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Application of the Grey Wolf Optimization Algorithm to Separate Middle Components in Multicomponent Mixtures

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ABSTRACT

This paper presents the optimization of a system of square cascades for separating the middle components of xenon. It also presents the optimal use of square cascades in this system. As an example, the separation of ^{130}Xe, an element whose middle isotope is much more complex than any of the other isotopes of xenon, is provided. The Grey Wolf Algorithm is applied for optimization. and the parameters of cascade feed flow rate, cut off the cascade, feed location, feed flow of gas centrifuges (GC), and the cut of the first stage are optimized in such a way that the maximum recovery of the target isotope and the maximum cascade capacity are achieved. Based on the optimization results, the more steps the cascade has, the fewer separation steps are needed for the nine selected cascades with 180 GCs. As a result, both the recovery factor and the amount of product increase.

***Keywords*:** Square Cascade; ^{130}Xe; GWO Optimization Algorithm; Centrifuge; Middle Isotopes

1. Introductions

Stable isotopes have a widespread application in the industry and medical sciences. So, the development of methods for extracting them from natural resources is essential. GC separation is a common method for the separation of stable isotopes. GCs are arranged in a square and taper configuration in separation cascades. In taper cascades, model cascades such as Q, R, and quasi-ideal are used to design the cascade, and the designed cascade can separate only one isotope [1-3]. So, the cascade cannot be applied for other isotopes; to do this; the configuration of cascade needs to be redesigned. Hence, it would be economically viable to have a cascade capable of separating multi-isotopes. Square cascades have this ability. In these cascades, two recycle flows at the two ends of the cascade and control valves between stages enable us to apply different process parameters and separate multi-isotope with the same cascade [4,5]. For separating middle components by square cascades, there is not any theoretical solution; however, optimization techniques can be applied to achieve a high concentration of them [6,7]. In previous studies,

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single-cascade optimization has been alone, and there is only one multi-cascade optimization to achieve high concentrations for middle isotopes [8]. In 2020, Azizov et al. optimized three connected square cascades for separating four stable isotope of tungsten with fixed separation factor[8]. The three cascades are connected in such a way that the light flow of the first cascade enters the second cascades and the heavy flow enters the third cascade. This configuration can be applied only for four specific isotopes of the tungsten element. So, the separation of middle isotopes of the complex mixtures such as Xe still needs further investigation.

In single cascade optimization, Palkin and Rozenbaum introduced the equations that make it possible to implement an analytical method for optimizing parameters of a cascade with optimal separation power and fixed external parameters[9]. In 2002, Palkin et al. applied the Hooke–Jeeves method for optimization of a square cascade. In this cascade, the concentration of the target isotope was specified in the output flows, and the Hooke–Jeeves method optimized the cascade configuration[10]. In 2018, Sulaberidze et al. used variable overall separation factors for optimization and got results for different objective functions based on the genetic algorithm[6]. Their research shows that the total flow is not suitable as an optimization criterion in cascades with variable separation factors. In 2020, Azizov et al. optimized a single square cascade with a specified configuration in order to avoid searching for the initial approximation for the concentration of the components of the separable mixture in outgoing flows[11]. In 2020, Imani et al. optimized a transient square cascade based on the PSO algorithm to achieve the maximum product [12]. In 2021, Dadashzadeh et al. used the GWO algorithm in order to minimize the number of GCs in a taper cascade[13]. Imani and his team used artificial neural networks to improve their square cascades.

In this paper, the aim is to separate the middle isotopes of the xenon element in several separation steps so that a path is determined for isotope separation, and the amount of cascade parameters in each step is in the most optimal condition. For this purpose, ^{130}Xe has been selected to provide the calculations. Separation of this isotope is associated with more complexity because it has a lower natural concentration than its adjacent isotopes [14]. In this method, the optimal path is obtained when, in a period of time and for a number of GCs, the cascade geometry (number of GCs in stages and number of stages) is determined optimally; for this geometry, the process parameters are determined to achieve the maximum amount of product. The objective function is to find the maximum amount of product in a periodperiod. In addition, several constraints apply to this objective function:

1. The final concentration should be equal to the desired concentration.
2. Cascade recovery factor should not be less than a certain value.
3. The value of parameter D in each separation step should not be less than a certain value.

The major difference of this work with the mentioned previous research is the format of the objective function and the number of parameters which is chosen for optimization. Adding the recovery term to the objective function increases the amount of product for the consumption of a specific amount of feed. The parameter D works as a measure for dividing isotopes in the cascades, and it moves the desired isotope into the product flow of each cascade. By simultaneous optimization of cascades in a separation path, the concentration of isotopes between separation steps is calculated automatically and converges to the optimal value. So, the purposed method reduces the amount of information that is needed for design.

