A Power Synthesis Module of DPCM3D Coupled by the Neutronics Code of ASTRA

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1. Introduction

DPCM3D (Direct 3-D Power Connection Method) module which introduces the 3DPCM [1] of SCOMS [2] produces a synthetic 3-D power distribution by coupling a neutronics code. Therefore, this module excludes a coefficient library and produces the coupling coefficients by an on-line calculation of the coupled neutronics code. In this paper, the ASTRA [3] code is adopted as a neutronics code and converted to a DLL (Dynamic Link Library) file for an on-line calculation. The computational performance is examined for the YGN-3 and YGN-1 cores.

2. Methods and Results

In this section, the 3-D power connection method (PCM3D) and the coupling scheme with the ASTRA code are first explained briefly, and then the performance of the DPCM3D module and the coupling scheme are examined.

2.1 PCM3D

In DPCM3D, the node power is determined from the neighboring node powers using the 3-D power connection factors as:

$$C_{l,k}\left(N_l^{nb}+N_k^{nb}\right)P_{l,k}-\sum_{j\in U}\left(P_{j,k}+P_{l,j}\right)=\sum_{j\in I}\left(P_{j,k}^d+P_{l,j}^d\right), \qquad (1)$$

where groups U and I mean the undetermined and instrumented node groups, respectively. N_l^{nb} and N_k^{nb} are the number of neighboring nodes in the radial and the axial directions. $C_{l,k}$ means the 3-D power connection factor which couples the node (l,k) power with the neighboring node powers. The right hand side (RHS) in Eq. (1) which includes the detected node powers is given as a source for node (l,k), which produces a fixed source problem. The left hand side (LHS) of Eq. (1) couples the node power of (l,k) to the undetermined neighboring powers. Therefore, the 3-D power distribution can be determined by an iterative scheme.

If the 3-D power distribution is given, the coupling coefficient of $C_{l,k}$ in Eq. (1) can be determined by using the neighboring powers as:

$$C_{l,k}=\frac{1}{P_{l,k}\left(N_l^{nb}+N_k^{nb}\right)}\left(\sum_{j=1}^{N_l^{nb}}P_{L_l^{nb}(j),k}+\sum_{j=1}^{N_k^{nb}}P_{l,K_k^{nb}(j)}\right), \qquad (2)$$

where $L_l^{nb}(j)$ and $K_k^{nb}(j)$ are the neighboring node and plane indices for node (l,k), respectively. However, the 3-D power distribution can not be given until the solution of Eq. (1) is obtained. Therefore, DPCM3D uses an approximate coupling coefficient of $C_{l,k}^C$ instead of rigorously defined one by using a 3-D power distribution of a neutronics code.

The detected node power in Eq. (1) is determined by using a power sharing factor (PSF) and a detector signal as:

$$P_{l,k}^d=\frac{1}{w_k}\sum_{k'}F_{l,kk'}P_{l,k'}^d \ , \qquad (3)$$

where

$P_{l,k}^d$ = detected node power of node (l,k),

$F_{l,kk'}=\dfrac{w_{kk'}P_{l,k}}{P_{l,k'}}$ = PSF from detector k' to node k,

$P_{l,k'}^d=w'_{l,k'}K_{l,k'}S_{l,k'}$ = incore detector power,

$S_{l,k'}$ = detector signal,

$w_k=\sum_{k'}w_{kk'}$, $w_{kk'}=h_{kk'}/h_{k'}$,

$h_{k'}$ = height of detector unit k',

$h_{kk'}$ = height of plane k included in detector unit k',

$w'_{l,k'}$ = detector absorption rate to power conversion factor,

$K_{l,k'}$ = detector surface flux to absorption rate conversion factor.

DPCM3D uses an approximate power sharing factor of $F_{l,kk'}^C$ instead of rigorously defined one by using a 3-D power distribution of a neutronics code.

2.2 Coupling between the DPCM3D and ASTRA code

Fig. 1 shows the coupling scheme between the DPCM3D module and the ASTRA code. A main program first activates the DPCM3D module and the ASTRA code, and then performs the coupled calculation. For the neutronics calculation, the main program sends the core state data such as the core inlet temperature (T_i), the core power (P_{th}), the critical boron concentration (CBC), the control rod position (Z_{rod}), Synthesized 3-D power distribution (P_s(x,y,z)) and the calculation mode (Mode) to the ASTRA code. According to the calculation mode, ASTRA performs the initialization or steady-state eigenvalue or the depletion calculation. After the neutronics calculation, ASTRA sends the calculated 3-D power distribution (P_c(x,y,z)), the detector absorption rate to power conversion factor ($w'_{l,k'}$) and the pin-to-box factor for the next DPCM3D calculation. P_c(x,y,z) is used to produce the DPCM3D constants as in Eq. (2) and (3).

