Optimization technology of gas centrifuge cascade with various structures for HALEU production with Gray Wolf Optimization Algorithm

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1. Introduction

Microgrid is a small-scale electrical grid system consisted of interconnected electrical loads and autonomous energy sources. The most defining feature of microgrid is that it can operate separately from currently existing electrical grid which is powered by a large-scale electricity generation facility. Due to the disconnection from the main grid, microgrid shows reduced electricity cost for remote region by negating the necessity of long electric transmission line.

Various energy sources like renewable energy are suggested for microgrid, and nuclear energy produced from a microreactor is one of the candidates.

A microreactor is a subset of Small Modular Reactor (SMR) with the capacity ranging from 1MWe to 20MWe. Generally, the design of microreactor is focused on achieving compact design and transportability. Considering that nuclear reactor has much higher energy density than other energy sources like fossil fuel or renewable energy, a microreactor is advantageous as an energy source for microgrid.

To minimize footprint, numerous microreactor models advertise the use of high assay low enriched uranium (HALEU) as fuel. HALEU is uranium fuel with U_{235} enrichment ranges from 5% to 20%.

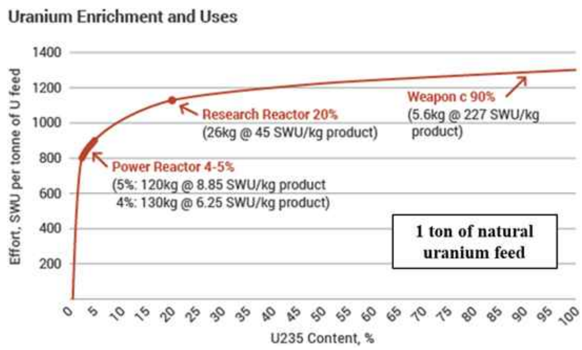


Fig. 1. Uranium fuel enrichment and required SWU

Due to high U_{235} enrichment of HALEU fuel compared to low enriched uranium (LEU) fuel which is generally used as fuel for a large-scale PWR, the production cost of HALEU fuel is much higher than that of LEU fuel (Fig. 1).

There are various elements that affect the enrichment cost of uranium fuel and structure of gas centrifuge cascade is one of the elements. In this study, the authors will study the effect of gas centrifuge cascade structure to the total enrichment cost of HALEU fuel.

2. Theoretical background

The previous work by Migliorini suggested several methods of modifying general centrifuge cascade for efficient uranium enrichment method [1]. One of these methods is inserting bypass line that returns certain ratio of product flow to feed flow line. By returning U_{235} enriched flow to feed flow line, U_{235} enrichment of feed flow can be increased and fuel with higher U_{235} enrichment can be produced. Fig. 2 shows the diagram of gas centrifuge cascade with bypass channel.

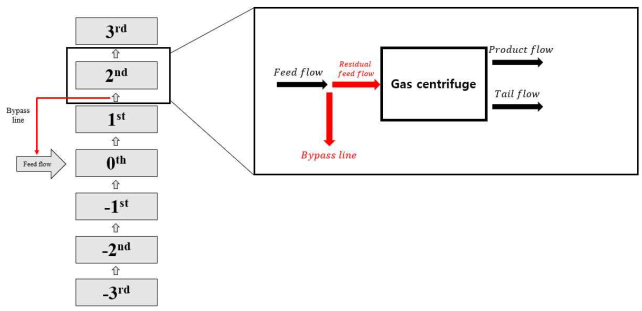


Fig. 2. Diagram of gas centrifuge cascade with bypass channel

A physical model for gas centrifuge cascade and Gray Wolf Optimization (GWO) algorithm for optimizing the gas centrifuge cascade is described in the previous works [2][3]. The primary goal for cascade optimization is the minimization of enrichment cost for HALEU. Considering the objective, it is rational to set the total cost of centrifuge cascade as the fitness value of GWO. To set the total cost of centrifuge cascade as a fitness function, the determination of function between the total cost consumption of gas centrifuge cascade and variables determining the structure of gas centrifuge cascade is needed.

The total cost of enrichment process in gas centrifuge cascade consists of 2 components, capital cost of facility and electricity cost required during operation. Electricity cost is assumed to be 83$/MWh in this study which is a value referred from KEPCO in 2022 [4].

