Neutronic Models for High-Performance Reflectors for the ATOM Core

Xuan Ha Nguyen, Seongdong Jang, and Yonghee Kim*
Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea
**Corresponding author: yongheekim@kaist.ac.kr*

1. Introduction

In PWRs, one of the ways of reducing fuel cycle cost is to minimize neutron leakage from the core. Several studies have demonstrated that the use of radial iron reflector can reduce significantly neutron leakage compared to conventional water-baffle one [1] [2]. The advantage of the iron reflector is more essential with small modular reactors (SMRs). This is because most of the SMRs are designed to have a long cycle length with single batch fuel management and their discharge burnup are quite low, around 30 GWd/tU.

Currently, a water-cooled SMR, named autonomous transportable on-demand reactor module (ATOM), has been developed at CSMRR (Center for Small Modular Reactor Research) [3]. The ATOM core adapts radial iron reflector to improve its neutron economy. In addition, a stainless steel-cladded ZrO_2 reflector is also introduced to enhance further the cycle length of the core. However, neutron spectrum in heavy reflectors (iron, ZrO_2 and etc.) is more complicated than that in typical water-baffle one, it is required a better neutronic model for these reflectors to accurately analyze the core performance in two-step procedure.

In this paper, several 1- and 2-dimensional spectral geometries (SGs) of the reflector are proposed to capture the inherent properties of the neutron spectrum in the reflector, core barrel, and downcomer water. Moreover, several core configurations are also introduced to accommodate these spectral geometries in a Monte Carlo-diffusion two-step analysis [4]. The Monte Carlo Serpent 2 [5] with nuclear library ENDF/B-VII.1 is used to provide the reference solutions and generate homogenized group constants (HGCs). Meanwhile, a diffusion core, COREDAX [6], is used to analyze the ATOM core using HGCs generated from Serpent 2.

2. Neutronic Models for the ATOM core

2.1 The ATOM core design.

The ATOM utilizes a newly proposed centrally-shielded burnable absorber (CSBA) concept [3]. Three variants of the CSBA-loaded fuel pellet designs are shown in Fig. 1.

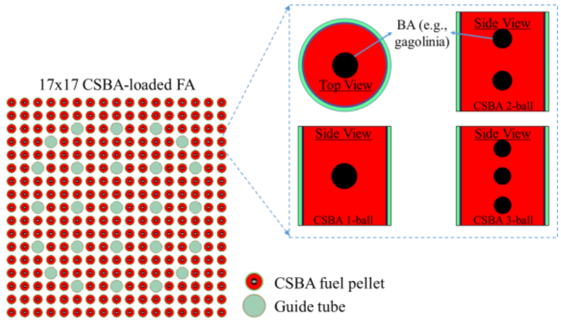

Fig. 1. CSBA-loaded fuel assemblies

Major design parameters of the ATOM core are listed in Table I and the radial cross sections for stainless steel (SS) and ZrO2 reflectors are depicted in Figs. 2 and 3, respectively. The smallest and largest radial reflector thickness are 11.3 cm and 25.2 cm. The core consists of 69 17x17 PWR fuel assemblies, and each fuel assembly is comprised of 264 CSBA-loaded fuel rods, 24 guide thimbles, and a central in-core instrumentation tube. The fuel enrichment is 5.0 w/o with a 95.5% theoretical density of the UO2 pellet. The average power density is 26.00 W/gU in the ATOM core.

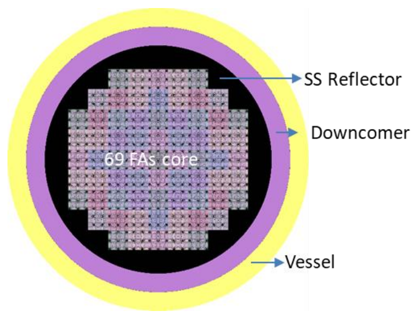

Fig. 2. Radial layout with SS reflector

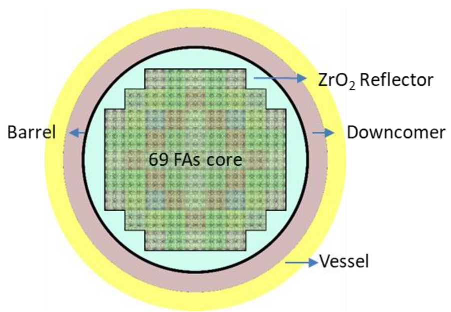

Fig. 3. Radial layout with ZrO_2 reflector

Table I: Major design parameters of the ATOM core

Parameters	Target Value	Unit
Thermal power	450	MWth
Active core height	200	cm
Equivalent	201.6	cm
Power density	26.0	W/gU
Radial Reflector	SS, ZrO2	
Fuel loading	Single-batch	
FA type	17 x 17	
Number of FAs	69	
Fuel materials	UO_2	
Fuel enrichment	5.0	w/o

The ATOM core is radially divided into three different regions for design optimization [3]. In each region, the CSBA design is different in terms of ball size and number of balls to optimize the reactivity depletion pattern and burnup-dependent power profile. Fig. 4 and Table II show the currently optimal CSBA design.

