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Work consumption reduction technology of gas centrifuge cascade for HALEU production with Gray Wolf Optimization Algorithm

Seok Jun Oh, Jeong Hwan Park, Jeong Ik Lee*
Nuclear Quantum Engineering department, KAIST, Yuseong-gu, Daejeon, 34141
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

As the interest to nuclear energy is increasing due to its zero-carbon emission, a microreactor is being actively developed. The microreactor is a subset of Small Modular Reactor (SMR) with capacity ranging from 1MWe to 20MWe.

Generally, the concepts of microreactors tend to achieve good transportability. Due to this design goal, the microreactor has advantages to be able to constructed in a small local electrical grid system such as a remote small town or a military base.

There are various models of microreactor design and each of them has different design parameters as shown in Table 1. Many of the concepts require high assay low enriched uranium (HALEU) with 5~20% U_{235} enrichment as fuel. Uranium fuel with higher U_{235} concentration has advantages on improving economy of reactor for longer core refueling period and smaller core size due to higher fuel burnup.

[Table 1. Microreactor data table] [1]

Reactor model	Coolant type	Fuel type	Fuel enrichment
eVinci$_{TM}$	Liquid sodium with heat pipe	TRISO fuel	5~19.75%
Aurora	Liquid sodium with heat pipe	Metallic U-Zr	<20%
Holos generators	Helium or carbon dioxide	TRISO fuel	8~15%
Xe-mobile	Helium	TRISO fuel	<20%
Nuscale	Light water	UO_2	<20%
Sealer	Liquid lead	UO_2 or UN	19.75%
U-battery	Helium	TRISO fuel	<20%
MMR	Helium	FCM or TRISO fuel	19.75%

However, compared to current U_{235} enrichment facilities which produce low enriched uranium (LEU) with U_{235} enrichment less than 5%, the enrichment facility for HALEU production will require more energy for producing the fuel. It means that it requires higher cost to produce HALEU fuel compared to LEU fuel.

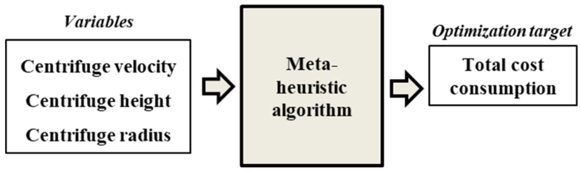
A gas centrifuge cascade is one of the separation methods used for uranium fuel enrichment facility. Compared to other enrichment methods such as gas diffusion, gas centrifuge cascade consumes less energy which means that gas centrifuge cascade can produce enriched uranium with lower cost.

Even though a gas centrifuge cascade consumes less energy than other enrichment methods, it still requires substantial energy consumption when it is used for HALEU production. For more efficient HALEU production, a work consumption optimization of uranium enrichment process is required.

There are many optimization methods for centrifuge cascade optimization and between these methods, the Gray Wolf Optimization Algorithm (GWO) will be used in this study.

2. Theoretical background

In this study, three variables are used to represent characteristics of a gas centrifuge cascade as shown in Fig. 1: rotational velocity of centrifuge, centrifuge radius, and centrifuge height. These parameters determine enrichment product and the total work consumption of centrifuge cascade.



[Fig. 1. Variables and optimization target of system]

The range of these variables for centrifuge cascade is based on data of AC-100 centrifuge, which is one of the biggest gas centrifuges used for uranium enrichment [2]. The range is shown in Table 2.

[Table 2. Range of design variables]

	Range of variables
Centrifuge velocity	0~900m/s
Centrifuge height	0~12m
Centrifuge radius	0~30cm

However, since the gas centrifuge cascade is consisted with multiple stage of centrifuge and these stages affect each other, an optimization problem of centrifuge cascade is very complicated to get exact optimum solution. For such complicated problem, a meta-heuristic algorithm can provide pseudo optimized solution.

The meta-heuristic algorithm is an algorithm that provides a sufficiently good solution with limited computational capacity for complicated engineering optimization problem. Solutions obtained by meta-heuristic algorithm may not be the best solution globally but it is good enough for an engineering problem.