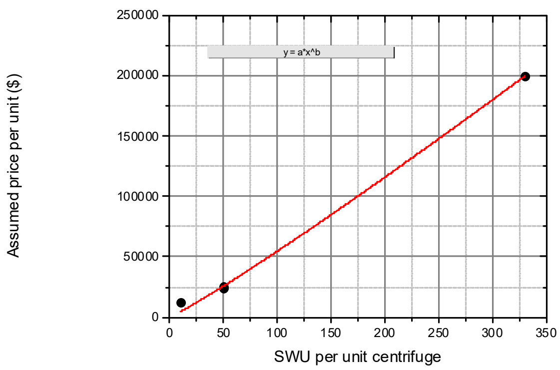
Since the capital cost of gas centrifuge cascade facility can be different depending on various conditions, it is assumed that the capital cost for enrichment facility is the construction cost of gas centrifuge unit while the other capital costs are ignored.

To set the function between the cost of single gas centrifuge unit and centrifuge unit capacity, the capital cost data of currently existing enrichment plants are analyzed. Table 1 shows the capital cost data for 4 currently operating enrichment plant worldwide.

From SWU capacity of a single centrifuge unit and total SWU capacity of enrichment plant, the total number of required centrifuge unit number for each facility can roughly be estimated and the cost for single centrifuge unit can also be estimated. Fig. 3 shows the capital cost of single centrifuge unit from curve fitting the data. Equation (1) shows the relationship between SWU capacity of centrifuge unit and capital cost for single centrifuge unit.

[Table 1. Capital cost and SWU capacity data for enrichment plants] [5]

Enrichment facility	**Total SWU capacity (SWU)**	**Centrifuge unit capacity (SWU)**	**Capital cost (million $)**
American centrifuge plant	3800000	330	2300
Urenco New Enrichment Facility	3000000	50	1500
New George Besse II	7500000	50	3700
Brazilian enrichment plant	203000	10	253



3	751.91	1.55	0.79
2	671.70	1.12	0.65
1	569.06	0.89	0.60
0	481.02	0.77	0.58
-1	481.02	0.67	0.50

[Table 5. Enrichment cost result for each cascade case]

	Uniform velocity	**GWO**	**GWO with bypass**
Cost per fuel ($/kg)	1264.9	929.03	887.75
Cost ratio	1	0.734	0.702

The whole centrifuge cascade is assumed to produce HALEU with 17% U_{235} enrichment which is assuming the same condition with the previous study.

Table 2 and Fig. 4 are the result for centrifuge cascade with uniform velocity throughout the whole stages. Uniform velocity case is used as the reference case before optimization and this is compared to the result with optimization.

Table 3 and Fig. 5 are the result of centrifuge cascade optimized with GWO algorithm. Compared to uniform velocity case, the required number of centrifuge cascade stage increased and rotation velocity of centrifuge cascade decreased.

Table 4 and Fig. 6 are the result of optimized centrifuge cascade with bypass channel. In the optimized case, it is shown that ideal bypass ratio of bypass channel is 18.5% from the product flow of cascade stage 1. Compared to Table 3, the required rotation velocity of centrifuge cascade decreased further.

Table 5 summarizes the result of required enrichment cost per 1kg of enriched uranium fuel for each case. Enrichment cost per 1kg of fuel is calculated by dividing whole cost consumption of enrichment facility with total amount of produced uranium fuel. Centrifuge cascade optimized with GWO requires 929.03$/kg which is 26.6% lower than uniform velocity case. For centrifuge cascade with bypass channel, 887.75$/kg of enrichment cost is required which corresponds to 70.2% of enrichment cost for uniform velocity cost.