Figure 1 illustrates a separation path and a square cascade. In the displayed separation path, the light

flow is collected after exiting from the first cascade and then enters the next cascade. Cascades 1, 2, 3 and 4 are the same, and only their operational parameters differ from each other. The square cascade shows how the control valves are placed among the stages.

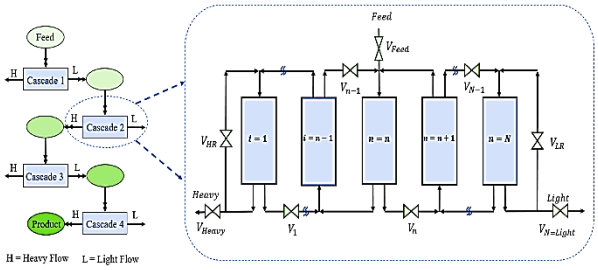


Fig. 1. Schematic diagram of a square cascade and a separation path.

In this study, the separation of middle isotopes of Xe, especially ^{130}Xe has been studied. To determine the best separation path using a square cascade, nine cascades which have the same number of GCs are optimized and compared with each other. Then the best cascade for separation of ^{130}Xe is selected. The concentration distribution is provided for the cascade with the optimal structure and path. In each step, the process parameters, including the cut of the first stage, feed location, feed flow rate, cascade cut and feed flow of GCs and are optimized by the GWO.

2. Research Theories

In square cascades, the number of GCs is the same for the entire stages, and the input flow rate at all stages is the same. The major difference between square cascades to taper ones is recycle-flow in the two ends of the cascade [15]. Simulation of these cascades can be done in two separate parts. First, inter-stage flow rates must be calculated, and second, the concentration distribution of isotopes can be achieved along the cascade. In the first part, the flow rates are obtained from the mass conservation equation at the mixing point and at each stage. In the second part, the concentration distribution of isotopes will be calculated by solving the partial mass conservation equations.

Flow Distribution

In figure 2, the parameters in a square cascade have been shown. The hydraulic parameters of square cascades are divided into external and internal parameters. Cascade waste flow (W), feed flow (F), and product flow (P) are external parameters of the cascade. Light flow of stages are the internal parameters of the cascade.L'_n), the feed flow of stages (L_n), the heavy flow of stages (L''_n), and cut of stages (θ_n) [7], [16], [17].

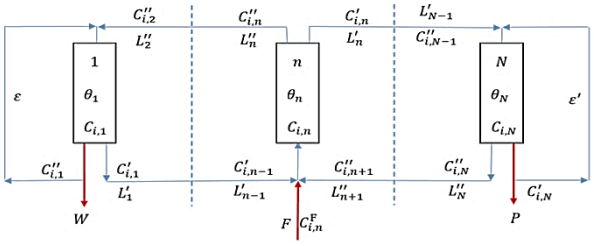


Fig. 2. Flow and concentration parameters in a square cascade.

The following equations can be placed in a linear equations system to achieve the unknown internal parameters (L''_n, L'_n , θ_n).

$$L_n - L'_n - L''_n - P_n - W_n = 0 \quad (1)$$

$$L_n = L'_{n-1} - L''_{n+1} + F_n \quad (2)$$

$$\theta_n = \frac{L'_n}{L_n} \quad (3)$$

$$\theta_{cas} = \frac{P}{F} \quad (4)$$

$$W + \varepsilon = L''_1 \quad (5)$$

$$P + \varepsilon' = L'_N \quad (6)$$

3. Concentration Distribution

The partial mass conservation equation can be written for isotopes in stage *n* as follows [18]:

$$L_n C_{i,n} - (L''_n + W_n) C''_{i,n} - (L'_n + P_n) C'_{i,n} = 0 \quad (7)$$

Similarly, at mixing point, the partial mass conservation equation for isotope *i* is obtained as follows:

$$(L''_{n+1}) C''_{i,n+1} + (L'_{n-1}) C'_{i,n-1} + F_n C^F_{i,n} = L_n C_{i,n} \quad (8)$$

In the above equations, $C'_{i,n}$ is the concentration of isotope *i* in the light flow, and $C''_{i,n}$ is the concentration of isotope *i* in the heavy flow. The separation factor relation is as follows [19]:

$$\frac{C'_{i,n}/C''_{i,n}}{C'_{j,n}/C''_{j,n}} = \alpha_0^{M_j - M_i} \quad (9)$$

