Solutions of PWR MOX/UO2 Transient Benchmark Problem using a Pinwise Two-step Core Calculation Code and a Direct Whole Core Calculation Code

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1. Introduction

In recent years, KEPCO Nuclear Fuel (KNF) has been working to advance the domestic nuclear design code system and has made some notable progress. The new pinwise core calculation code, which will be the successor to the three-dimensional (3D) core analysis code ASTRA (Advanced Static and Transient Reactor Analyzer) [1], succeeded in achieving fast calculation speed and high accuracy with the efficient solver based on the finite difference method (FDM) [2]. In addition, many novel features including enhanced cross-section (XS) library, advanced resonance treatment method, and the direct whole core calculation (DWCC) capability were implemented in the lattice transport code KARMA (Kernel Analyzer by Ray-tracing Method for fuel Assembly), and those are being validated [3].

This work aims to verify the transient module of the pinwise core calculation code. The PWR MOX/UO2 transient benchmark problem [4] was selected for this purpose. For the consistent code-to-code comparison, the multigroup (MG) pinwise XSs (PXSs), core kinetic parameters, and the reference solutions were generated by KARMA. The result showed that the two codes agreed well in the peak power prediction.

2. Methods

2.1. KARMA core model

From a pin-cell level, all the components including fuel pellet, integral fuel burnable absorber (IFBA), air gap, and cladding were explicitly modeled by following specifications described in Ref. [4]. In addition, each fuel pellet was subdivided into three regions with the same volume for proper consideration of the spatial self-shielding effect and the resulting heterogeneity in the depletion. The moderator region was also subdivided into three regions to take the thermal flux gradient.

Since the active core contains a number of burned fuel assemblies, as shown in Fig. 1, the lattice depletion calculations were performed for each assembly to obtain detailed mixture information at the target burnup point. All the mixtures were assigned at the right positions by using an auxiliary code written in Fortran. The axially homogeneous active core with 365.76 cm height is equally subdivided into 20 planes.

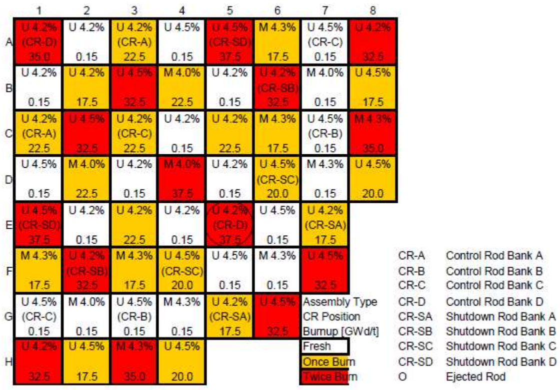

Fig. 1. Configuration of the PWR MOX/UO2 core [4]

The active core is surrounded by the radial and the axial reflectors, all of which are 21.42 cm thick. The radial reflector contains stainless steel baffle which is 2.52 cm thick, while the axial reflector is filled with the moderator. Temperature of the reflectors were fixed the same with the core inlet temperature, 560K.

2.2. KARMA calculations

The flat-source method of characteristics (MOC) solver was employed with the transport corrected P0 option and the ray parameters of a 0.04 cm spacing and 16 azimuthal and 3 polar angles in the octant sphere. The library employing 47-group structure is generated from the ENDF/B-VII.1 data using a code package called LICOS (**Li**brary generation **Co**de **S**ystem) [3].

For the PXS generations, an 8-group structure was selected as the condensed group and the branch matrix provided in Ref. [4] was employed. The use of the 8-group was determined to yield the accurate pinwise core calculation results for the problem with remarkably high heterogeneity. The reflector PXSs were obtained from a set of local problems which represents a small part of the reflector. For the core kinetic parameter generations, on the other hand, the adjoint weighting was not applied in that the importance of each delayed neutron precursor group can be accounted in the 8-group calculation.

The rod-ejection transient calculation was performed with the Crank-Nicolson method [5]. The time step size was 0.005 sec. The control rod moved at a constant speed and completely got out of the core in 0.1 sec. In order to take the thermal hydraulic effect, simplified closed channel model in KARMA was used with the thermal conductivity and the gap conductance data provided in NEACRP benchmark specification for a Westinghouse three-loop plant.

