

RESEARCH ON LOADING PATTERN OPTIMIZATION FOR VVER REACTOR

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Abstract: A study on fuel loading pattern optimization of a VVER reactor was performed. In this study, a core physics simulator was developed based on a multi-group diffusion theory for the use in the problem of fuel loading optimization of VVER reactors. The core simulator could handle the triangular meshes of the core and the computational speed is fast. Verification of the core simulator was confirmed against a benchmark problem of a VVER-1000 reactor. Several optimization methods such as DS, SA, TS and a combination of them were investigated and implemented in coupling with the core simulator. Calculations was performed for optimizing the fuel loading pattern of the core using these methods based on a benchmark core model in comparison with the reference core. Comparison among these methods have shown that a combination of SA+TS is the most effective for

the problem of fuel loading pattern optimization. Advanced methods are being researched continuously.

Keywords: *optimization method, diffusion theory, VVER-1000, SRAC, peaking factor, multiplication factor.*

I. INTRODUCTION

In pressurized water reactor, the fuel reloading is performed annually. In-core fuel management is an important problem of nuclear engineering which involves the optimal arrangement of hundreds of fuel assemblies in the core. The optimal arrangement can be defined as a configuration which has the maximum cycle length or maximum effective multiplication factor (K_{eff}) for the given fuel inventory while satisfying safety constraints such as limitation on power peaking factor. This problem has been considered since the first nuclear reactors were constructed. Recently, there are many programs developed to find out optimal Loading Patterns (LP) of reactor cores. Besides, there are many optimization methods such as Simulated annealing (SA), Genetic Algorithm (GA), Tabu Search (TS), Evolution Algorithms (EA)... are investigated and applied to solve the LP optimization problem.

In this research, a fuel loading pattern optimization code (LPO-V code) is developed to find out optimal LPs for VVER which was one of the candidates for the nuclear power plant in Vietnam. This code is combined by a Static Core Simulator module (SCS) and a Core Optimization Search module (COS). A benchmark problem of VVER is used to verify the code.

II. METHODOLOGIES

2.1. Finite difference method and simulator module

A finite difference method (FDM) proceeds by replacing the derivatives in the differential equations by finite difference approximations. This gives a large algebraic system of equations to be solved in place of the differential equation, something that is easily solved on a computer. In many reactor analysis codes, FDM is used to solve diffusion equation of reactor core to find out K_{eff} , power distribution... Equation (1) is normal form of the diffusion equation.

$$\begin{cases} \frac{dJ_g(x)}{dx} + \Sigma_{rg}(x)\phi_g(x) = Q_g(x) \\ J_g(x) = -D_g(x)\frac{d\phi_g}{dx} \end{cases} \quad (1)$$

Using FDM, equation (1) is transformed to a linear equation system which has matrix form as equation (2):

$$A\Phi = Q \quad (2)$$

In 1D and 2D models, the form of A matrixes is shown in Figure 1, which most of the elements except three or five diagonals are zero.

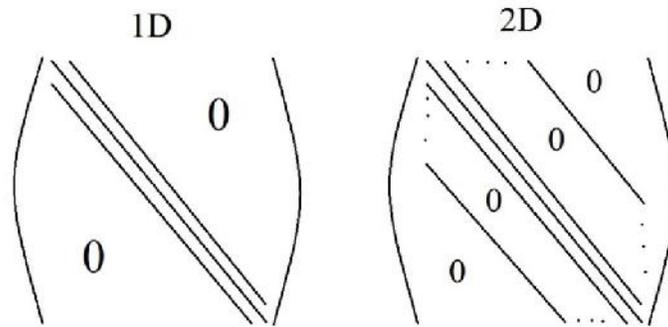


Figure 1: Forms of A matrixes

The simulator module (SCS) was developed based on finite difference method. This module can calculate K_{eff} and Peaking factor of VVER used for LP optimization problem. The accuracy of SCS was verified by comparing with module CITATION of SRAC code [1] and benchmark results (section 3). Besides, the module calculates only K_{eff} and power distribution for triangular model. Therefore, the calculation rate is faster than module CITATION which can calculate 12 geometry types and many neutronic characteristic.

2.2. Hybrid method of Simulated Annealing and Tabu Search methods

The simulated annealing (SA) bases on the simulation of the crystal vibration in annealing metal [2]. When a melting metal is annealed slowly, the energy state of a crystal in the solid metal becomes lower than that of quickly annealed metal. Though the basic concept of SA is the hill climb method which only accepts a better solution than the current one, a probability acceptance of worse solution is allowed to escape from local optima.