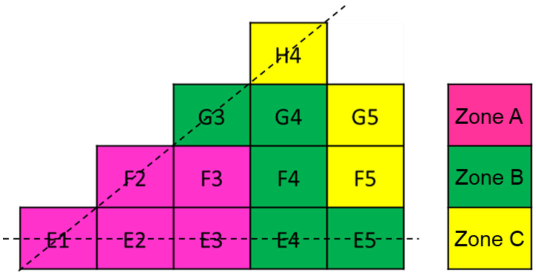

Fig. 4. CSBA loading scheme of one-eight ATOM core

Table II: Zone-wise CSBA loading

Optimal CSBA design			
Zone	**Zone A**	**Zone B**	**Zone C**
BA design	1-ball	2-ball	3-ball
CSBA radius	1.69 mm	1.26 mm	0.07 mm

2.2 Neutronic Models for the ATOM core

In PWRs, due to short neutron mean free path [7] in water-baffle reflector and its simple geometry, the effect of SS barrel and downcomer water is minor to the neutronic performance. Therefore, in standard two-step calculation 1-D spectral geometry is used to generate the reflector HGCs with a lattice code as shown in Fig. 5. In addition, the SS barrel and downcomer water are excluded from the spectral geometry. These HGCs are then fed to a diffusion code for whole-core calculation. For further improved modeling, a small 2-D spectral geometry can be used for corner water-baffle reflectors.

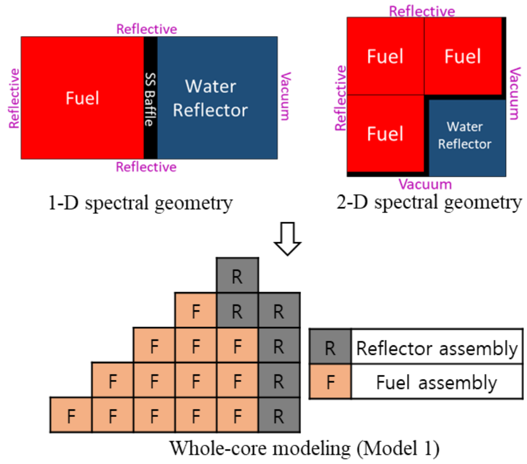

Fig. 5. Standard two-step calculation

Since the heavy reflectors are applied to the SMRs for enhance cycle length, the neutronic models must be improved to capture the neutron spectrum in radial reflector, SS barrel, and downcomer water. This is because the neutron mean free path in SS and ZrO_2 are quite longer than that in water and the radial reflector thickness ranges from 11 cm to 25 cm. In this paper, to model accurately the SMR core several 1-D, simplified and exact 2-D SGs are proposed as shown in Fig. 6. The use of simplified SGs is to reduce the computational effort and expect to have a similar performance with exact one. On the other hand, several 2-D whole-core configurations are introduced to accommodate these SGs as shown in Fig. 7. It should be noted that the Model 2 only adapts the corner downcomer water since the reflector thickness is quite small here. Meanwhile Model 3 fully express the whole downcomer water surrounding the core. The comparison between those three models are to analyze the effect of downcomer water on the core performance. Due to the limitation in terms of geometric modeling for nodal diffusion code, both reflector and downcomer thickness are set to be assembly size.

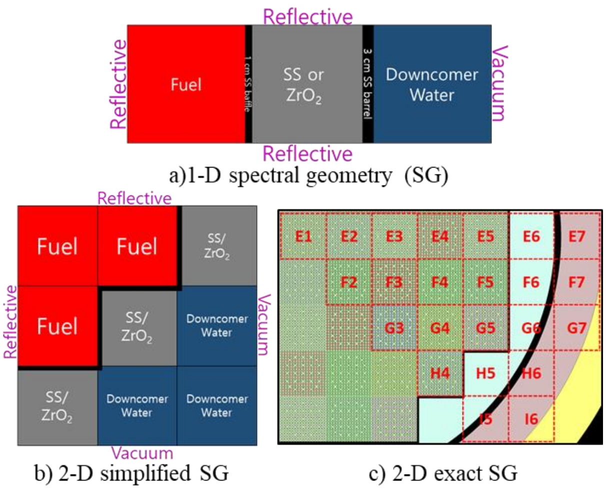

Fig. 6. Spectral geometries for non-water reflector

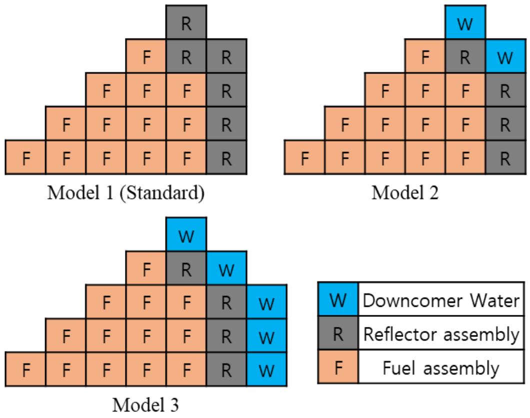

Fig. 7. 2-D whole-core modeling for the ATOM core

3. Numerical Results and Discussion

In this research, the Monte Carlo-diffusion two-step procedure is used since the current commercial lattice codes cannot model accurately the 3-D CSBA-loaded fuel assembly. Therefore, Monte Carlo Serpent 2 code is used to provide the reference solution and two-group HGCs. The two-group HGCs for fuel regions are generated from single lattice calculation with reflective boundary condition. The 3-D nodal diffusion code, COREDAX, is used to perform 2-D whole-core ATOM problem at BOC condition for the neutronic evaluation of radial non-water reflectors. Note that the uncertainties for k-eff and HGCs in Serpent 2 calculations are less than 1.0 pcm and 10 pcm, respectively, resulting from 500 active and 100 inactive cycles with 40 million histories per cycle.

