Verification of RAST-K hexagonal transient solver with OCED/NEA benchmark problem of KALININ-3 NPP

Jaerim Jang, Alexey Cherezov, Yunki Jo, Tuan Quoc Tran, Siarhei Dzianisau, Woonghee Lee, Jinsu Park, and Deokjung Lee*

Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919, Republic of Korea
**Corresponding author. Email: deokjung@unist.ac.kr*

1. Introduction

This paper presents the verification results of our in-house code RAST-K for Kalinin-3 NPP Benchmark compared to ATHLET/KIKO3D and PARCS nodal codes [1][2][3][4][5]. Kalinin-3 NPP is one of OECD/NEA benchmark problems and has a hexagonal FA geometry [1][3][4][5]. The purpose of this paper is to assess the performance of a newly developed RAST-K transient module compared with other developed code systems. PARCS code is used for code-to-code comparison [2]. This paper contains the calculation results at hot zero power (HZP) condition. The transient calculation scenario in this study is based on ejection of the control rod bank with the largest rod worth.

2. Code system

RAST-K v2.0 is our in-house nodal code that has been validated and verified using nuclear design reports and other available code systems [6]. Hexagonal geometry analysis solver in RAST-K has been developed based on TPEN method [7][8][9]. The solver has already been verified for MOX-3600, CAR-3600, MET-1000, and MOX-1000 at steady state condition [7][8][9].

Transient calculation module of RAST-K is developed based on transient fixed source problem. Figure 1 presents the flow chart of transient calculation.

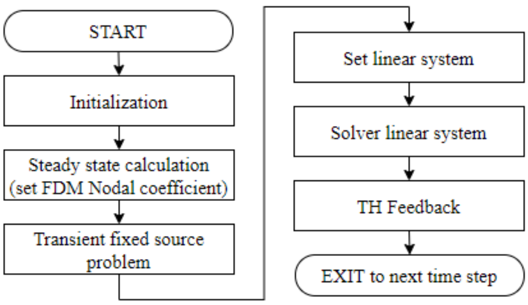

Figure 1 Flow chart

3. Specification of benchmark model

3.1. Core specification

Figure 2 presents the Kalinin-3 NPP loading pattern with six different types of fuel assemblies (FAs). Kalinin-3 NPP is using a VVER-1000 reactor, which contains 163 FAs. Notation of X is the control rod bank 10. According to the reference [1], the calculation is performed with 82.95% inserted control rod bank 10 from bottom of active height. To compare the results with document [1], the control rod bank 10 location is fixed in accordance with the reference.

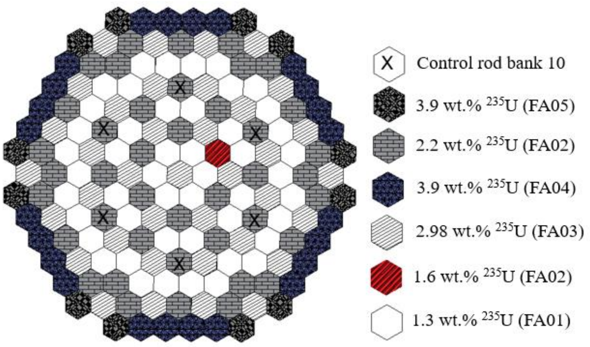

Figure 2 Radial layout of Kalinin-3 NPP

3.2. Fuel Assembly specification.

The detailed radial layouts of FAs are presented in Figure 3 and Figure 4. In total, one fuel assembly contains 312 fuel pins, one central instrumentation tube and 18 guide tubes. FA03, FA04 and FA05 are loaded with 5 wt.% gadolinia fuel. FA03 and FA04 contain nine gadolinia rods, FA05 contains six gadolinia rods.

