Feasibility Study on Optimization of Fast Reactor for MA Transmutation under Negative Sodium Void Reactivity Conditions By HHO

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1. Introduction

The fuel arrangement of the fast reactor core is optimized to maximum Minor Actinides (MA) transmutation by Haris Hawks Optimization (HHO), a recently developed search algorithm. In order that the fast reactor has inherent safety features, the negative sodium void reactivity is used as the constraint.

2. Calculation conditions

This section describes the calculation conditions of the fast reactor core, HHO's overview, and search parameters used in HHO.

2.1 Core calculation conditions

ERANOS 2.3 [1]. is used for core analysis. The RZ cylindrical coordinate system is used for the core calculation and analysis. The system has three regions, which are the fuel arrangement region, shield region, and sodium plenum region. In this study, a simple core system is used for HHO's feasibility study about core optimization. The fuel arrangement region has 6 cells in the Z direction and 4 cells in the R direction, which means a total of 24 cells. There are 2 kinds of MOX fuels, fuel with MA and fuel without MA. Each fuel has 12 pieces. The fuel with MA contains Am241 as MA. The atomic number densities of the fuel assembly region of the SFR benchmark [2] were homogenized. The compositions of each fuel are shown in Table I. These fuels are arranged in 24 cells of fuel arrangement region. Sodium void reactivity and the amount of MA transmutation depend on the arrangement of these fuels. Therefore, by using HHO for the fuel arrangement of the core, MA transmutation is optimized under negative sodium void reactivity conditions. The shield region and sodium plenum region are fixed in the optimization. One example of the core system is shown in Fig. 1.

Table I: Compositions of each fuel

(a) ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu

	^{235}U	^{238}U	^{238}Pu	^{239}Pu	^{240}Pu
Fuel with MA	0.10	51.58	0.74	10.05	5.47
Fuel without MA	0.13	64.44	0.92	12.55	6.84

(b) ^{241}Pu, ^{242}Pu, ^{241}Am, ^{16}O

	^{241}Pu	^{242}Pu	^{241}Am	^{16}O
Fuel with MA	0.65	1.96	17.62	11.83
Fuel without MA	0.82	2.45		11.85

(unit : wt%)

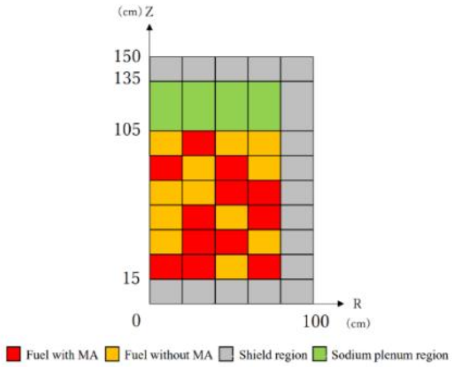

Fig.1. One example of Core system

The number of energy groups is 25, and the flux is calculated by diffusion equation. To calculate sodium void reactivity, effective multiplication factors before and after the sodium voiding are calculated. Under the sodium voided conditions, it is assumed sodium is voided in both of plenum region and fuel region. The objective function is evaluated by

$$F=V*\Phi-10*(n+|n|), \qquad (1)$$

where, V is the volume of fuel with MA expressed in cm^3, Φ is neutron flux in fuel with MA expressed in $cm^{-2}\ s^{-1}$, and n is sodium void reactivity expressed in pcm. Generally, the flux level should be high at the region of fuel with MA to improve the MA transmutation. Therefore, in Eq. (1), when the sodium void reactivity is negative, the objective value is evaluated as the multiplication of flux at fuel with MA by the volume of the region. The MA transmutation is approximately considered in Eq. (1), thus the burnup calculation is not performed in the present study. Also, the function is defined so that the function value significantly falls when sodium void reactivity is positive. In the second term of the right-hand side of Eq. (1), to keep negative sodium void reactivity in the optimization, (n+｜n｜) is multiplied by 10 which is determined by the results of the sensitivity analysis.

