Development of Regulatory Audit Core Safety Code : COREDAX

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1. Introduction

Korea Institute of Nuclear Safety (KINS) has developed a core neutronics simulator, COREDAX code, for verifying core safety of SMART-P reactor, which is technically supported by Korea Advanced Institute of Science and Technology (KAIST). The COREDAX code would be used for regulatory audit calculations of 3-dimendional core neutronics.

The COREDAX code solves the steady-state and time-dependent multi-group neutron diffusion equation in hexagonal geometry as well as rectangular geometry by analytic function expansion nodal (AFEN) method. AFEN method was developed at KAIST, and it was internationally verified that its accuracy is excellent [1~4].

The COREDAX code is originally programmed based on the AFEN method. Accuracy of the code on the AFEN method was excellent for the hexagonal 2-dimensional problems, but there was a need for improvement for hexagonal-z 3-dimensional problems. Hence, several solution routines of the AFEN method are improved, and finally the advanced AFEN method is created. COREDAX code is based on the advanced AFEN method [5~7].

The initial version of COREDAX code is to complete a basic framework, performing eigenvalue calculations and kinetics calculations with thermal-hydraulic feedbacks, for audit calculations of steady-state core design and reactivity-induced accidents of SMART-P reactor. This study describes the COREDAX code for hexagonal geometry.

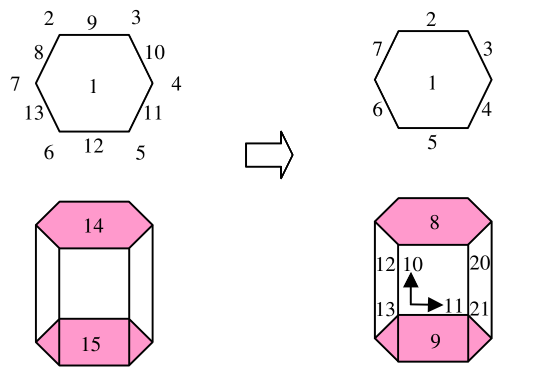
2. Basic Methodology

It is well known that the AFEN method is based on finding an analytic solution to give neutron flux distributions, not on obtaining an approximation solution used in other methods. Through verifying 3-dimensional benchmark problems, it is recognized that the AFEN method gives an ordinary result due to unfamiliarity of the axial analytic functions. Hence, the advanced AFEN method is developed from improving the AFEN method.

2.1 Advanced AFEN

The AFEN method is extendable to 3-dimensional geometry from two-dimensional. For 3-dimensional hexagonal geometry, the AFEN method finds 15 nodal unknowns; 6 corner points, 6 radial surfaces, a top surface, a bottom surface, and a node average. It was identified from benchmarking that 6 corner point unknowns are not recommendable. Hence, an advanced AFEN is proposed.

The advanced AFEN method excludes 6 corner point unknowns, and adds 12 unknowns of momental interfaces of y and z directions at side surfaces, and then analytically finds 21 nodal unknowns [5]. Figure 1 shows nodal unknowns of AFEN and advanced AFEN.



[AFEN : 15] [Advanced AFEN : 21]

Figure 1 Ordering of Nodal Unknowns

As a result, the analytic nodal solution based on the advanced AFEN method is derived as follows [6,7]:

