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Development of Multi-objective Optimization Program for Reactor Core Design Using Simulated Annealing

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Introduction

- The innovative small modular reactor (iSMR) is designed for soluble boron free and flexible operation in consideration of safety, economy, and flexibility.
- In order to implement the soluble boron free operation, excess reactivity control strategy and shutdown margin must be secured using burnable absorbers and control rods.
- Similarly, to perform the flexible operation, reactivity control strategy according to the power distribution is required.
- In order to satisfy these design requirements, it is important to develop optimized design methods for fuel assembly, fuel loading pattern, control rod program and core control strategy.
- In this study, we present an optimization method developed, inter alia, for the optimal fuel loading pattern layout.

Methods

Optimization Modeling

- Before performing reactor core design optimization, the objective function, design variables and constraints must be defined.
  - Objective function: The object to be found as an optimal value.
    ex) cycle length, peaking factor, burnup of the fuel.
  - Design variable: The variable that affects the value of the objective function and can be controlled.
    ex) layout of the loading pattern.
  - Constraints: The conditions that must be satisfied in the design.
    ex) placing specified fuel assemblies in specific location.

Simulated Annealing

- The simulated annealing is an algorithm inspired by the phenomena of annealing.
  - The internal energy is lowered as the molecular structure finds its optimal arrangement when a metal is slowly cooled from a high to a low temperature.
  - Simulated annealing provides a suitable way for finding the optimal arrangement, such as the layout of the loading patterns.
- The process of the simulation annealing is shown in Fig. 1.
- The probability of accepting to a new state is determined by the formulas.
  - $p = \exp\left(-\frac{\Delta E}{kT}\right);\ \Delta E = E_{new} - E$
  - $r = \text{random}[0,1]$
- If the temperature is low enough, stop and output the solution.
  - If the objective function is superior to the current state, it is accepted.
  - Even if the objective function is poor, it is accepted on the basis of probability.
  - This notion addresses the issue of optimization algorithms becoming stuck in local optima.

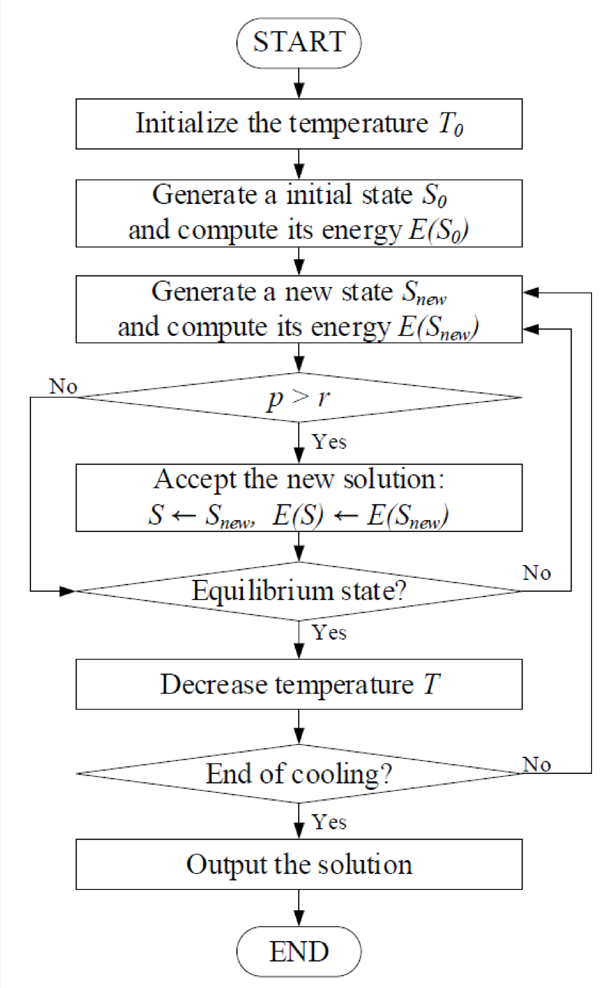

Fig. 1. Simulated annealing process

Multi-objective Optimization

- As a way of comparing multi-objective functions, by giving weights to the objective functions, it is feasible to determine whether the representative value is optimal.
- There is another approach to determining the Pareto frontier.
  - The Pareto frontier is a set of solutions that represents the optimal trade-off between all the objective functions.
  - The Pareto frontier refers to a solution that is not dominated by any other solution in the feasible solution space.

Code Development

- An optimization program was developed by attaching the reactor core analysis code to the input/output file process modules.
  - ASTRA served as the reactor core analysis code.
  - After running the code, the desired objective functions are extracted from the output file and the input file is updated with new design variables.
- Simulated annealing compares the current objective function against the new objective function to determine whether to accept the new objective function.
- Candidates' solutions are compared to determine whether to include them.

Tests & Results

- Peaking factor optimization was performed according to the loading pattern layout.
- Figure 2 depicts the core structure, which is octant symmetrical and measures 9 x 9.
  - The fuel assembly is categorized into five types according to the concentration and number of burnable absorbers; A01, A02, A03, A04, and A05.