In addition, the following limits should be applied in the input and output flow for each stage:

$$\sum_i C''_{i,n} = 1 \qquad \sum_i C'_{i,n} = 1 \qquad \sum_i C_{i,n} = 1 \quad (10)$$

By placing the equation (8) into equation (7), the following equation is obtained:

(11)

$$-L'_{n-1} C'_{i,n-1} + (L'_n + P_n) C'_{i,n} + (L''_n + W_n) C''_{i,n} - L''_{n+1} C''_{i,n+1} = F_c C^F_{i,n}.$$

In Equation (11), F_c equals to zero for every stage except for the stage where cascade feed enters. The equation can be written in a simplified format like below:

(12)

$$-\varphi_{i,n-1} C'_{i,n-1} + \omega_{i,n} C'_{i,n} + \delta_{i,n} C''_{i,n} - \gamma_{i,n+1} C''_{i,n+1} = r_{i,n}$$

To solve the above equation, the q iteration method is used. In this method, the ratio of the concentration of an isotope in the light flow to the concentration of the isotope in the heavy flow is defined as the q parameter [20]:

$$q = C'_i / C''_i \quad (13)$$

By placing this equation to the separation factor equation, the below equation would be obtained:

$$\frac{C'_{i,n}/C''_{i,n}}{C'_{j,n}/C''_{j,n}} = \frac{q_{i,n}}{q_{j,n}} = \alpha_0^{M_j - M_i} \quad (14)$$

$$q_{i,n} = q_{j,n} \alpha_0^{M_j - M_i} \quad (15)$$

Using Equation (15), the concentration $C'_{i,n}$ can be determined:

$$C'_{i,n} = C''_{i,n} q_{i,n} = C''_{i,n} q_{j,n} \alpha_0^{M_j - M_i} \quad (16)$$

By placing the equation (16) to the left side of equation (12), the following relation is obtained:

$$-\varphi_{i,n-1} q_{i,n-1} C''_{i,n-1} + \omega_{i,n} q_{i,n} C''_{i,n} + \delta_{i,n} C''_{i,n} - \gamma_{i,n+1} C''_{i,n+1} = r_{i,n} \quad (17)$$

By solving the above equation for isotopes in each stages, the concentration of all isotopes can be.

Determining the separation path in each step

In the separation of middle isotopes, a high concentration of the middle isotope cannot be achieved in one separation step. For a long cascade, the concentration of isotopes in the output flow of the cascade is constrained to certain values that can be obtained by applying the following equations [21]:

$$C_{P,k}^{max} = \frac{C_{F,k}}{\sum_{i=1}^{k} C_{F,i}} \quad (18)$$

$$C_{W,k}^{max} = \frac{C_{F,k}}{\sum_{i=k}^{N} C_{F,i}} \quad (19)$$

Therefore, these equations can determine which output flows of the cascade (heavy or light) is more appropriate for the separation of the desired isotope. The product flow that can be light or heavy output flow of the first step, according to the above equation, is collected as a feed for the next step, and the same manner can be performed for the next step until the final concentration is reached.

D parameter

In order to separate the middle components, the mixture of isotopes should be divided into two groups so that the desired middle isotope is considered as the end isotope of one of these groups. D parameter is presented as a measure of the separation of two groups of isotopes. The optimal value for this function is one. If the desired isotope is in the heavy group, it is considered as the lightest component in that group, but if it is in the light group, it is considered as the heaviest component in that group. Therefore, if the two groups can be separated from each other, the middle isotope in the light or heavy group is considered as the final isotope. The mathematical expression of the D function is as follows [22, 23]:

$$D = \frac{P}{F}\sum_{i=1}^{target} C'_{i,N} + \frac{W}{F}\sum_{i=target}^{I} C''_{i,1} \qquad (20)$$

When the two groups of light and heavy are completely separated from each other, $D = 1$, in other cases, $D < 1$.

3. Optimization

Objective function

In square cascade, five process parameters, including cascade cut, feed flow rate of the cascade, feed location, the cut of the first stage, and feed flow rate of GCs, are changed in optimization. After determining the separation path and selecting the structural parameters of the cascade, in order to achieve the desired isotope concentration, the cascades in each separation step must be optimized to achieve the set goal. In this type of optimization, all parameters of each cascade are optimized simultaneously. The objective function specified in this article is:

$$OF = \min\left(K_1\frac{W}{\mathrm{F}} + K_2(1 - R_{calc}) + K_3(1 - D) + K_4\left|C_{i,calc} - C_{i,De}\right|\right) \qquad (21)$$