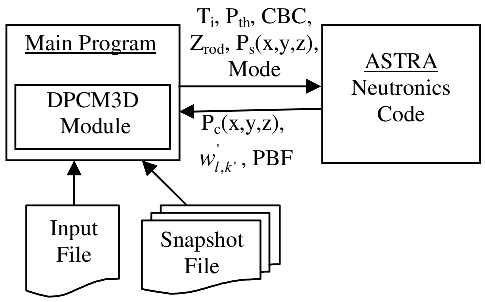

Fig. 1. Coupling Scheme between the DPCM3D Module and the ASTRA code

2.3 DPCM3D Module Stand-alone Test

In this Section, the DPCM3D module is tested for the YGN-3 and YGN-1 cores by using a given reference power distribution and the detector signals. The constants of $F^{C}_{l,kk'}$ and $C^{C}_{l,k}$ are generated from the reference power distribution. The detector signals are also generated from the reference power distribution. Therefore, DPCM3D module should reproduce the reference power distribution. Test calculation shows the same eigenvalues and about maximum power distribution errors of 0.0004 % and 0.0006 % for YGN-3 and YGN-1 cores, respectively. These trivial errors are less than the truncation error of about 0.02 % caused by the number of digits for the power distribution and detector signals.

2.4 Coupled Simulation Test

In this Section, DPCM3D module is tested for a realistic core conditions for YGN-3 core by coupling with the ASTRA neutronics code. This test includes not only the normal depletion case but also the rodded and the power variation cases. Both the core state signals and the reference solutions are assumed to be given by the ASTRA stand-alone calculation.

Coupled simulation is tested for total 25 cases including 1 BOC, HFP, ARO case, 5 core power variation, 9 control rod variation and 10 depletion cases as shown in Table I. The results of the coupled simulation test are shown in Table II. Coupled calculation almost reproduces the reference solutions within the 5 pcm eigenvalue and 0.07 % of pin power distribution errors.

Table I. Cases for Coupled Simulation Test

Case #	Variation Type	Variation
1	BOC, HFP, ARO	None
2 ~ 6	Core Power (%)	15, 20, 40, 60, 80
7 ~ 15	Control Rod (%)	R5, R4, R3 Bank: 20 % Insertion by PDIL Program
16 ~ 25	Depletion (EFPD)	1,2,3,4,5,6,7,8,9,10

Table II. Results for Coupled Simulation Test

Case	ε_k	ε_m^{nod}	ε_m^{pin}	Case	ε_k	ε_m^{nod}	ε_m^{pin}
1	0	3	-3	14	0	6	5
2	0	4	-3	15	0	-6	6
3	0	-3	3	16	5	-4	-7
4	0	-3	-3	17	1	-4	-4
5	0	-3	3	18	1	-3	3
6	0	-3	-3	19	0	3	-3
7	0	-4	3	20	0	3	3
8	0	5	-3	21	0	2	3
9	0	4	3	22	0	3	3
10	0	5	4	23	0	3	3
11	0	4	-4	24	0	3	3
12	0	4	5	25	0	3	3
13	0	5	-5				

ε_k = Eigenvalue Error, pcm

$$\varepsilon_m^{nod} = \max_{n=1,N}\left(\frac{P_s^n - P_{sa}^n}{P_{sa}^d}\times 10^4\right),$$

$$\varepsilon_m^{pin} = \max_{p=1,N}\left(\frac{P_s^p - P_{sa}^p}{P_{sa}^p}\times 10^4\right)$$

3. Conclusions

In this paper, the DPCM3D module is produced and coupled with the ASTRA neutronics code. In the DPCM3D stand-alone test, DPCM3D shows trivial errors which are less than the truncation errors. In the coupled simulation test, the DPCM3D module shows an acceptable result of less than 5 pcm eigenvalue and 0.07 % pin power distribution errors. These results mean that the DPCM3D module and ASTRA DLL are produced properly and they work soundly.

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