2.3. Pinwise calculations

The 2D/1D diffusion FDM solver taking each pin-cell as the base mesh was employed. Errors originating from the diffusion theory and the coarse mesh size were simultaneously corrected by the superhomogenization (SPH) factor, as well as the errors from the pin-level homogenization and the group condensation.

The transient calculation was performed with the Crank-Nicolson method and the time step size was set to 0.005 sec. The fuel and moderator models are briefly shown in Table I. In test calculations, it was observed that the effective fuel temperature (T_{eff}) model provided in Ref. [4] (TF1) leads to inconsistencies in the thermal feedback effect. Therefore, another model in Ref. [6] (TF2) was additionally used. The TF2 model corrects the volume-weighted average temperature ($\bar{T}_f$) of the fuel by difference between the pellet centerline temperature (T_c) and the surface temperature (T_s).

Table I. Fuel and moderator model for the pinwise calculation

Effective fuel temperature	TF1: $T_{\text{eff}} = \omega T_c + (1-\omega)T_s$, $\omega = 0.3$
	TF2: $T_{\text{eff}} = \bar{T}_f - \frac{1}{18}(T_c - T_s)$
Gap conductance	Function of linear power density
Heat transfer coefficient	Dittus-Boelter
Total active core flow	15849.4 kg/s

3. Results

3.1. Steady state hot zero power core cases

The hot zero power (HZP) core calculations aimed to check the consistency of core models for the two codes. The steady state calculations were performed for two cases, one with the all regulating rods are inserted (ARI) and the other with the ejected rod (N-1). The critical boron concentration (CBC) was searched for the ARI case and the k-eigenvalue calculation was performed for the N-1 case with the CBC of the ARI case to predict the static rod worth of the ejected rod.

Table II and III briefly show the result, and Fig. 2 shows the reference radial power and the assembly ΔP (%) distributions of the N-1 core. The results were highly satisfactory in respect that the no notable deterioration of the agreement was observed in between the ARI and the N-1 cases, although the ejection of the rod lead to severe skewness of the power distribution. Peaking factor (Fr, Fxy, and Fq) predictions were also matched well.

It is worth noting that quite large pin power errors were observed in the fresh MOX assemblies, because the MOX PXSs obtained from the single lattice contains errors originating from differences in the flux spectra. The result shows the need for application of an improved homogenization technique to improve the accuracy of the pinwise calculation for MOX loaded cores.

Table II. Results of the HZP ARI core calculation

		KARMA	Pinwise	Diff.
CBC (ppm)		1246.3	1263.3	17.0 ppm
Peaking Factor	Fr	1.893	1.890	-0.13%
	Fxy	1.896	1.891	-0.26%
	Fq	2.843	2.841	-0.08%
Assembly 2D ΔP (%)			RMS	0.82%
			MAX	2.56%
Pinwise 2D ΔP (%)			RMS	1.20%
			MAX	-6.22%
Pinwise 3D ΔP (%)			RMS	1.22%
			MAX	-6.89%

Table III. Results of the HZP N-1 core calculation

		KARMA	Pinwise	Diff.
Reactivity (pcm)		647.5	642.2	-5.3 pcm
Peaking Factor	Fr	6.133	5.989	-2.35%
	Fxy	6.161	5.997	-2.67%
	Fq	9.211	9.000	-2.29%
Assembly 2D ΔP (%)			RMS	0.81%
			MAX	2.53%
Pinwise 2D ΔP (%)			RMS	1.19%
			MAX	-6.25%
Pinwise 3D ΔP (%)			RMS	1.20%
			MAX	-6.91%

