Verification of a depletion solver in RAST-K Fast Reactor

Tuan Quoc Tran, Siarhei Dzianisau, Tung Dong Cao Nguyen, Deokjung Lee*
[a] *Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919, Republic of Korea.*
[*] *Corresponding author: deokjung@unist.ac.kr*

1. Introduction

The nuclide depletion calculation is one of the most expensive calculations in the design and analysis of the reactor core. The change of nuclide concentrations can be described by the Bateman equation, and the kernel of reactor burnup calculation is the solution of Bateman equation. At present, the most popular and common method for solving Bateman equation is Chebyshev Rational Approximation Method (CRAM) [1], which is known for its good accuracy and moderate time consumption. In other to take advantage of this method, CRAM is implemented in nodal diffusion code RAST-K for fast reactor with hexagonal lattice (R2-HEX) at the Ulsan National Institute of Science and Technology (UNIST). The cross section set for 24-group energy structure can be generated by MCS-XS to be used in RASTK-HEX [2]. This paper presents preliminary verification against the reference Monte Carlo code MCS [3].

2. Code Description

2.1 RAST-K Diffusion Code

The three-dimensional (3D) two-group nodal diffusion code RAST-K v2.0 [4] has been developed by the COmputational Reactor physics and Experiment laboratory (CORE) of Ulsan National Institute of Science and Technology (UNIST) with the initial application goal to Light Water Reactors (LWRs). It was successfully verified and validated to make sure that it can provide results in good agreement with the measured data of LWRs [4]. In order to use it for Fast Reactor (FR) cores, the RAST-K code is under further development for the hexagonal-z geometry (R2-HEX) including the extension of two-group rectangular solver to multi-group hexagonal solver and the update of thermal-physical properties of fast reactor core materials. To solve the multi-group neutron diffusion equation in the 3D hexagonal-z geometry, the triangle-based polynomial expansion nodal (TPEN) [5] method is implemented in the R2-HEX code. The burnup calculation for fast reactor in R2-HEX is based on solving the transmutation equation by CRAM module.

2.2 MCS Monte-Carlo Code

MCS is a continuous energy Monte Carlo code capable of criticality, depletion, multi-physics and shielding calculations for large scale power reactor analysis. MCS has been developed at UNIST since 2013. MCS neutron/photon transport capability has been verified and validated against the various benchmarks [3]. The CRAM solver is implemented in MCS to solve the Bateman equation and it is optimized to exploit the sparsity of the burnup matrix to reduce the computing time. The burnup chain can include up to 3820 isotopes given in the ENDF decay library, but only 1373 of those isotopes are used by default for burnup calculations in MCS [3]. Recently, MCS has the capability to produce multi-group cross section for fast reactor analysis. The applicability of MG XSs generation is quantified on the sodium fast reactor (SFR) ABR-1000 design with a metallic fuel from the OECD/NEA SRF benchmark [6].

3. Method and Result

3.1 Core Model

The in-house conceptually designed core, Small Modular Lead-bismuth eutectic Fast Reactor (SMLFR), has been selected for verification in this work. This SMLFR consists of the Uranium-Nitride as fuel material, Lead Bismuth Eutectic (LBE) as coolant material, and 15-15Ti as a cladding material. The thermal power of the SMLFR is 300 MW, with an assumption of 40% thermal efficiency. It is also designed to achieve around 8-10 years of a lifetime without refueling. The core inlet and outlet temperatures are 300^{o}C and 450^{o}C, respectively. The fuel enrichment for the LEU region is 14.0 w/o ^{235}U while natural ^{235}U content is used for the blanket region. In total, the core consists of 144 fuel assemblies (FA) and 18 control assemblies. The assembly pitch is 17 cm. The core is designed with an axial height of 1.0 m and diameter of 2.4 m. The loading pattern of SMLFR is shown in Figs. 1-2. The A1 is a neutron source assembly. The A2 and A3 are blanket and igniter assemblies. The A4 and A5 are primary and secondary control assemblies, and A6 is a reflector assembly.

3.2 Numerical Results

This section presents the calculation results and comparison with reference value generated by MCS code. The reference solution as well as the homogenized 24-group cross section (XS) for R2-HEX were prepared using MCS code. The nominal conditions used for

SMLFR fuel depletion were taken as follows: LBE density ρ= 10.27 g/cm^3, fuel temperature T_f = 700 K. The XS set for 24-group energy structure is generated by MCS to be used in RASTK-HEX. The same library ENDF/B-VII.0 [6] was used to obtain reference solution and to generate homogenized macro and microscopic cross sections. The core is divided into 18 axial meshes with 1440 depletion zones. MCS simulation was performed with 200 inactive cycles, 800 active cycles, and 25,000 histories per cycle.