In the objective function, the final concentration C_i and the recovery factor of the cascade, R, are applied as constraints. The *calc* subscript represents the simulation result and the *De* subscript represents the desired value of the parameter. The first term of the OF minimizes the amount of waste production and maximizes the capacity of cascades. The second term optimizes the amount of feed consumption per production of the desired isotope. The third term helps the algorithm that, in each cascade, the desired isotope separates in the selected path. For example, if the parameter D for each step is the maximum amount in each cascade, the desired isotope is collected in the right output flow and the last term works as a limit, which helps the concentration of desired isotope converge to the designed ones. In the objective function, the fixed values of K_1 and K_3 are equal to 10, K_2 is equal to 1000, and K_4 is equal to 10000. These values are considered as a weighted coefficient in order to make the objective function terms in to a same order of magnitude. The cascade recovery factor is calculated according to the following equation:

$$R = \frac{Product\ concentration\ of\ target * Product\ (gr)}{Feed\ concentration\ of\ target * Feed\ (gr)} \qquad (22)$$

The amount of product and total mass consumption of the separation path can be easily calculated. The amount of total operation time of each cascade is equal to a one year, so the sum of operation time of

each cascade is equal to one year. Each cascade has the same operation time.

$$OT = \frac{M}{Feed} \tag{23}$$

Where OT is operation time, and M is consumed feed mass. For a separation path that have three steps (light, heavy, light), the amount of total mass consumption (M_1) in one year is calculated as follows:

$$\begin{aligned} one\ year &= OT_1 + OT_2 + OT_3 \\ &= \frac{M_1}{Feed_1} + \frac{M_2}{Feed_2} \\ &\quad + \frac{M_3}{Feed_3} \end{aligned} \tag{24}$$

$$M_2 = M_1 * \theta_{cas\,1}$$
$$M_3 = M_2 * (1 - \theta_{cas\,2})$$

In the above equation, θ_{cas} is the cut of the cascade which is obtained from optimization, and the separation path determines how the M_2 and M_3 calculate from M_1. When the amount of M_1 is determined, it would be easy to calculate the amount of product.

Grey Wolf Algorithm

The Grey Wolf is a meta-heuristic algorithm that imitates the hunting of grey wolves [24]. The details of this algorithm are beyond this paper and detail can be found in [4,24]. This algorithm generates a random population of wolves (answers). For example, in a separation path with three steps, every cascade has five parameters that can be optimized, and 15 parameters will be created randomly. These values are between a maximum and minimum, which is defined by the user. For example, the three-step separation has random parameters:

$$\begin{aligned} T = [&NF_1 \quad Feed_1 \quad \theta 1_1 \quad SF_1 \quad \theta_{cas\,1} \quad NF_2 \quad \\ &Feed_2 \quad \theta 1_2 \quad SF_2 \quad \theta_{cas\,2} \quad NF_3 \quad Feed_3 \quad \theta 1_3 \quad SF_3 \quad \theta_{cas\,3}] \end{aligned} \tag{25}$$

In the above vector, *Feed* is the input feed flow rate, *NF* is the feed location, *SF* is the feed flow rate of GCs, $\theta 1$ is the cut of the first stage and θ_{cas} is the cascade cut. Figure 3 shows the GWO algorithm. In the algorithm shown in the blue square, the square cascade simulation is performed.

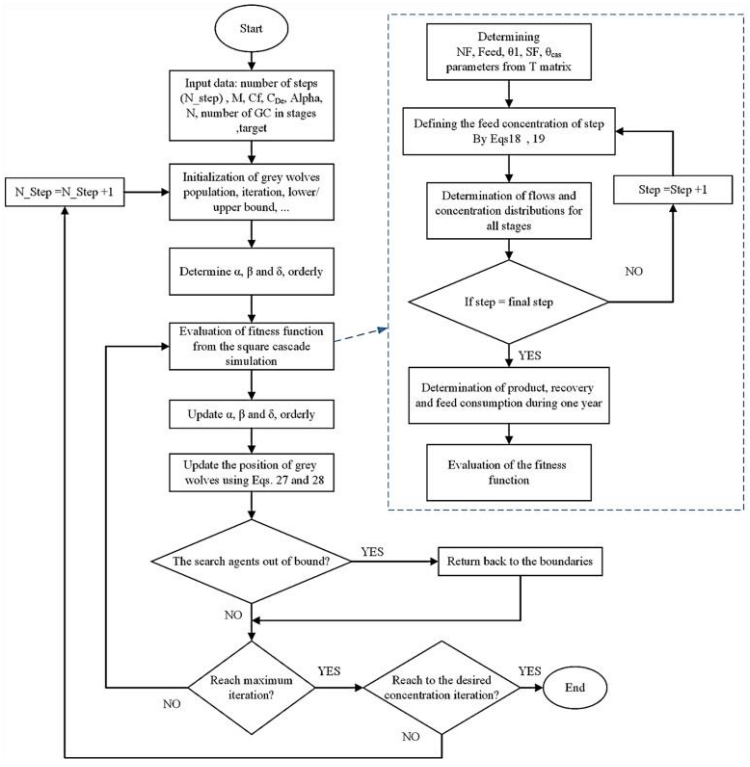


Fig. 3. Grey wolf optimization algorithm.

