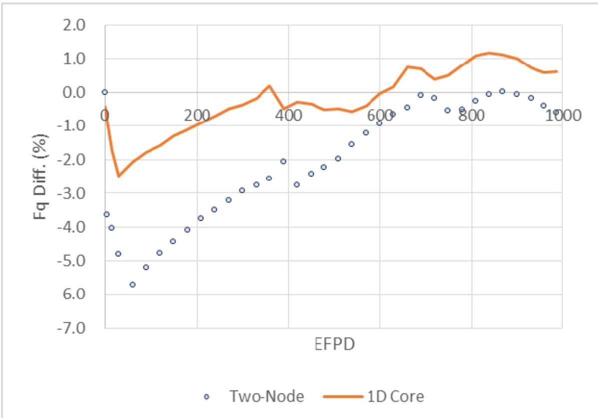

Fig. 5. Relative Fq difference

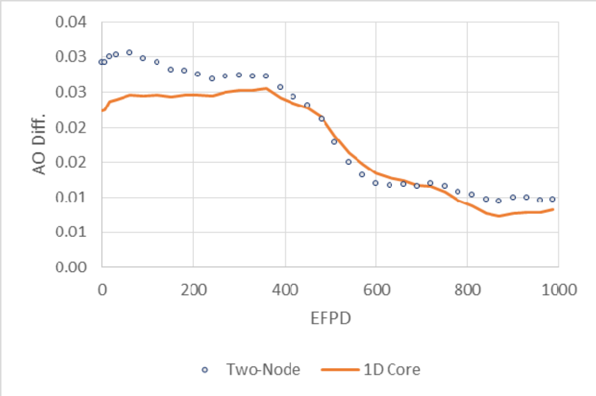

Fig. 6. AO difference

Fig. 7 and Fig. 8 show the difference of the relative axial power shape at BOC and EOC. Since MASTER cannot model axial spacer grid explicitly, relative axial power has some error in both models. However, the solution with the reflector XS from the 1D core model follows the reference much better compared to that of the conventional two-node model especially at core boundaries.

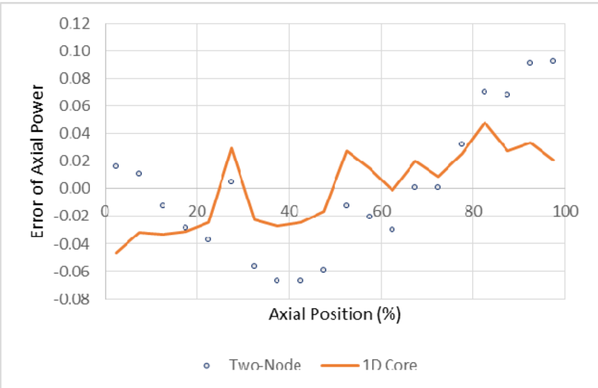

Fig. 7. Difference of relative axial power shape at BOC

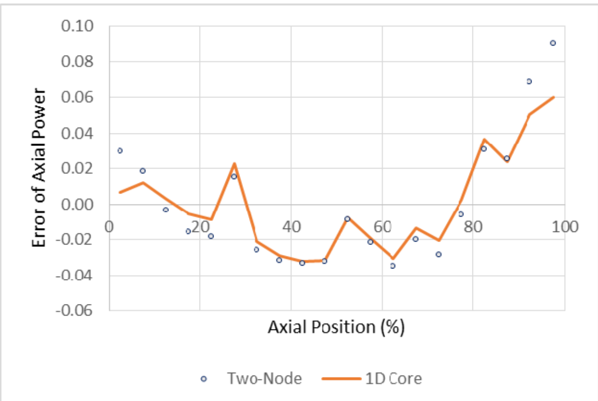

Fig. 8. Difference of relative axial power shape at EOC

4. Conclusion

As a part of the researches to improve SMART core design methodologies within the framework of the DeCART2D/MASTER two-step based code system, axial reflector XS generation model has been revised and evaluated. While the conventional FA/reflector two-node model used for most core designs to generate reflector XS cannot consider the actual configuration of fuel rods that intersect at right angles to axial reflectors, the revised model reflects the axial fuel configuration by introducing the radially simplified core model. The significance of the model revision is evaluated by observing HGC generated by DeCART2D, reflector XS, and core design parameters generated by adopting the two models. And it is verified that about 30 ppm CBC error can be reduced and maximum Fq error decreases from about 6 % to 2.5 % by applying the revised model. Error of AO and axial power shapes are also reduced significantly. Therefore it can be concluded that the simplified 1D core model improves the accuracy of the axial reflector XS and leads to the two-step procedure reliability enhancement.

Since it is hard for core designs to be free from the two-step approach, it is necessary to find and improve dated methodologies that are employed in the two-step procedure and able to be reformed with acceptable resources. It is argued in this study that the old-fashioned FA/reflector two-node model is one of them because it is still used for reflector XS generation in two-step based core designs although computing performance has been extremely increased. The simplified 1D core model suggested in this research can be a good option to replace the two-node model to improve the credibility of the two-step approach.

Some limitations are still, however, remained in the proposed 1D core model such as the simplification of the active core region without considering the volume ratio of fuel and moderator materials and neglecting of axial cutback regions. Studies to improve the 1D axial reflector XS generation model by considering these factors will be performed in the near future.

5. Acknowledgement

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