There are many meta-heuristic algorithms and Gray Wolf Optimization Algorithm (GWO) is one of them. GWO is one of the bio-stimulated algorithms that imitates hunting process of pack of gray wolves [3].

GWO is a population-based algorithm which uses multiple number of search agents to search an optimum point which is called the prey in GWO. The basic principle of GWO is based on encircling prey with search agents and closing the encircling line by moving toward the prey slowly as shown in the following equations.

$$\vec{D} = \left|\vec{C}\cdot\vec{X}_p(t) - \vec{X}(t)\right| \cdots (1)$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A}\cdot\vec{D} \cdots (2)$$

where $\vec{X}_p$, $\vec{X}$ and t are position vector of prey, grey wolf and the iteration number.

Equations (1) and (2) show the process that search agents moves from an iteration step t to t+1. The vectors $\vec{A}$ and $\vec{C}$ are expressed as:

$$\vec{A} = 2\vec{a}\cdot\vec{r}_1 - \vec{a} \cdots (3)$$

$$\vec{C} = 2\vec{r}_2 \cdots (4)$$

where the variable $\vec{a}$ decreases linearly from 2 to 0 during iterations and $\vec{r}_1$ and $\vec{r}_2$ are random vectors in the range [0,1].

Between search agents, 3 agents with the best result becomes alpha, beta and delta at every step. In real problem, since the position vector of prey is not a revealed information, equations (1) and (2) cannot be used directly. Instead of using the position vector of prey, positions of alpha, beta and delta wolves are used.

$$\vec{D}_\alpha = \left|\vec{C}_1\cdot\vec{X}_\alpha - \vec{X}(t)\right| \cdots (5)$$

$$\vec{D}_\beta = \left|\vec{C}_2\cdot\vec{X}_\beta - \vec{X}(t)\right| \cdots (6)$$

$$\vec{D}_\delta = \left|\vec{C}_3\cdot\vec{X}_\delta - \vec{X}(t)\right| \cdots (7)$$

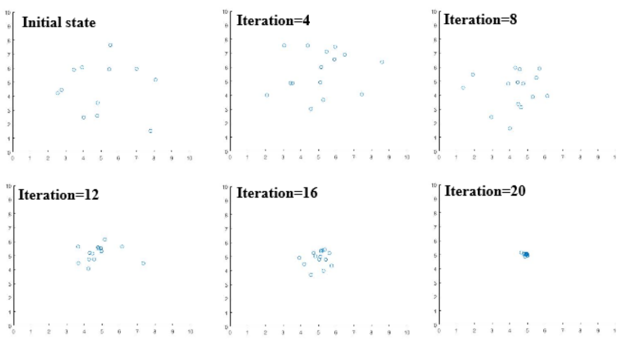
$$\vec{X}_1(t) = \vec{X}_\alpha - \vec{A}_1\cdot\vec{D}_\alpha \cdots (8)$$

$$\vec{X}_2(t) = \vec{X}_\beta - \vec{A}_2\cdot\vec{D}_\beta \cdots (9)$$

$$\vec{X}_3(t) = \vec{X}_\delta - \vec{A}_3\cdot\vec{D}_\delta \cdots (10)$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \cdots (11)$$

where $\vec{X}_\alpha$, $\vec{X}_\beta$, $\vec{X}_\delta$ are positions of alpha, beta and delta wolves.



[Fig. 2. Optimization process example of GWO]

Each search agent determines the next position $\vec{X}(t+1)$ by solving Equations (5) ~ (11) based on positions of alpha, beta and delta wolves. As iteration proceeds, encircling line becomes smaller and finally converges to the guessed position of prey (Fig. 2).

To evaluate the optimized result of each search agent for the determination of alpha, beta and delta wolves, there should be a function, which is called the fitness function. The fitness function is determined by the purpose of optimization. The fitness function represents the variable to be minimized or maximized during the optimization process.

Since GWO is consisted with very simple processes of comparing fitness function of each search agent and determining alpha, beta and delta wolves, iterating process and convergence of GWO is faster than other optimization algorithms. The gas centrifuge cascade is consisted of many variables and the fast optimization of GWO has advantage for the problem.