5. Results and Discussion

Comparison the results of GWO with other optimization algorithms

To confirm the validity of the proposed code, the results are compared with the values reported in [25]. In addition, the results are compared with other optimization algorithms such as HS, DA, SCA, ALO, and SSA [26–30]. In the introduced optimization problem, by varying the feed flow of GCs in each stage and inter-stage cuts, the goal is to achieve the minimum number of GCs. The other cascade parameters are presented in Table 1. By setting the objective function and performing optimization, Figure 4 represents the average of 10 runs for each optimization algorithm. As seen, the GWO algorithm has a minimum objective function value among other algorithms. It also has a minimum convergence rate to the other algorithms.

In table 2, the result of the best GWO run is compared with the result of Palkin. It can be seen that the results are very close together, and the GWO improved the ultimate result by 1%. Because of the excellent results of GWO, the GWO can be used as a suitable method for designing the square cascade.

Table 1. The parameters for optimization in [25].

Unit separation factor	$\exp(1+\theta-\theta^2-\ln(f))\text{^}(1/3)$		
Parameter	Feed	Product	Waste
flow, gr/sec	15.9	2.1	13.8
Concentration,%			
^{235}U	0.85	4.4	0.3
^{234}U	0.016	0.099	0.003
^{232}U	1.5e-7	1.1e-7	7.7e-9
^{236}U	0.35	1.29	0.2
^{238}U	98.784	94.211	99.497

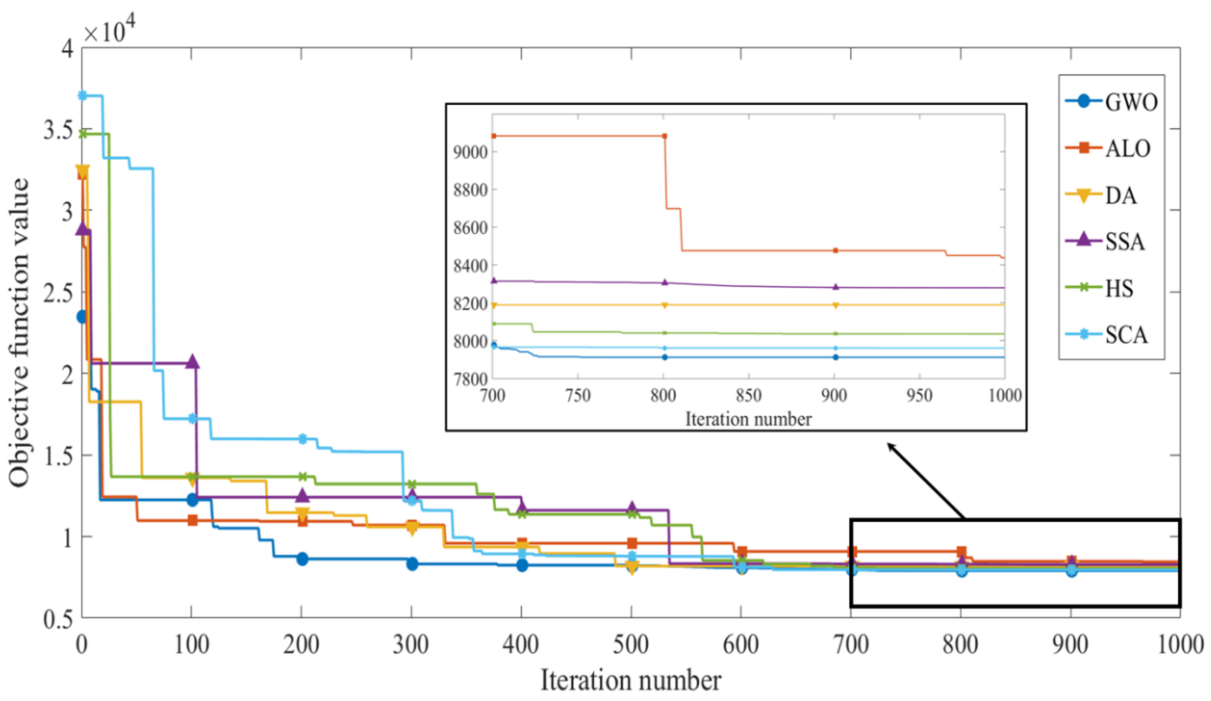


Fig. 4. Objective function vs. iteration numbers for different optimization algorithms.

