Development and Verification of the HELIOS/CAPP Code System

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) is developing the HELIOS/CAPP code system for the analysis of a pebble type very high temperature gas cooled reactors (VHTRs). The HELIOS/CAPP code system adopted a two-step core analysis procedure. In the first step, the HELIOS code is used to generate few-group cross section table sets and, in the second step, the CAPP code is used to perform core physics analyses.

In this paper, some modifications in the analysis methodologies and implementation issues of the CAPP code are briefly described and the verification results of the HELIOS/CAPP code system are also presented.

2. Methods and Results

2.1 Modifications in the RPT and ECF Model

Figure 1 shows the concept of the reactivity-equivalent physical transformation (RPT). Not only the fuel but also the graphite moderator is mixed together in the fuel zone of the original RPT model, which makes it difficult to separate the fuel temperature effect and the moderator temperature effect on the cross-sections. To resolve this problem, the new RPT model was proposed. In the new RPT model, all the compositions other than the fuel kernels are homogenized in the outer zone. Results showed that the cross-sections are accurately represented as a function of the fuel temperature and the moderator temperature without any cross-term between the two variables. The equivalent cylindrical fuel (ECF) model was also modified from the original one. In the new model, the reactivity of the fuel was preserved while the average chord length of the fueled zone was preserved in the original model.

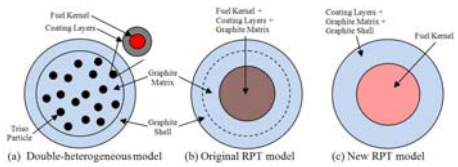


Figure 1. The Original and the new RPT model

2.2 Cross-section Representation

The homogenized microscopic cross-sections of the nuclides in a pebble are represented as follows :

$$\sigma_{xg}^{j}\left(r,b,T_m,\sqrt{T_f}\right)=\sigma_{xg}^{j,ref}\left(r,b\right)+\Delta\sigma_{xg}^{j,T_m}\left(r,b,T_m\right)+\Delta\sigma_{xg}^{j,T_f}\left(r,b,\sqrt{T_f}\right), \quad (1)$$

where r , b , T_m , and T_f are the distance from the core/reflector interface, the burnup of the pebble, the moderator temperature, and the fuel temperature, respectively. Once the micro cross-sections are determined, the macro cross-sections of a pebble are calculated by using the nuclide number density. The macro cross-sections of a spectral zone are calculated by volume-weighted pebble homogenization instead of flux-volume-weighted one. It was found that this approximation does not introduce considerable error[1].

2.3 Pebble Recycling Module

Figure 2 shows the pebble mixing and recycling model. The pebbles extracted from the core are stored in the boxes according to their burnup. The pebbles in a box are mixed together and averaged. The boxes are sorted according to the user-defined recycling priority. The pebbles are regrouped into *N* batches with equi-volume. The last batch is discharged and the rest pebble batches are recycled to the top of the core. The fresh pebble batch is also loaded at the top of the core.

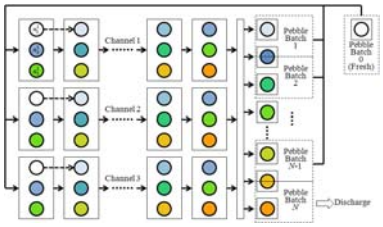


Figure 2. Pebble mixing and recycling model

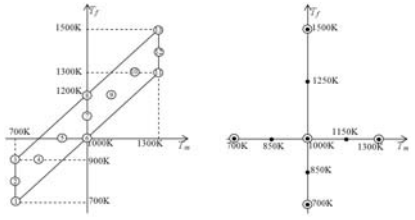
2.4 Verification of Single Pebble Analysis

In this test, the temperature dependency of the infinitive multiplication factor for a single pebble was investigated. Table 1 shows the results of the test for the pebble used in the PBR200[2] and Figure 3(a) shows the temperature state points. The five circles and the nine dots in Figure 3(b) are the state points used to generate the cross-section sets for the case C1 and C2, respectively. The McCARD code was used to solve the reference double heterogeity (DH) model. The HELIOS/CAPP errors with respect to the HELIOS results are the errors coming only from the cross-section interpolation and synthesis by Eq. (1).