The diagram of SA method is shown in Figure 2 and divided into steps as follows:

- (1) Assume an initial LP.
- (2) Execute the core burnup calculation using a core calculation code and evaluate the fitness of LP.
- (3) Generate a candidate LP from the initial (or base) LP by random shuffles of the fuel assemblies. Shuffles of binary or ternary assemblies are performed once, twice or three times.
- (4) Estimate the fitness value of a candidate LP generated through the core burnup calculation.
- (5) When the fitness of a candidate LP is higher than that of the base LP, the candidate LP is adopted as the base LP.
- (6) When the fitness of a candidate LP is lower than that of the base LP, the candidate LP is accepted with a probability of $e^{-C/T}$.
- (7) Repeat the procedures from (3) to (6). The number of repetitions is called the Markov length.
- (8) The system temperature is decreased according to:

$$T^{n+1} = T^n \quad (3)$$

where n represents the number of stages or generations and α is the annealing factor, which is smaller than 1.0. When α is chosen to be closer to 1.0, the system temperature decreases more slowly.

- (9) Return to (3) until the system temperature reaches low enough and the frequency of change in the base LP is less than a certain value.

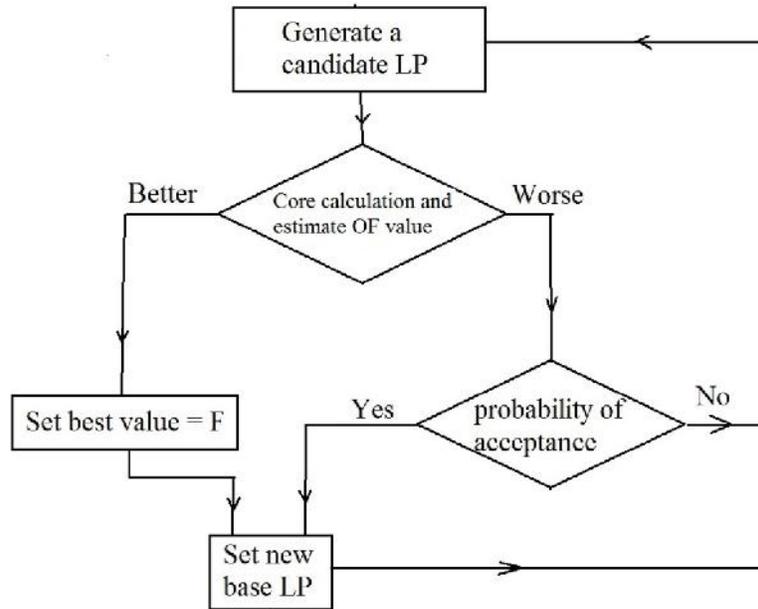


Figure 2: Diagram of SA method

The advantage of SA is escaping local optima ability. Therefore, the solutions can reach global optimum. However, drawback of this method is low efficiency so that many more LPs need to be calculated to reach a given fitness value.

Because of the above reasons, we proposed a hybrid of SA and Tabu Search (TS) method to enhance the efficiency of the original methods. Tabu search method is primarily used for solving combinatorial optimization problems [3]-[5]. The suitable strategies of TS method were combined with SA in the SA+TS hybrid method. These strategies include:

- Tabu list: that is used to store the most recently visited LPs, and these are not allowed to be revisited.
- Neighborhood sub-space: that include all LPs between the two successive acceptances of worse LP. Then the best LP of the neighborhood sub-space is chosen as new base LP.
- Intensification: that is used to more thoroughly explore the search space close to the locations of the best LPs found. When intensification is performed, the search is returned to the best determined LP and search parameters can be adjusted.

The SA+TS hybrid method was used as the main method in COS module. Besides, the original SA and TS also were applied in this module to evaluate and compare the methods.

III. RESULTS AND DISCUSSION

3.1. Loading pattern optimization for VVER code

After SCS and COS modules were developed, they were combined to create a loading pattern optimization for VVER code (LPO-V). This code was programmed by FORTRAN language and its diagram is presented in Figure 3. The LPO-V code can be used to find out optimal LP for reactors which have hexagonal fuel assembly such as VVER reactors and Dalat Nuclear Research Reactor.