6. Optimization results for separation of middle isotopes

In this paper, to show how the middle isotopes of the xenon element are separated, the middle isotope of ^{130}Xe was selected. The optimum concentration for this isotope considered 80%. Table 3 shows the natural feed composition of xenon isotopes. Assuming that the number of centrifuges is 180, different paths to achieve the desired enrichment over a year were examined.

The number of GCs is considered between conventional cascade; this number has many divisors, and it is possible to create nine different square cascades with the same number of GCs. So, it provides many options for comparison. To perform the design, the specifications of the GC were required. In this paper, the separation factor of the GC is a function of the feed flow under Figure 5. The minimum limit of flow rate to the GC is 2.5 and the maximum limit of flow rate to the GC is 20 mg/s.

Table 2. Comparison of the optimal parameters for between GWO and Palkin (N represents the number of GC in each stage and f is GC feed flow rate).

Step No.	N,10^3 (Palkin)	N, 10^3 (GWO)	f, mg/sec (Palkin)	f, mg/sec (GWO)	(Palkin)θ	(GWO)θ
1	0.4	0.365	64.3	68.62	0.47	0.4546
2	0.7	0.594	67.7	73.01	0.46	0.4223
3	0.94	0.849	69.5	73.53	0.46	0.4877
4	1.14	1.057	70.6	72.06	0.46	0.4211
5	1.29	1.231	71.8	70.70	0.46	0.4742
6	1.01	1.013	73.2	72.95	0.46	0.4702
7	0.78	0.850	73.8	72.00	0.45	0.4667
8	0.6	0.672	74.2	68.23	0.46	0.4225
9	0.44	0.479	74.6	69.94	0.46	0.4842
10	0.32	0.358	75.1	72.17	0.46	0.4545
11	0.21	0.239	75.9	69.67	0.46	0.4207
12	0.13	0.134	77.4	72.13	0.46	0.4907
13	0.06	0.072	80.5	65.61	0.47	0.4438
Sum	8.02	7.912				

Table 3. Natural feed concentration of xenon gas.

Xe 124	Xe 126	Xe 128	Xe 129	Xe 130	Xe 131	Xe 132	Xe 134	Xe 136
0.00095	0.00089	0.01910	0.26401	0.04071	0.21232	0.26909	0.10436	0.08857

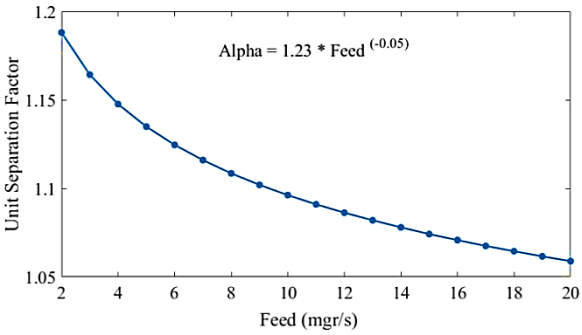


Fig. 5. Variation of separation factor in terms of inlet gas flow to centrifuge.

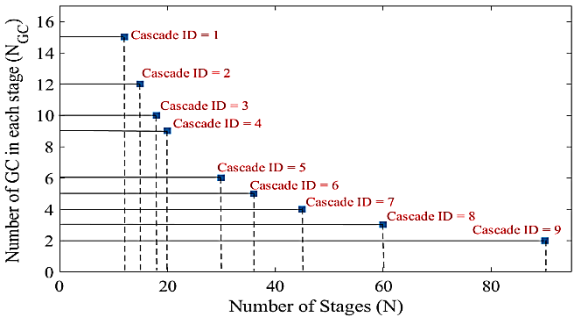


Fig. 6. Different scenarios of square cascades with 180 centrifuges.

Given that the number of centrifuges is 180, different scenarios of square cascades with this number of GCs are shown in Figure 6.

Therefore, by examining these nine cascades, the best number of stages can be selected. For this purpose, the separation path and the concentration of desired isotope in the product were presented by performing optimization according to Tables 4 and 5. The results showed that the fewer number of cascade stages for the same number of centrifuges, the more separation steps were required to reach 80% concentration. According to Table 5, the separation path was obtained for all nine cascades. Separation is done once through the light flow and in the next step from the heavy flow.