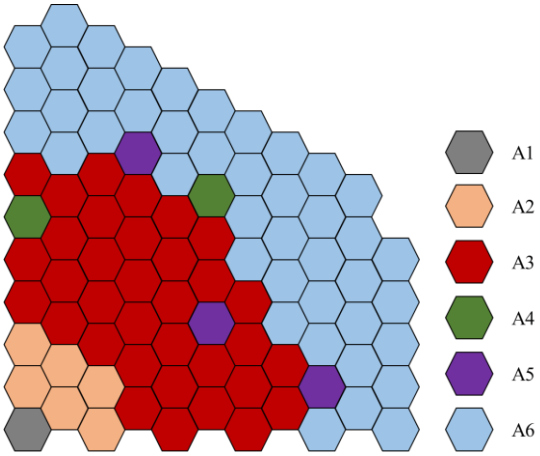

Fig. 1. Radial loading pattern.

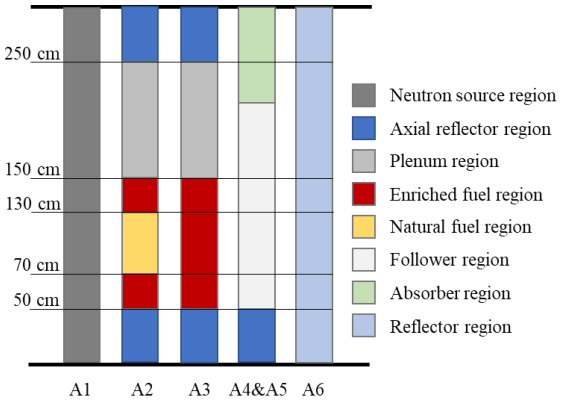

Fig. 2. Axial loading pattern.

In this study, the depletion calculation for a 2D SMLFR fuel assembly was done by using R2-HEX and MCS. The comparison of some important isotopes was done for proving the accuracy in CRAM solver implementation. Fig. 3 shows the comparison of main nuclides in a 2D fuel assembly. The same tendency and comparable values are shown for both codes. The difference of number density for the main nuclides (^{235}U, ^{238}U, ^{239}Pu) is negligible (less than 0.1%) between MCS and MCS/R2-HEX. Discrepancies are due to accumulation of difference due to affect the evolution of the analyzed isotopes inventory. The number of isotopes tracked in this case is 221 actinide and fission product nuclides by R2-HEX and over 250 actinide and fission product nuclides by MCS. The SMLFR 3D core depletion by MCS and MCS/R2-HEX without fuel performance feedback has been performed and analysed with all control rods out. The core multiplication factor is shown in Fig. 4. The standard deviation of MCS k_{eff} is 14 pcm. As compared to MCS, the MCS/R2-HEX code system shows a gradual decrease of multiplication factor following the time of operation.

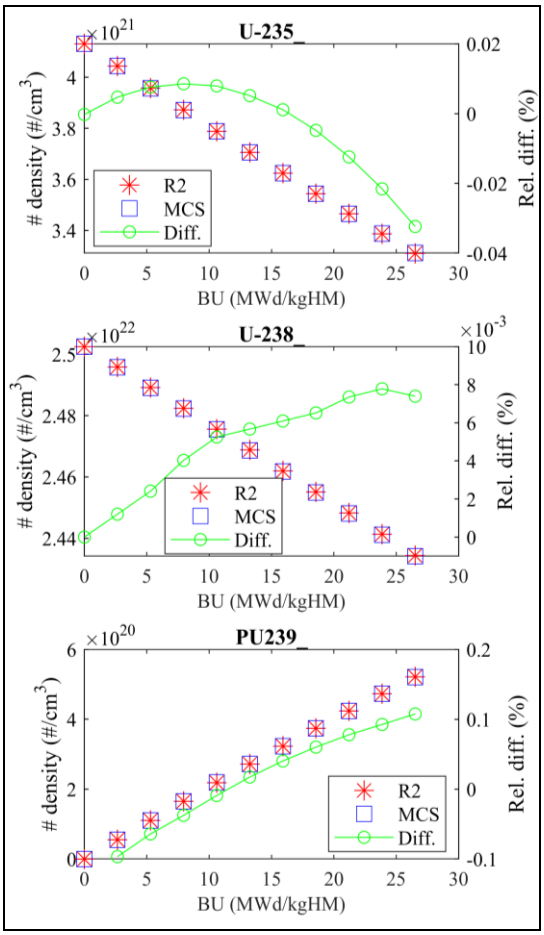

Fig. 3. Comparison of selected nuclides.