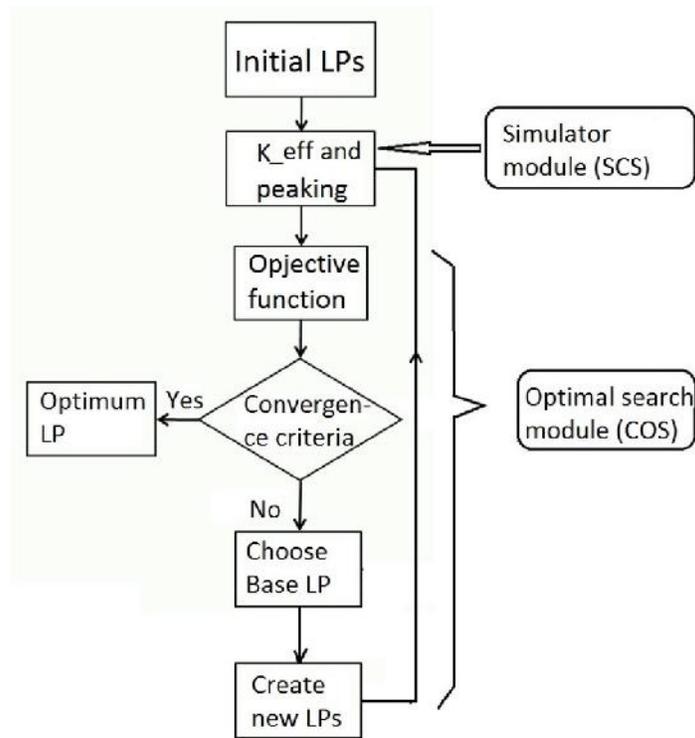


Figure 3: Diagram of LPO-V code

3.2. Benchmark problem and verification of SCS module

A benchmark problem of VVER-1000 [6] was used to verify SCS module. Simultaneously, data of the benchmark problem was used as input for the new LP optimization code. The core is hexagonal symmetry with assemblies shown in Table 1.

Table 1: Fuel assemblies in 1/6 VVER-1000

Type	UOX				MOX			Total
Burnup (MWd/kg)	0	15	32	40	0	17	33	
No. of assembly	5	5	5	3	3	3	3	27

SCS module was applied to calculate 5 states of the VVER-1000 reactor core in the benchmark problem. The comparison of K_{eff} of the core shown a good agreement between SCS results and benchmark results calculated by MCNP-4C (Table 2).

Table 2: Comparison of K_{eff} between SCS and MCNP-4C in the benchmark problem

States	SCS	MCNP4-C	Deviation (pcm)
S1	1.0366	1.0377	-101.77
S2	1.0503	1.0513	-97.86
S3	0.9341	0.9342	-1.07
S4	1.1376	1.1387	-95.41
S5	1.1530	1.1540	-84.56

Besides, a calculation rate test was also performed. SCS module and CITATION (the fastest core calculation module that we have had) were applied to calculate 2000 LPs of VVER-1000 simultaneously and the calculation times were compared (Table 3).

Table 3: Time comparison between SCS and CITATION

Code	Time (second)	
	Cygwin	Ubuntu
CITATION	3190	3177
SCS	501	320
Increase (times)	6.37	9.93

The comparison results show that calculation rate of SCS is faster than CITATION about 6 to 10 times. The reason is SCS only calculate K_{eff} and power distribution for triangular geometry, while CITATION can calculate much more neutronic characteristic for 12 geometry types. Therefore, SCS module is more suitable for optimization problem of VVER.

3.3. Loading pattern optimization for VVER-1000

The data of the benchmark problem was used as input for the LPO-V code to find out new optimal LPs. In this research, some conditions were assumed:

- Calculation for 40 random initial LPs
- The core is hexagonal symmetry
- Objective function:

$$F = K_{eff} - W_p \cdot \max(0, P_{peaking} - C_{peaking}) - W_1 \cdot \max(0, C_{lowest} - P_{lowest}) \quad (4)$$

where: $C_{peaking} = 1.45$: safety margin of peaking factor

$C_{lowest} = 0.42$: margin of lowest relative power distribution factor

$P_{peaking}$: peaking factor

P_{lowest} : lowest relative power distribution factor (lowest factor)

W_p, W_1 : Constant factors

Three methods were applied to find out optimal LP of VVER-1000. The average results of K_{eff} and objective function are shown in table 4. The comparison shows that objective function values of SA+TS hybrid method are largest with equivalent number of calculated LPs. In addition, the standard deviations of the hybrid method are smallest. Therefore, the hybrid method is the most efficiency and stable in the three methods.

Table 4: Optimization results of three methods

	Method	Results				
		n	K_{eff}	peaking factor	Lowest factor	F
=0.85	SA	6160	1.15079	1.440	0.427	1.15079
	TS	5661	1.15314	1.434	0.427	1.15314
	SA+TS	5661	1.15349	1.435	0.425	1.15349
=0.95	SA	18087	1.15411	1.436	0.425	1.15411