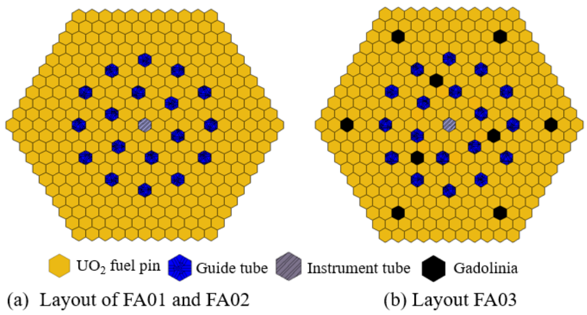

Figure 3 Radial layout of FA01, FA02 and FA03

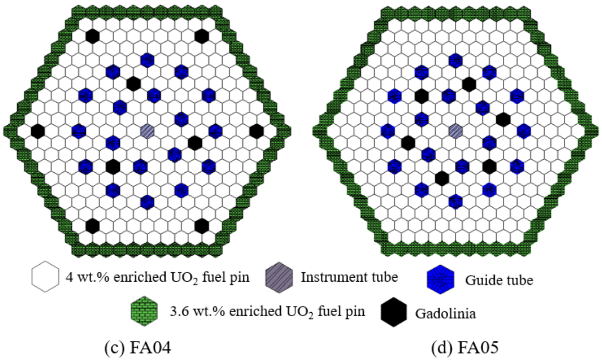

Figure 4 Radial layout of FA04 and FA05

3.3. Cross section data file with control rod

OECD/NEA provides the cross-section data file for 96 EFPDs. Assembly discontinuity factor (ADF) and corner discontinuity factor (CDF) are fixed as one in this calculation. Benchmark problem provides the cross-section (XS) library in NEMTAB format and contains 64 XS sets [1]. Those 64 XS points are generated for four conditions of fuel temperature (540 K, 900 K, 1300 K, and 1700 K), moderator temperature (540 K, 560 K, 580 K, and 600 K), and moderator density (660 kg/m^3 700 kg/m^3, 740 kg/m^3, and 780 kg/m^3). Boron concentration is fixed as 660 ppm. In addition, the following four cross section data sets are provided by OECD/NEA: (1) nemtab_load_2 (rod out condition), (2) nemtabr1_load_2 (rod in condition), (3) nemtab_load_1 (rod out), and (4) nemtabr1_load1 (rod in) [1]. The regions of each XS data are presented in Figure 5. The XS data for 'Rod in' condition is calculated with inserted B_4C control rods using a simplified control rod geometry. Figure 6 presents the axial composition of Kalinin-3 control rods. The simplified control rod geometry is shown in subplot (b). Figure 5 (b) presents control rod bank positions in the benchmark core loading pattern. There are 10 control rod banks used in Kalinin-3 NPP benchmark.

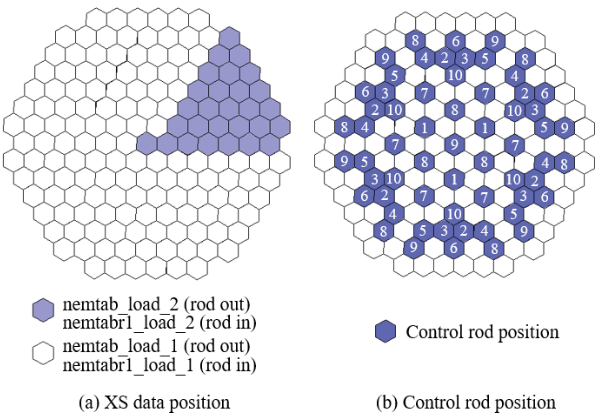

Figure 5 Cross-section data position with control rod bank

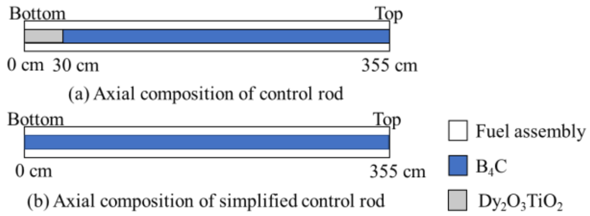

Figure 6 Axial composition of control rod

3.4. Calculation conditions

This section presents the calculation conditions and design parameters used for modelling of the Kalinin-3 NPP benchmark scenario. The design parameters are listed in Table 1. In hot zero power condition, 0.1% of nominal power condition (2907 MW) is used for calculation.