3.1 Stainless steel reflector

Table III presents the comparison between Serpent 2 reference and COREDAX solutions in terms of multiplication factor, assembly-wise power error, and root mean square (RMS) error of assembly power. Note that in these COREDAX calculations, the 1-D spectral geometry is used. Noticeable differences can be found in multiplication factor for the all three core models. However, Model 2 and 3 show quite smaller maximum relative power errors and RMS errors.

Table III: The performance of 1-D SG for SS reflector

Case	K-eff	Diff. (pcm)	Max. FA power error (%)	RMS Error (%)
Serpent 2	1.04722	-	-	-
Model 1	1.04823	96	-4.70	2.54
Model 2	1.04576	-143	2.15	1.07
Model 3	1.04609	-108	2.15	1.09

On the other hand, Table IV and V illustrate the performance of simplified 2-D and exact spectral geometries with the three whole-core models. Similar behaviors to 1-D spectral geometry can be observed in 2-D ones. Both Model 2 and 3 show a superior performance compared to the Model 1. It is indicated that the downcomer water must be modelled for accurate solution of the whole-core calculation. In addition, the downcomer water in the corner region is more important than that in other positions since the thickness of the reflector is smallest at the corner.

Table IV: The performance of simplified 2-D SG for SS reflector

Case	K-eff	Diff. (pcm)	Max. FA power error (%)	RMS Error (%)
Serpent 2	1.04722	-	-	-
Model 1	1.04894	164	-6.13	3.47
Model 2	1.04631	-87	1.33	0.71
Model 3	1.04668	-52	-1.90	1.03

Table V: The performance of exact 2-D SG for SS reflector

Case	K-eff	Diff. (pcm)	Max. FA power error (%)	RMS Error (%)
Serpent 2	1.04722	-	-	-
Model 2	1.04649	-70	1.00	0.47
Model 3	1.04709	-13	2.19	1.07

3.2 Zirconium dioxide reflector

Table VI and VII show the performance of the simplified 1-D and 2-D SGs for ZrO_2 in the three models against Serpent 2 reference solution. Both Model 1 and 2 present quite large difference, more than 100 pcm, in terms of multiplication factor. Meanwhile, the ones obtained from Model 3 are closer to the reference with relative small RMS errors. Moreover, the use of Model 2 results in similar maximum and RMS errors to Model 3, but worst multiplication factor. This means Model 2 does not always capture the neutron spectrum in the reflector, barrel and downcomer regions.

Table VI: The performance of 1-D SG for ZrO_2 reflector

Case	K-eff	Diff. (pcm)	Max. FA power error (%)	RMS Error (%)
Serpent 2	1.05193	-	-	-
Model 1	1.05393	190	-5.88	3.06
Model 2	1.05015	-170	2.15	1.25
Model 3	1.05162	-30	2.80	1.25

Table VII: The performance of simplified 2-D SG for ZrO_2 reflector

Case	K-eff	Diff. (pcm)	Max. FA power error (%)	RMS Error (%)
Serpent 2	1.05193	-	-	-
Model 1	1.05300	102	3.77	1.96
Model 2	1.05017	-168	2.24	1.22
Model 3	1.05103	-86	2.05	0.84

The performance of exact 2-D spectral geometry is shown in Table VIII with Model 2 and 3. Both of them have about 60.0 pcm difference for the multiplication factor, while the use of Model 2 results in better relative power and RMS errors. In overall, the accuracy of Model 2 is quite sensitive to the SG, but Model 3 always show a consistent performance with any SG.

Table VIII: The performance of exact 2-D SG for ZrO_2 reflector

Case	K-eff	Diff. (pcm)	Max. FA power error (%)	RMS Error (%)
Serpent 2	1.05193	-	-	-
Model 2	1.05132	-58	2.61	0.72
Model 3	1.05257	61	2.88	1.20

4. Conclusions

In this paper, the several neutronic models for non-water reflectors of the ATOM core are proposed. It is demonstrated that the barrel and downcomer regions must be included in a Monte Carlo-diffusion two-step procedure for accurate modeling of the core. In addition, it is recommended to use the exact or at least color-set SGs to capture the neutron spectrum in a complex reflector design, especially for diffusive reflector materials like SS and ZrO_2. Further improvement in neutronic models for high-performance reflectors will be done to overcome the geometric limitation in a two-step analysis.

ACKNOWLEDGMENTS

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