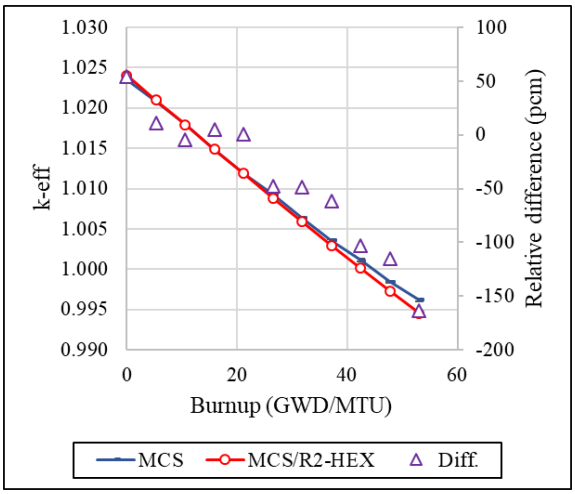

Fig. 4. k_{eff} comparison between MCS and MCS/R2-HEX.

The maximum difference of k_{eff} between MCS/R2-HEX and MCS is –164 pcm. Figs. 5-6 show the power distribution of MCS/R2-HEX and MCS at the beginning

of cycle (BOC), middle of cycle (MOC), and end of cycle (EOC).

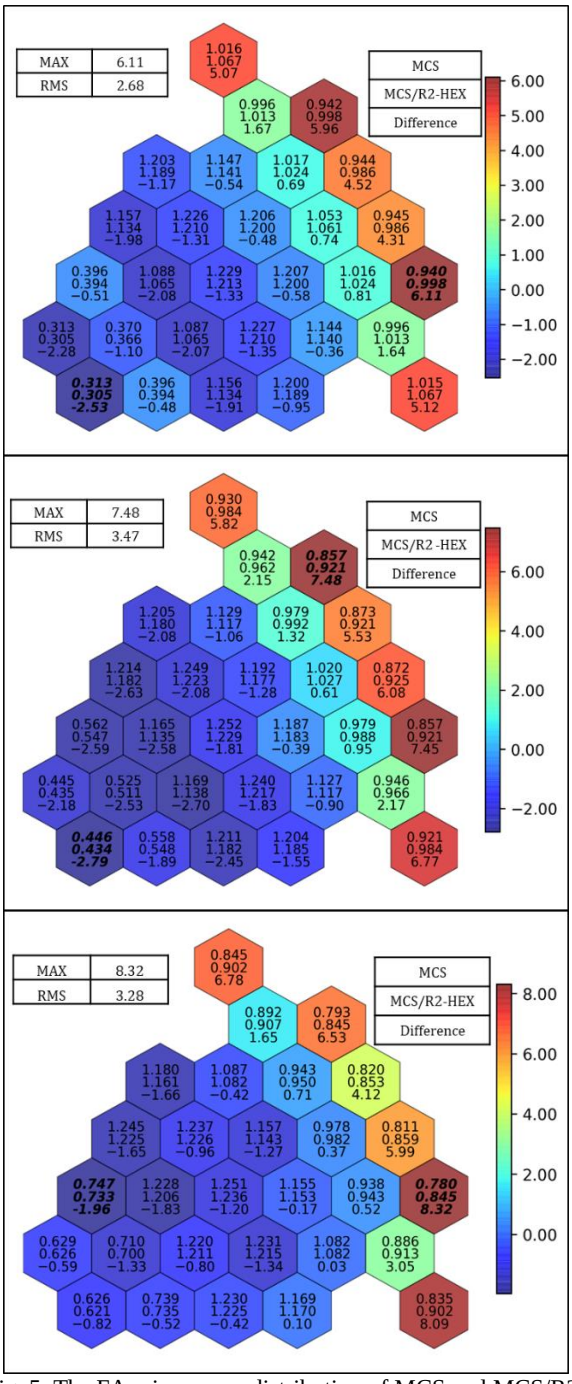

Fig. 5. The FA-wise power distribution of MCS and MCS/R2-HEX (top: BOC; middle: MOC; bottom: EOC).