Table 1 Design parameters

Parameter	Value	Unit
Power	2907^a	MW
Moderator temperature	552.15 K	K
Fuel temperature	552.15 K	K
Boron concentration	660	ppm
Control rod position (#10)	309.23^b	cm
Active height	355	cm
FA pitch	23.6	cm
Fuel pin radius	0.37850	cm
Inner cladding radius	0.37925	cm
Outer cladding radius	0.38615	cm
Guide tube radius	0.56	cm
Number of fuel pins in FA	312	
Number of guide tubes in FA	19	
Number of reflector FA	48	
Number of FA	163	

a is reactor power for full power condition (nominal power condition); *b* is calculated from bottom of active core

4. Calculation results

4.1. Verification code system

ATHLET/KIKO3D and PARCS code are used for code-to-code comparison. PARCS code was developed by Purdue University and had been approved by NRC [2]. ATHLET/KIKO3D had been validated using the Kalinin-3 NPP data [1].

4.2. Multiplication factor

Table 2 shows the multiplication factor value for the case when control rod bank 10 is partially inserted (*i.e.*, 82.95% inserted from bottom of active height). The reference results are ATHLET/KIKO3D results [1], where KIKO3D is a spatial kinetic code system. Compared to the reference [1], RAST-K has a difference of 71 pcm. In addition, compared the PARCS code, RAST-K has a difference of 24 pcm.

Figure 7 presents the relative difference of radial power between PARCS and RAST-K. The maximum difference is 0.5 % and the minimum difference is –0.4%.

Table 2 Multiplication factor with inserted control rod bank 10

Code	k_{eff}	Difference [pcm]
ATHLET/KIKO3D [1]	1.00770	
RAST-K	1.00841	71
PARCS	1.00865	95

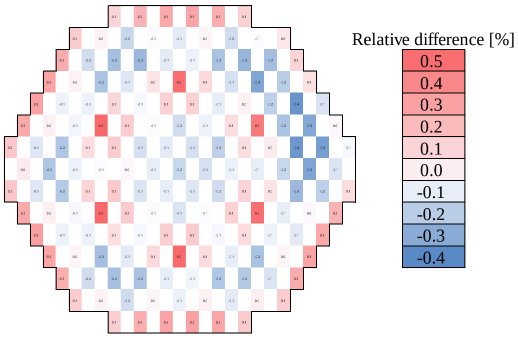

Figure 7 Relative difference of radial power

5. Transient calculation with CR bank #8

To verify the capability of RAST-K transient calculation, verification is performed in comparison with PARCS code. Sample transient scenario is used for calculation and sample scenario is selected to consider control rod bank worth.

5.1. Control rod bank worth

Table 3 contains each control rod bank worth calculated by RAST-K. The positions of control rod banks are presented in Figure 5 (b) As shown in the table, the control rod bank #8 has the largest rod worth. Therefore, control rod bank #8 is used for rod ejection calculation. The k_{eff} of all rod out condition is 1.00965.

Table 3 Control rod bank worth

Rod bank	Rod worth [pcm]	Rod bank	Rod worth [pcm]
1	571	6	1148
2	226	7	1120
3	1151	8	1609
4	1084	9	1171
5	1085	10	1174

5.2. Verification results

Control rod bank #8 is being ejected from 0 cm of active height to 355 cm during 0.1 second. The time step of 0.025 second is used for calculation and power condition is presented in Figure 8. Compared to the results calculated using PARCS code, the relative difference of power is within ±0.2%. Right-side y value contains the reactor power divided by nominal power (*i.e.*, 2907 MW). Maximum power level reached 7000% of nominal power condition. Figure 9 contains the total reactivity difference between the RAST-K and PARCS results. Figure 10 shows the reactivity difference as function of fuel temperature, moderator temperature, and control rod position. The maximum relative difference of total reactivity between PARCS and RAST-K is within ±0.4%.

Figure 11 and Figure 12 contain the temperature condition during rod ejection. For moderator temperature condition shown in Figure 11, the relative difference is smaller than ±0.012% boundary. The maximum fuel temperature difference is about ±0.5%.