2.2 Overview of HHO

HHO is a search algorithm inspired by eagle hunting and consists of 2 exploration phases and 4 exploitation phases [3]. The number of solutions (search agents) can be freely set by user. The advantage of HHO lies in its ease of implementation. Also, compared to other algorithms, HHO has been reported to perform better in optimization of various fields such as engineering, computer science, and medicine [4]. Especially, compared to conventional algorithm such as Genetic Algorithm (GA), HHO has been reported to show significantly better results for high dimensional problems. In this optimization, the dimension of solutions corresponds to the number of cells in fuel arrangement region (24) [5]., so we believe HHO is the efficient for the core optimization because the dimension of this optimization is large.

2.3 HHO's number of solutions and maximum number of iterations

The number of solutions is N, and the maximum number of iterations is T. N and T of each pattern are shown in Table II. The multiplication N with T are shown approximate computational cost of HHO. To gain insight into best setting of N and T, fuel arrangement is optimized by 3 HHO patterns with equal computational cost. 10 optimizations were performed by each pattern.

Table II: N and T of each pattern

pattern	N	T	N×T
1	25	100	2500
2	50	50	2500
3	100	25	2500

3. Results

3.1 Objective function values of optimal solutions

Average objective function values and standard deviations of optimal solutions for each pattern are shown in Fig. 2. Pattern 3 got optimal solutions with poorer objective function value and accuracy compared with pattern 1 and 2. It is possible that patterns 1 and 2 converged within the upper limit of the number of iterations, but pattern 3 didn't converge. In other words, T of pattern 3 may still be insufficient.

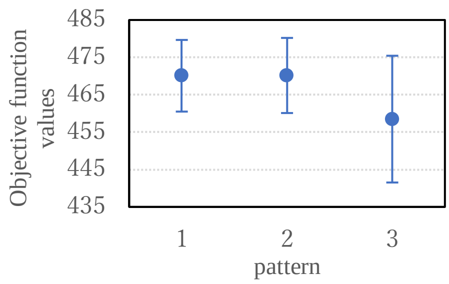

Fig. 2. Average objective function values of optimal solutions for each pattern
(Error bars show standard deviations)

3.2 Best optimal solution

Best optimal solution's sodium void reactivity and objective function value was -45.9 pcm and 480.8, respectively. Fuel arrangement of best optimal solution is shown in Fig. 3. The flux distribution in the Z direction was calculated for core system of best optimal solution (Fig. 4). In fuel arrangement of best optimal solution, fuel without MA tended to be concentrated in the upper part and fuel with MA in the lower part. This tendency shifted neutron flux to the upper part and neutron flux near sodium plenum region was larger. High flux at the upper part leads to the increase in neutron leakage under the sodium voiding.

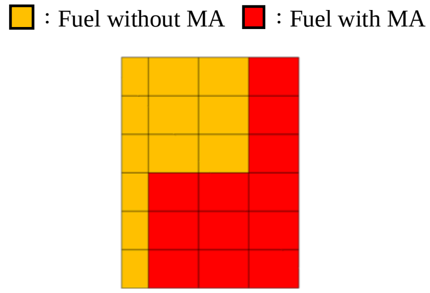

Fig. 3. Fuel arrangement of best optimal solution

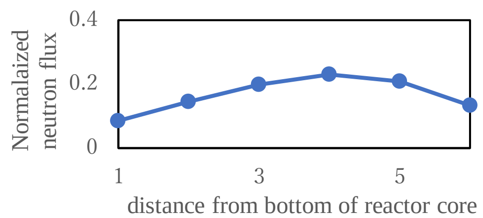

Fig. 4. Normalized neutron flux in the Z direction

4. Conclusions

As a feasibility study, it was confirmed optimization of the fuel arrangement of the core can be performed by HHO. In the present study, the core was optimized by arranging fuel with MA at the lower part and fuel without MA at the upper part.

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