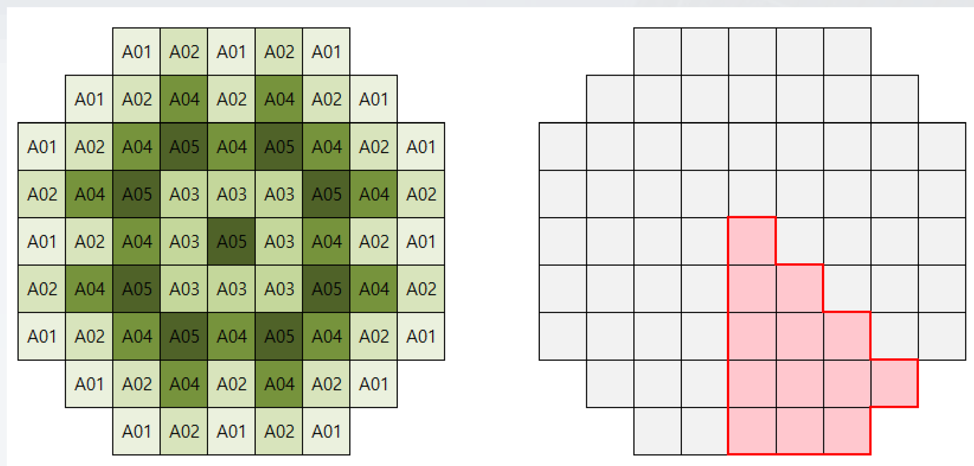

Fig. 2. The core structure and octant symmetry

- When generating a new loading pattern, the positions of two random fuel assemblies are exchanged, or one fuel assembly is randomly replaced with another type.
- The multi-objective functions were based on the Fq (local pin peaking factor) and Fr (radial pin peaking factor) values from the output file that was calculated using the ASTRA code.
- The temperature is updated by multiplying a constant cooling rate, which is 0.95.
- Only the beginning of cycle was calculated.
- To assess the adequacy of the simulated annealing, randomly selected layouts were compared with the computed outcomes.
  - Both simulated annealing and random sampling calculated 10,000 cases.

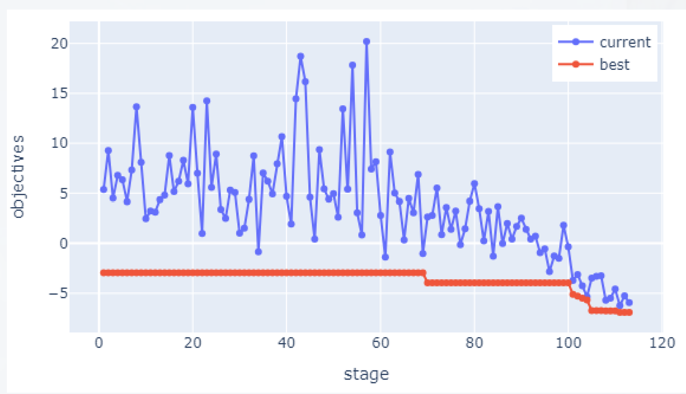

Fig. 3. The objective function graph per stage

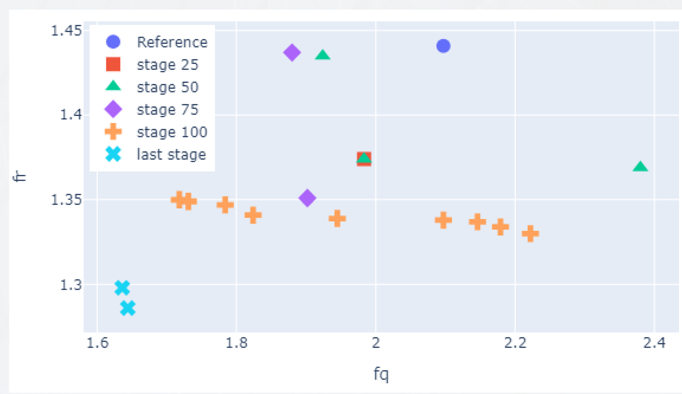

Fig. 4. Optimization candidates per stage

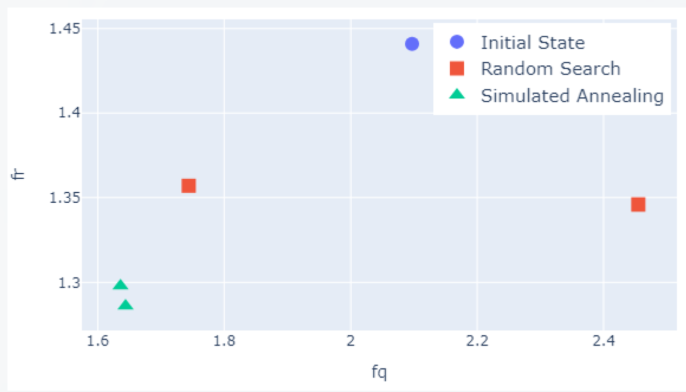

Fig. 5. Candidates for random search and simulated annealing

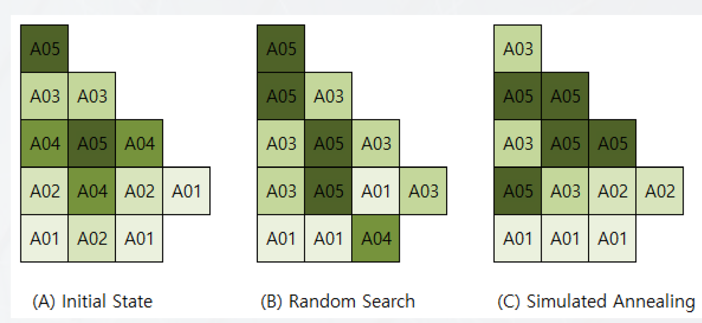

Fig. 6. The optimal loading pattern

Table I: Results of random search and simulated annealing

Objective Function	Initial State	Random Search	Simulated Annealing
Fq	2.097	1.744	1.644
Fr	1.441	1.357	1.286

Conclusions

- Simulated annealing offers effective solutions to combinatorial optimization problems.
- The optimal loading pattern layout obtained in this study may not be an appropriate core design because it only considered peaking factors.
- However, if additional objective functions and constraints are considered, a more optimal solution can be obtained.

Acknowledgements

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