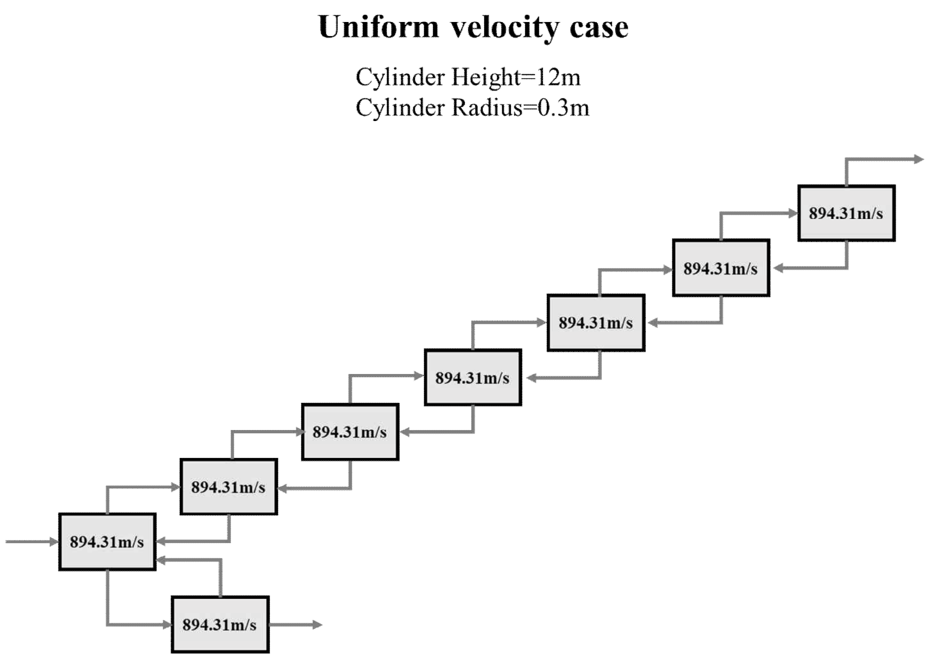


Fig. 4. Result of uniform velocity case

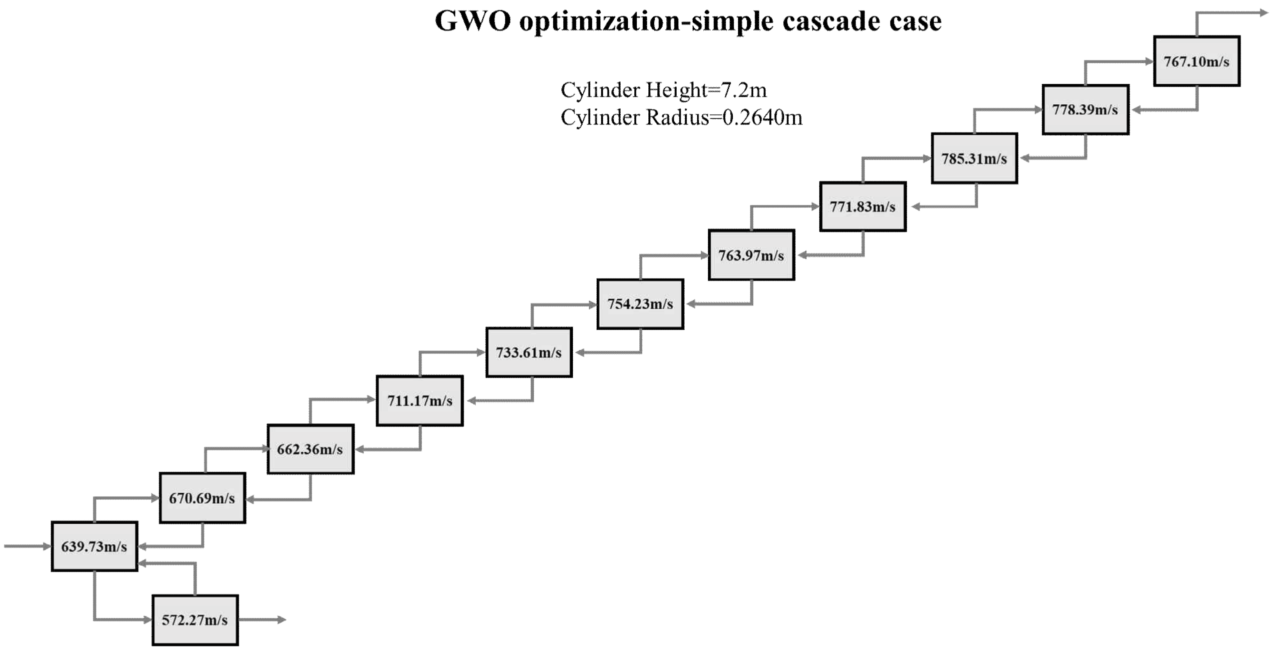


Fig. 5. Optimization result of simple cascade with GWO

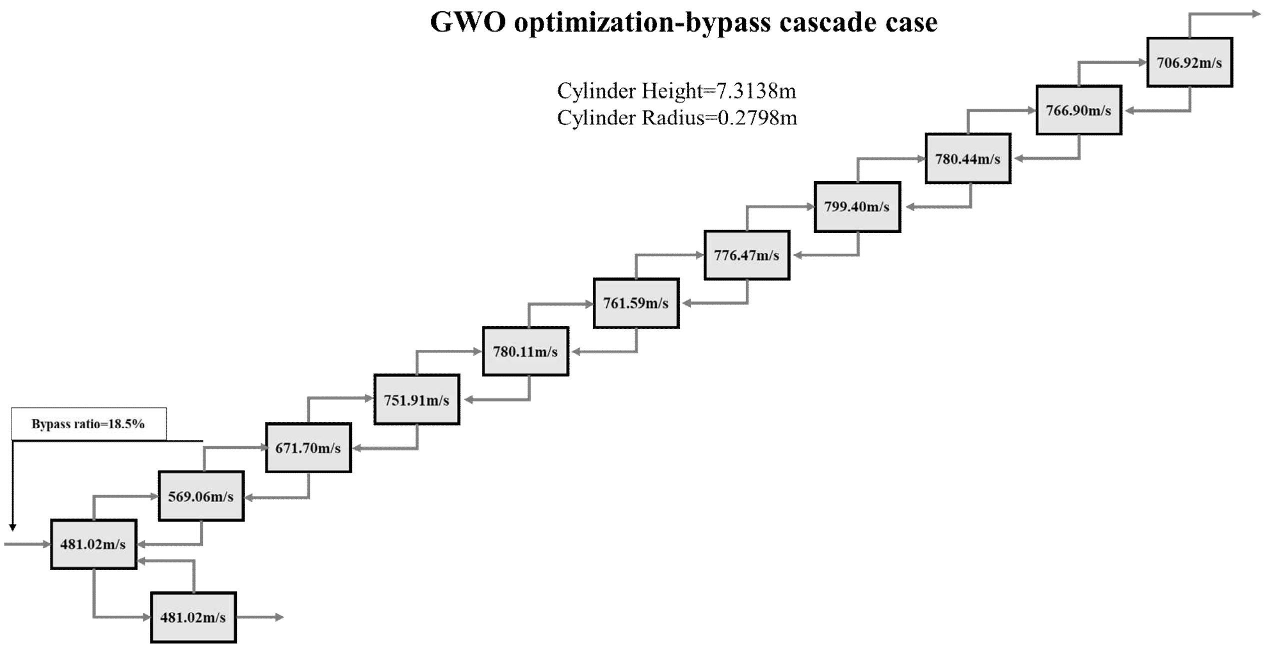


Fig. 6. Optimization result of cascade with bypass installation

4. Conclusions

Due to high U_{235} enrichment of HALEU fuel, production of HALEU requires higher cost consumption compared to LEU fuel currently used in large-scale nuclear reactors. Considering that HALEU fuel is required for many suggested microreactor models, minimization of HALEU fuel production cost is important topic for efficient electricity production of HALEU.

A bypass channel installed on gas centrifuge cascade can increase the U_{235} enrichment of product flow which can be very helpful in production of uranium fuel with high U_{235} enrichment like HALEU. However, as the side effect of bypass channel installation, a certain ratio of product flow is utilized as bypass flow and it results in decrement of final product flow for centrifuge cascade.

The optimized gas centrifuge cascade with GWO requires 929.03$ per 1kg of enriched uranium fuel, which is 26.6% lower than the uniform velocity case. When bypass channel is installed to cascade, the enrichment cost decreases to 887.75$/kg which is lower than the simple cascade optimized with GWO. From these results, the bypass channel installation to centrifuge cascade is beneficial and the positive effect is more pronounced than the negative effect.

Even though this study showed that bypass installation is effective for saving enrichment cost, there can be additional cost resulted from structural complexity of bypass which is not fully considered in this study. Moreover, the cost reduction can be different depending on the conditions and the requirements of enrichment facility. For more detailed analysis, more realistic capital cost model for centrifuge cascade should be developed.

REFERENCES

[1] Patrick James Migliorini, 'Modeling and simulation of gas centrifuge cascades for enhancing the efficiency of IAEA safeguards'

[2] Seok Jun Oh, 'Work consumption reduction technology of gas centrifuge cascade with turbine', Korean Nuclear Society autumn meeting, 2022

[3]Seok Jun Oh, 'Work consumption reduction technology of gas centrifuge cascade for HALEU production with Gray Wolf Optimization Algorithm', Korean Nuclear Society autumn meeting, 2023

[4] KEPCO Electric rates table, Industrial tariff, Available online: https://home.kepco.co.kr/kepco/EN/F/htmlView/ENFBHP00103.do?menuCd=EN060201

[5] S. Dadashzadeh, M. Aghaie, A. Zolfaghari, 'Implementation of Gray Wolf Optimization algorithm to recycled gas centrifuge cascades', Progress in Nuclear Energy, 2021,137,103769