$$
\begin{aligned}
\phi_g^n(x,y,z) = {} & a^n_{g,10} Sinh(\kappa_g^n x_1) + a^n_{g,20} Cosh(\kappa_g^n x_1) + a^n_{g,11} Sinh(\kappa_g^n x_2) + a^n_{g,21} Cosh(\kappa_g^n x_2) \\
& + a^n_{g,12} Sinh(\kappa_g^n x_3) + a^n_{g,22} Cosh(\kappa_g^n x_3) \\
& + b^n_{g,10} y_1 Sinh(\kappa_g^n x_1) + b^n_{g,20} y_1 Cosh(\kappa_g^n x_1) + b^n_{g,11} y_2 Sinh(\kappa_g^n x_2) + b^n_{g,21} y_2 Cosh(\kappa_g^n x_2) \\
& + b^n_{g,12} y_3 Sinh(\kappa_g^n x_3) + b^n_{g,22} y_3 Cosh(\kappa_g^n x_3) \\
& + c^n_{g,10} z Sinh(\kappa_g^n x_1) + c^n_{g,20} z Cosh(\kappa_g^n x_1) + c^n_{g,11} z Sinh(\kappa_g^n x_2) + c^n_{g,21} z Cosh(\kappa_g^n x_2) \\
& + c^n_{g,12} z Sinh(\kappa_g^n x_3) + c^n_{g,22} z Cosh(\kappa_g^n x_3) \\
& + d^n_{g,10} Sinh(\kappa_g^n z) + c^n_{g,20} Cosh(\kappa_g^n z),
\end{aligned}
$$

here,

$$
\kappa_g = \sqrt{|\lambda_g|}, \quad \lambda_g = \text{eigenvalues of } [\Lambda] \,,
$$

$$
[\Lambda] = [\mathrm{D}]^{-1}\left([\mathrm{A}] - \frac{\vec{\chi}}{k_{eff}}[\mathrm{F}]^T\right).
$$

2.2 Dynamics Methodology

Time-dependent neutron diffusion equation is discretized by the exponential transformation method. To accelerate the iteration for convergence, the coarse group rebalance (CGR) method is used. Also, to correct the control rod cusping, 3 methods of volume weighting, forward flux weighting, and adjoint flux bilinear weighting can be chosen [8].

2.3 Thermal-hydraulic Model

The typical heat conduction equation in the fuel and clad is considered. For coolant temperature, mass equation, momentum equation, energy equation and state equation are solved [6,7].

2.4 Cross Section Generation Model

Initial version of the COREDAX code has a basic cross section model which reads the given data set and linearly interpolates cross sections for the thermal-hydraulic condition calculated. The cross section model of the COREDAX code needs to be improved.

3. Benchmarking

3.1 VVER-440 (Steady State)

VVER-440 benchmark is a 3-dimensional steady-state core with hexagonal fuel assembly. VVER-440 core geometry is given in References [5~7]. Table 1 shows the results of the COREDAX code.

Table 1 Results of COREDAX Code for VVER-440

No. of Planes	AFEN k_{eff} (% error)	Advanced AFEN (k_{eff} % error)
12	1.01198259 (0.065)	1.01126696 (-0.0052)
24	1.01173547 (0.037)	1.01125753 (-0.0062)
60	-	1.01125544 (-0.0063)

3.2 Modified VVER-440 (Control Rod Withdrawal)

To find benchmark problem for hexagonal core transients is not easy. In this study, the VVER-440 benchmark above is modified to core transient that the control rod is withdrawal. Since there is not an exact solution, this analysis just gives a physical trend. Figure 2 shows the control rod movement.

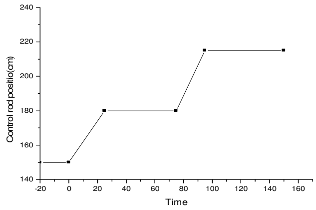


Figure 2 Control Rod Position vs. Time

Figure 3 shows the results of the COREDAX code for 3 options of homogenizing nodes that control rod is positioned, to correct the control rod cusping effect.

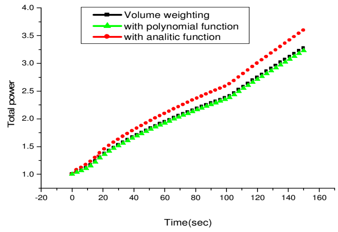


Figure 3 Results of COREDAX Code for modified VVER-440

4. Conclusion

The COREDAX code to be used for regulatory audit calculations has been developed and was tested on various benchmark problems, and it showed that its accuracy is excellent. The initial version of the code has a basic framework to simulate the steady states and transients of the core; in particular, hexagonal geometry core, SMART-P reactor. The COREDAX code will be continuously improved, and be applied to SMART-P core safety analysis in the near future.

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