Figure 4 shows the infinitive multiplication factor during single pebble depletion calculation. The error of the HELIOS/CAPP code system goes up to about 1500 pcm at the burnup of 100GWD/MTU. However, most of the error of the HELIOS/CAPP code system comes from the HELIOS code rather than the CAPP code.

Table 1. Results of single pebble test

State Point	McCARD (DH)	HELIOS (H)		HELIOS/CAPP (C1)			HELIOS/CAPP (C2)		
	k_{inf}	k_{inf}	Δρ (pcm) H-DH	k_{inf}	Δρ (pcm) C1-DH	Δρ (pcm) C1-H	k_{inf}	Δρ (pcm) C2-DH	Δρ (pcm) C2-H
1	1.47842	1.47731	-51	1.47731	-51	0	1.47731	-51	0
2	1.46879	1.46748	-61	1.46809	-32	28	1.46764	-53	7
3	1.46008	1.45833	-82	1.45892	-54	28	1.45847	-76	7
4	1.45733	1.45674	-28	1.45874	66	94	1.45723	-5	23
5	1.44807	1.44679	-61	1.44821	7	68	1.44714	-44	17
6	1.44555	1.44554	0	1.44554	0	0	1.44554	0	0
7	1.43782	1.43755	-13	1.43868	42	55	1.43820	18	31
8	1.43065	1.43061	-2	1.43185	59	61	1.43089	12	14
9	1.43576	1.43647	34	1.43958	185	150	1.43753	86	51
10	1.42086	1.42209	61	1.42509	209	148	1.42283	97	37
11	1.41884	1.42137	125	1.42250	181	56	1.42156	135	9
12	1.41219	1.41503	142	1.41578	180	37	1.41532	157	14
13	1.40614	1.40898	143	1.40908	148	5	1.40910	149	6



(a) State Points for Temperature Variation Verification (b) Temperature Variation Points for Cross-section Generation

Figure 3. Temperature state points

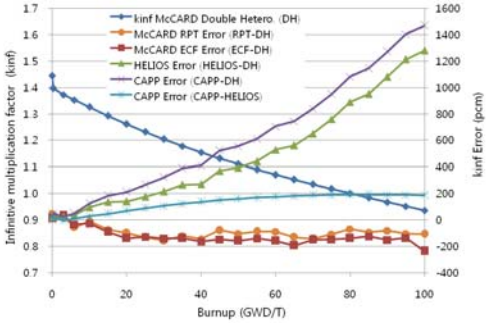
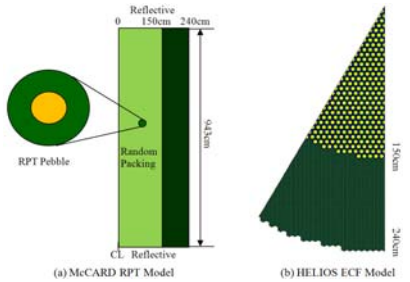


Figure 4. Single pebble depletion results

2.5 Verification of an Infinite Cylinder Core Analysis

Figure 5 shows the infinite cylinder core models derived from PBR200 reactor. Table 2 shows the multiplications of the core at various state points. Figure 6(a) and 6(b) show the power distribution of the fresh core at 1000K and the multiplication factor during the depletion calculation at 1000K.