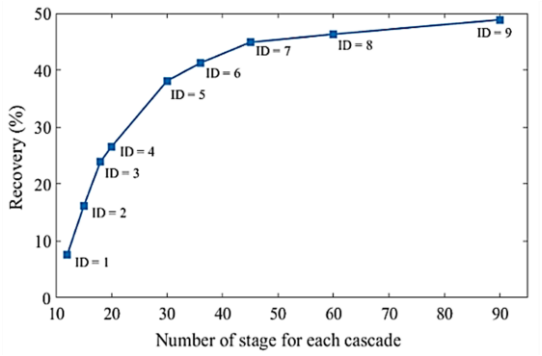
^{130}Xe isotope is in the light group in one step (light group of xenon isotopes 124, 126, 128, 129 and 130) and is separated by light flow. Because in this group, ^{130}Xe is the heaviest isotope, in the next step, separation was done through heavy flow.

Table 4. ^{130}Xe isotope concentration per step for nin3 square cascades.

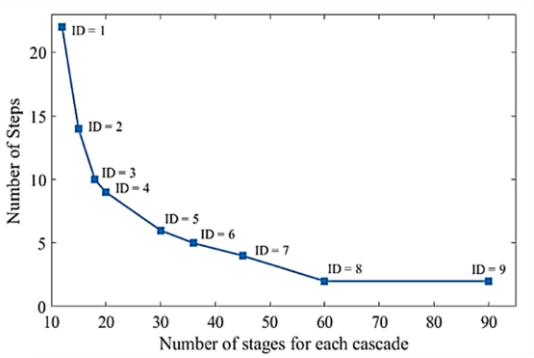
Step	Product concentration of desired isotope in different steps								
	ID = 1	ID = 2	ID = 3	ID = 4	ID = 5	ID = 6	ID = 7	ID = 8	ID = 9
1	0.0745	0.0822	0.0887	0.0924	0.1049	0.1087	0.1115	0.1131	0.1137
2	0.0910	0.1140	0.1458	0.1754	0.3792	0.5268	0.6920	0.8000	0.8000
3	0.1119	0.1412	0.1850	0.2299	0.5381	0.7174	0.8021		-
4	0.1363	0.1966	0.2914	0.3664	0.7126	0.8025	-		-
5	0.1552	0.2297	0.3574	0.4628	0.8052	-	-		-
6	0.1874	0.3093	0.4728	0.5913	-	-	-		-
7	0.2070	0.3581	0.5639	0.6895	-	-	-		-
8	0.2515	0.4412	0.6602	0.7730	-	-	-		-
9	0.2753	0.5052	0.7340	0.8051	-	-	-		-
10	0.3292	0.5797	0.8000	-	-	-	-		-
11	0.3593	0.6424	-	-	-	-	-		-
12	0.4155	0.7019	-	-	-	-	-		-
13	0.4513	0.7521	-	-	-	-	-		-
14	0.5045	0.8000	-	-	-	-	-		-
15	0.5430	-	-	-	-	-	-		-
16	0.5904	-	-	-	-	-	-		-
17	0.6281	-	-	-	-	-	-		-
18	0.6694	-	-	-	-	-	-		-
19	0.7034	-	-	-	-	-	-		-
20	0.7398	-	-	-	-	-	-		-
21	0.7691	-	-	-	-	-	-		-
22	0.8000	-	-	-	-	-	-		-

Table 5. ^{130}Xe isotope separation path for nine square cascades.

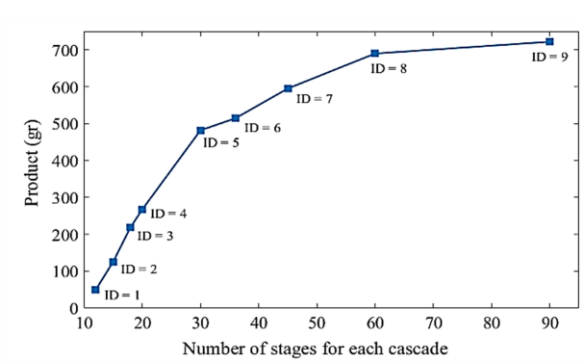
Step	Product flow in different steps (L: Light flow, H: Heavy flow)								
	ID = 1	ID = 2	ID = 3	ID = 4	ID = 5	ID = 6	ID = 7	ID = 8	ID = 9
1	L	L	L	L	L	L	L	L	L
2	H	H	H	H	H	H	H	H	H
3	L	L	L	L	L	L	L		-
4	H	H	H	H	H	H	-		-
5	L	L	L	L	L	-	-		-
6	H	H	H	H	-	-	-		-
7	L	L	L	L	-	-	-		-
8	H	H	H	H	-	-	-		-
9	L	L	L	L	-	-	-		-
10	H	H	H	-	-	-	-		-
11	L	L	-	-	-	-	-		-
12	H	H	-	-	-	-	-		-
13	L	L	-	-	-	-	-		-
14	H	H	-	-	-	-	-		-
15	L	-	-	-	-	-	-		-
16	H	-	-	-	-	-	-		-
17	L	-	-	-	-	-	-		-
18	H	-	-	-	-	-	-		-
19	L	-	-	-	-	-	-		-
20	H	-	-	-	-	-	-		-
21	L	-	-	-	-	-	-		-
22	H	-	-	-	-	-	-		-