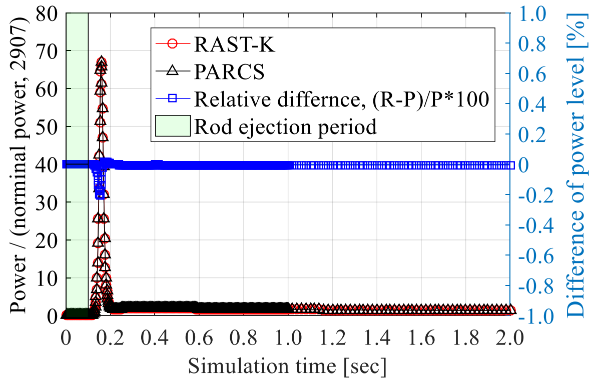

Figure 8 Core power of during rod bank ejection

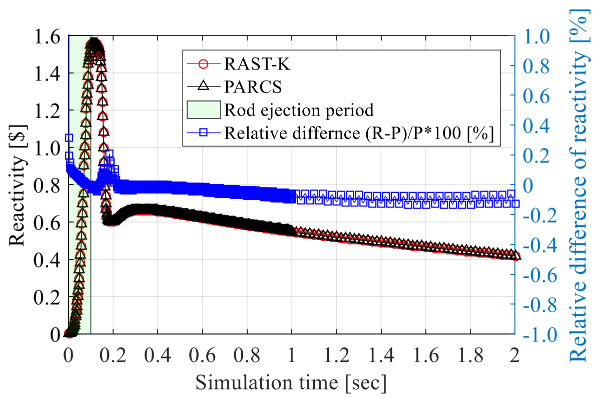

Figure 9 Total reactivity difference during rod bank ejection

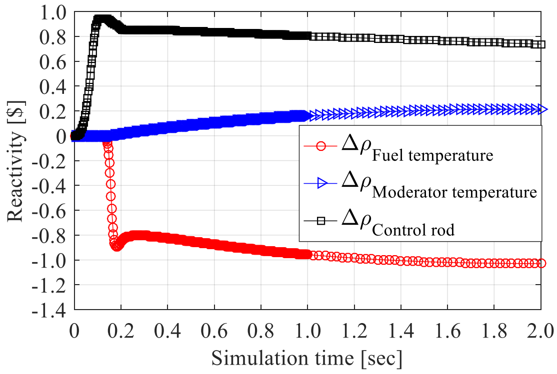

Figure 10 Reactivity difference according to fuel temperature, moderator temperature, and control rod

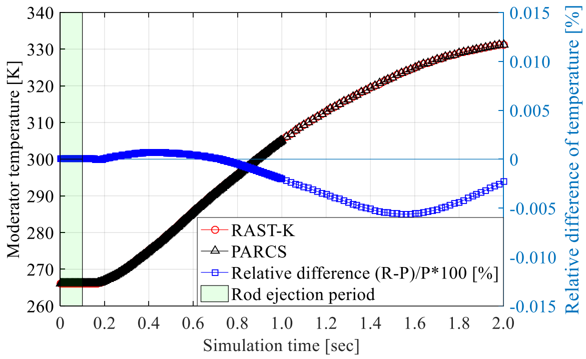

Figure 11 Moderator temperature during rod ejection

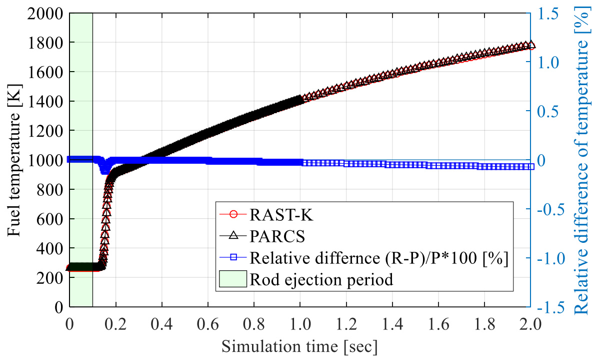

Figure 12 Fuel temperature during rod ejection

6. Conclusion

This paper presents the verification results of RAST-K code using Kalinin-3 NPP benchmark. Three major analyses are performed in this paper: (1) a comparison of multiplication factor with ATHLET/KIKO3D and PARCS at HZP condition, (2) a comparison of radial power distribution with a nodal code PARCS, and (3) sample rod ejection calculation using the highest rod worth control rod bank. In HZP condition, the multiplication difference of RAST-K is 71 pcm compared to ATHLET/KIKO3D and 24 pcm compared to PARCS. In addition, the maximum observed radial power difference between PARCS and RAST-K is 0.5%. Finally, the maximum difference of reactivity in sample rod ejection scenario was found at ±0.2%.

This study demonstrates a successful verification of the transient calculation module implemented in RAST-K for hexagonal geometry as compared with PARCS and ATHLET/KIKO3D.

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