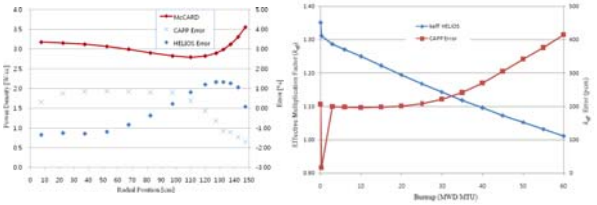


(a) McCARD RPT Model (b) HELIOS ECF Model

Figure 5 Infinite Cylinder Core Model

Table 2. Multiplication factors at the fresh core

State Point	McCARD (RPT)	HELIOS (H)		HELIOS/CAPP (C)			State Point	McCARD (RPT)	HELIOS (H)		HELIOS/CAPP (C)		
	k_{inf}	k_{inf}	Δρ (pcm) H-RPT	k_{inf}	Δρ (pcm) C-RPT	Δρ (pcm) C-H		k_{inf}	k_{inf}	Δρ (pcm) H-RPT	k_{inf}	Δρ (pcm) C-RPT	Δρ (pcm) C-H
	Tr=700 K							Tr=1000 K					
1	1.38143	1.37920	-117	1.38268	65	182	6	1.35146	1.35072	-41	1.35450	166	207
3	1.36655	1.36438	-116	1.36789	72	188	8	1.33997	1.33903	-52	1.34351	197	249
4	1.36208	1.36002	-111	1.36491	152	264	10	1.32706	1.32681	-14	1.33316	345	359
6	1.34729	1.34550	-99	1.34883	85	184	11	1.32682	1.32402	-159	1.32863	102	262
8	1.33552	1.33382	-95	1.33784	130	225	13	1.31680	1.31438	-140	1.31784	60	200
10	1.32220	1.32200	-11	1.32763	309	321	Tr=1300 K						
11	1.32210	1.31899	-178	1.32316	61	239	11	1.32894	1.32759	-77	1.33339	251	328
13	1.31251	1.30936	-183	1.31238	-8	176	13	1.31888	1.31793	-55	1.32266	216	271



(a) Power Distribution (b) Multiplication Factor during depletion

Figure 6. Results of the Infinite Cylinder Core Model

2.6 Verification of the PBR200 Equilibrium Core

Figure 7 compares the power distribution of the fresh core at 1000K. Figure 8 shows the k_{eff} of the CAPP code during the depletion of PBR200 with pebble flow.

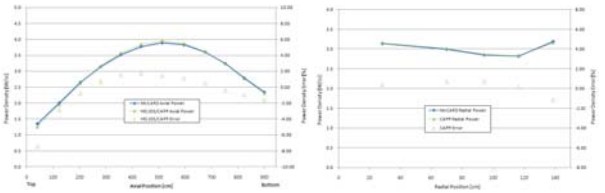


Figure 7. Power Distribution of the PBR200 core

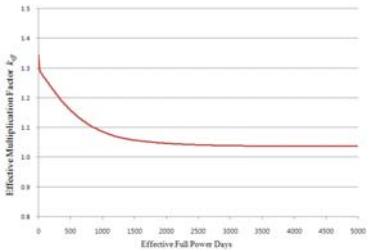


Figure 8. Multiplication factor during depletion

3. Conclusions

The HELIOS/CAPP code system for the analysis of the pebble type VHTR core was developed and verified against various benchmark problems. The HELIOS code overestimates the k_{∞} of the single pebble by about 1500 pcm during depletion calculation, which is the main source of the HELIOS/CAPP code system error. A reliable reference solution for the PBR200 equilibrium core should be obtained for further verification of the HELIOS/CAPP code system.

ACKNOWLEDGEMENT

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[1] Hyun Chul Lee, et al., "Development of the HELIOS/CAPP Code System for the Analysis of Pebble Type VHTR Cores," PHYSOR 2010, Pittsburgh, Pennsylvania, USA, May 9-14, 2010.
[2] Chang Jeun Jo, et al., "Preconceptual Design of the 200 MWth Prism and Pebble-bed Type VHTR Cores," PHYSOR 2008, Interlaken, Switzerland, September 14-19, 2008.