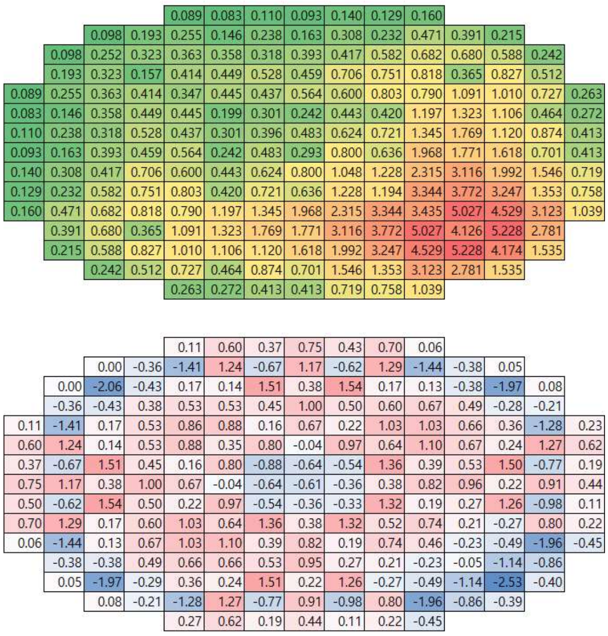

Fig. 2. Assembly-wise radial power (top, KARMA) and ΔP (%, bottom, pinwise) distributions of the N-1 core

3.2. Transient rod ejection case

The results are summarized in Table IV. The peak time predicted by the pinwise calculation shows only 0.005 sec difference with the reference, and the difference of the peak power is 5.9% with TF1 and -4.5% with TF2. This satisfactory result clearly verifies the reliability of transient module implemented in the pinwise code.

Table IV. Results of the transient rod ejection case

	Peak time (sec)		Peak power (%)	
	Value	Error	Value	Error
KARMA	0.275	-	226.0	-
Pinwise, TF1	0.280	0.005	239.2	5.9
Pinwise, TF2	0.280	0.005	215.7	-4.5

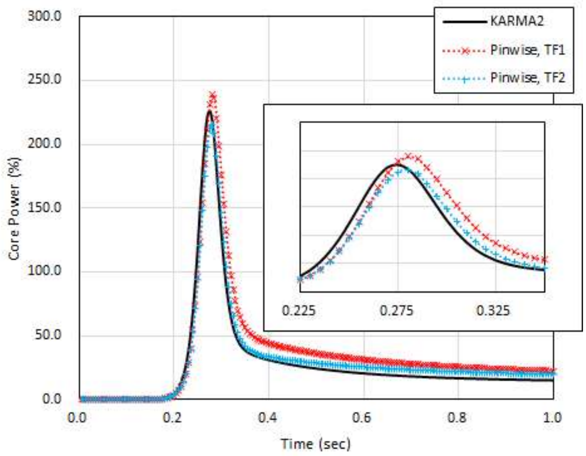

Fig. 3. Transient core power behavior

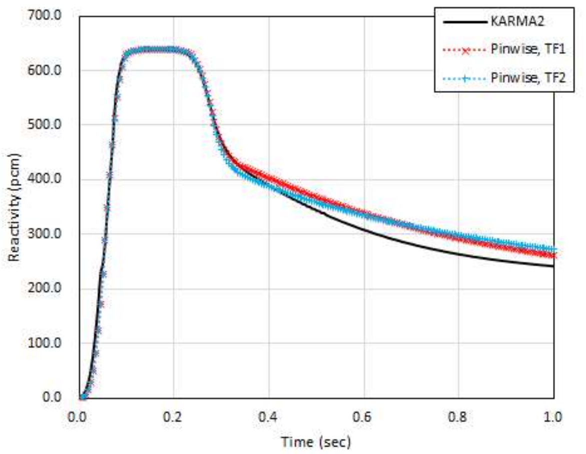

Fig. 4. Transient core reactivity behavior

The difference originating from the fuel temperature models becomes notable after 0.3 sec. The core power behavior in Fig. 3 and the reactivity behavior in Fig. 4 indicate that the fuel temperature feedback is stronger with the TF2 model, especially at the rear end of the power peak. It leads to the core power behavior matches better with the reference.

4. Conclusion

Transient module of the pinwise core calculation code was successfully verified through the consistent code-to-code comparison. Comparing with the reference DWCC solution yielded by KARMA, the 8-group pinwise core calculation accurately predicted the core power behavior. Difference of the peak time was only about 0.005 sec, and that of the peak power was less than 5.9% and 4.5% with the different fuel temperature models.

In future works, various energy group structures will be employed, and more extensive problems will be used for not only the verification but also the validation of the pinwise core calculation code.

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