	TS	15121	1.15403	1.439	0.424	1.15403
	SA+TS	15119	1.15560	1.437	0.424	1.15560

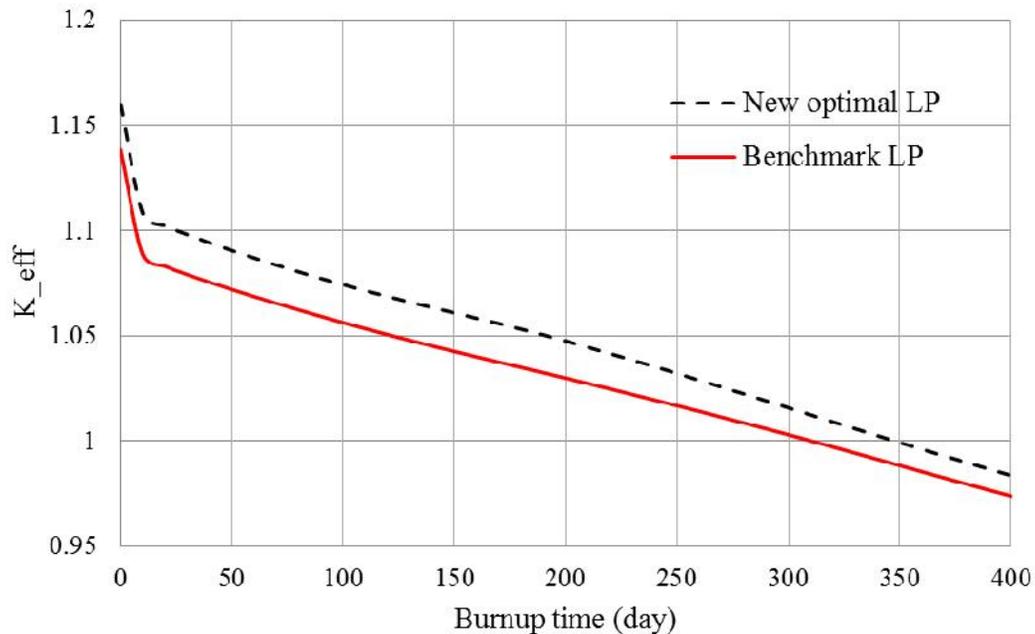


Figure 4: Burnup calculation for the new LP and the benchmark LP

The best new LP found by SA+TS was used to perform burnup calculation and compared with the benchmark LP (Figure 4 and Table 5). The result shows that burnup time of new LP is larger than Benchmark LP about 9.68%. This is a raw comparison because the new optimal LP has been selected based on K_{eff} and peaking factor in beginning of cycle without considering other safety and thermal-hydraulic characteristic. However, this comparison shows the ability of LPO-V code to find out optimal LP for VVER reactor.

Table 5: Comparison of the new LP and Benchmark LP

	Benchmark LP	New LP	Increase (%)
Peaking factor	1.508	1.433	
Lowest factor	0.409	0.422	
K_{eff}	1.139	1.159	1.76
Burnup (day)	310	340	9.68

IV. CONCLUSION

In this research, a LP optimization for VVER (LPO-V) code was developed with two modules: simulator module (SCS) and optimization module (COS). The SCS was verified by a benchmark problem of VVER-1000 and shown a good accuracy and fast calculation rate. Several optimization methods also were applied in COS and SA+TS is the best method.

A Benchmark problem was used to test the LPO-V code. The code can find LPs that value of objective function of these LPs are better than the value of Benchmark LP. A Burnup comparison between the optimal LP and benchmark LP was also performed. The result shown that burnup time of new LP is larger than Benchmark LP about 9.68% while peaking factor of the new LP is lower. Therefore, the efficiency of LPO-V code has been verified.

However, this research also has some drawback such as using simple optimization methods, objective function with only 3 parameters (K_{eff} , peaking factor and lowest factor). Therefore, we plan to investigate modern optimization methods, multi-cycle problem and constructing methods of objective function in the future.

REFERENCES

- [1] Keisuke Okumura, Teruhiko Kugo, Kunio Kaneko, Keichro Tsuchhashi, "SRAC2006: A Comprehensive Neutronics Calculation Code System", Japan Atomic Energy Agency, February 2007.
- [2] A. Yamamoto, "A quantitative comparison of loading pattern optimization methods for in-core fuel management of PWR", Journal of Nucl. Sci. and Technol., 34, 339-347, 1997.
- [3] F. Glover and M. Laguna, "Tabu Search" Modern Heuristic Techniques for Combinatorial Problems, C. R. REEVES, Ed., Blackwell Scientific Publications, Oxford, United Kingdom, 1993.
- [4] C. Lin et al., "Pressurized water reactor loading pattern design using the simple tabu search", Nucl. Sci. Eng. 129, 61-71, 1998.
- [5] J. H. Natasha, T. P. Geoffrey, "Pressurized water reactor in-core nuclear fuel management by tabu search", Annals of Nuclear Energy, 75, 64-71, 2015.
- [6] Eugeny Gomin, Mikhail Kalugin, Dmitry Oleynik, "VVER – 1000 MOX core computation benchmark", OECD, 2006.