A physical model for gas centrifuge cascade is described in the previous work [4]. The optimized result with GWO will be compared with the result for centrifuge cascade with uniform velocity distribution through all cascade stages.

Since this study requires several design parameters of reference microreactor such as burnup of uranium fuel and thermal power output which are generally not released publicly, a reactor model with the information has to be selected. 4S reactor developed by Toshiba is therefore selected as the reference reactor in this study since 4S reactor is one of the microreactor models with all of the required data publicly available. The baseline assumption in the reference of 4S reactor for work consumption analysis of centrifuge cascade is shown in Table 3.

[Table 3. Baseline assumption for microreactor] [5]

Parameter	Value
Electric power output	10MW
Thermal efficiency	33%
Core power	$30MW_{th}$
Fuel enrichment	17%
Discharge burnup	34MWd/kgU
Feed flow concentration	0.7%

3. Results

To compare the required centrifuge unit number for both cases, radius and height of centrifuge cylinder of centrifuge cascade with uniform velocity case is fixed to be the same with the optimized result from GWO. All simulations for centrifuge cascade are processed with MATLAB.

From the design parameters of 4S reactor, how much enriched uranium 4S reactor requires can be calculated. For 1year operation of single 4S reactor, 322.06kg of enriched uranium with 17% U_{235} enrichment is required.

The work consumption of centrifuge cascade is used as fitness function of GWO. This means that the optimization algorithm aims to minimize the work consumption of centrifuge cascade.

For the design parameters shown in Table 4, it is shown that the optimized centrifuge cylinder's height is 12m and radius is 0.186m.

[Table 4. Design parameters for centrifuge cylinder before and after optimization]

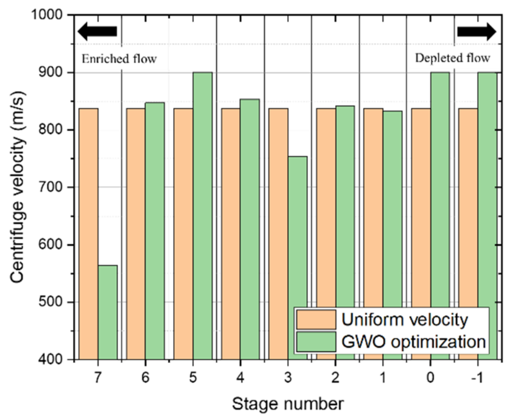
	Cylinder properties
Centrifuge height	12m
Centrifuge radius	0.186m

As shown in the optimization result for both cases (Table 5), centrifuge cascade optimized result with GWO consumes 15.4% less work and requires 43% less centrifuge unit than simple cascade with uniform velocity distribution.

[Table 5. Work consumption and required centrifuge unit number of both cases]

	Simple cascade	**GWO**
Required centrifuge unit number	59	34
Work consumption(kW)	5.704	4.828

The optimized velocity distribution with GWO is shown in Fig. 3.



[Fig. 3. Velocity distribution of optimized centrifuge cascade for both cases]

4. Conclusions

Since the enrichment of HALEU consumes large amount of energy, the optimization of centrifuge cascade to minimize enrichment facility cost consumption is essential to produce HALEU economically. In this study, GWO algorithm is proven to be an effective optimization method for this problem.

Compared to the simple cascade with uniform velocity distribution, the centrifuge cascade optimized with GWO requires 15.4% less work than the simple cascade does. This means that the optimized enrichment facility can produce HALEU fuel with less energy cost.

The optimized centrifuge cascade requires 43% less centrifuge units than the simple cascade case. This further means that by optimizing the centrifuge cascade, the capital cost of enrichment facility can be saved and designing an enrichment facility with smaller footprint is possible.

Even though meta-heuristic algorithms such as GWO are very powerful tool to solve a complicated optimization problem, they have innate limitation that they cannot ensure that the optimum is a local optimum. Thus, to reduce this shortcoming, it is noted that increasing the number of search agents and making multiple attempts of optimization process to obtain better result is required.

Acknowledgements

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