The standard deviation of MCS's power values is less than 0.4%. The maximum difference of FA-wise power and axial power is less than 9% and 6%, respectively. The difference remains low in the central region and gradually increase towards the outer area. It can be explained by the neutron spectrum softening in the peripheral FAs due to having reflector assemblies nearby. The power of FA facing reflector assembly radially can be more precise by using 3D super-cell model for peripheral fuel assemblies.

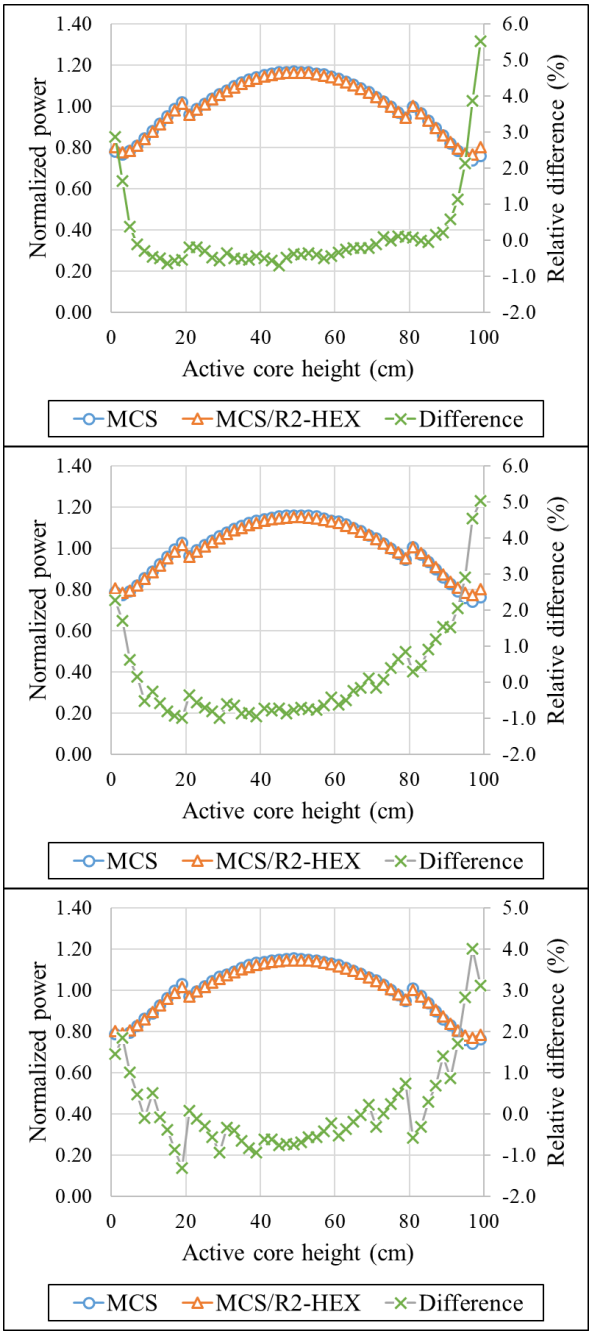

Fig. 6. The axial power distribution of MCS and MCS/R2-HEX (top: BOC; middle: MOC; bottom: EOC).

3. Conclusions

The CRAM solver is implemented in R2-HEX for solving Bateman equation. The micro cross section tables are prepared by MCS code for R2-HEX depletion calculation. The results obtained by MCS/R2-HEX are compared with Monte-Carlo MCS code. A designed SMLFR core was selected for analysis. The comparison

of selected nuclide's number density was done for a 2D assembly. Both codes showed the same tendencies and comparable values, in particular for the main isotopes (in terms of higher atomic density) ^{235}U, ^{238}U and ^{239}Pu, which show that both codes are depleting the fuel at the same rate. As for the comparison of multiplication factor and power distribution, the difference between MCS and MCS/R2-HEX was found acceptable. Based on the results, it can be observed that both codes show the same tendency. In general, the difference can be explained by the difference in neutronic solver (deterministic and MC) and the differences in depletion chains. In conclusion, this work successfully verified the depletion solver implemented in R2-HEX. In future work, the verification and validation against measurement data will be conducted.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No.NRF-2017M2A8A2018595).

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