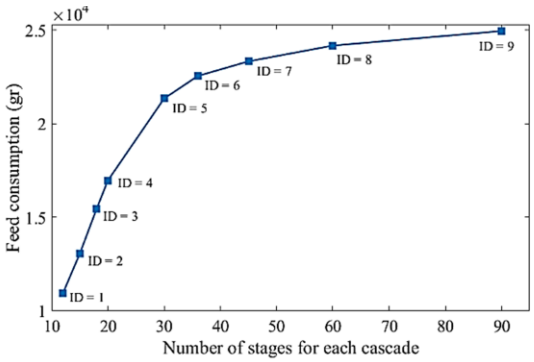
A. Recovery factor variation according to the number of stages.



B. Number of separation steps according to the number of stages.



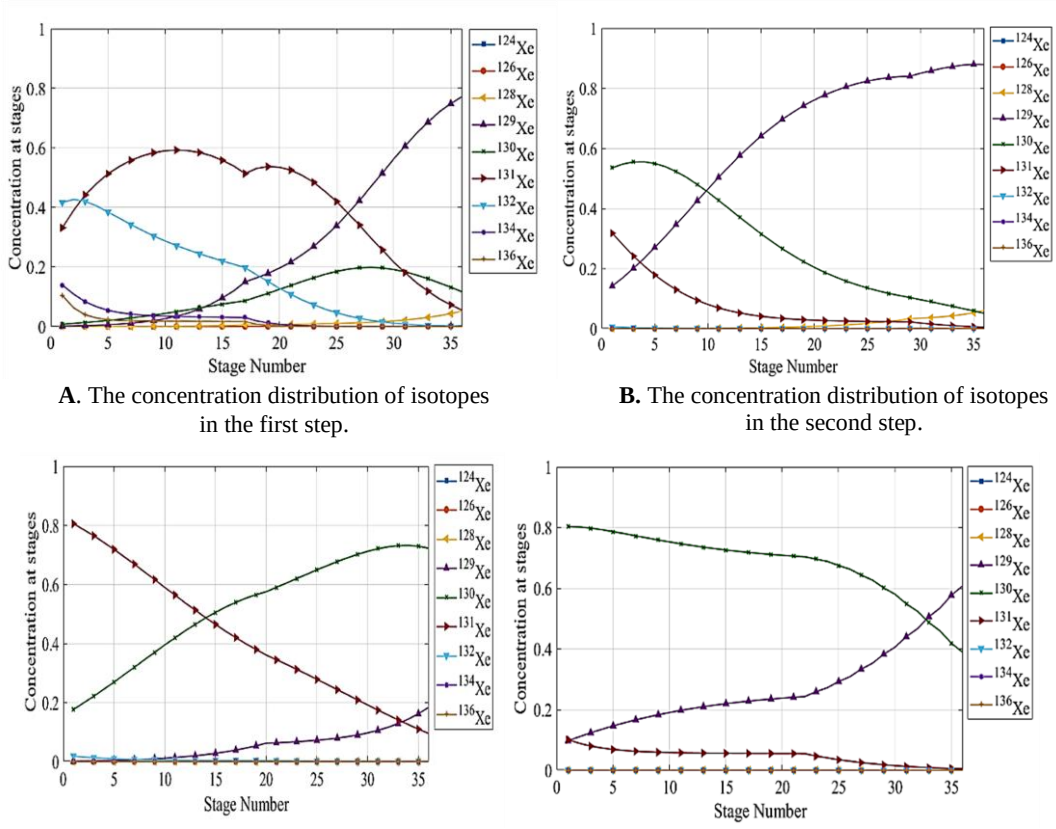
C. The amount of product according to the number of stages.



D. The amount of consumed feed according to the number of stages.

Fig. 7. Variations of the recovery factor, separation steps, feed consumption and product according to the number of stages.

Figure 7 shows the amount of recovery factor, the amount of product, feed consumption and the number of separation steps in proportion to the number of stages of the nine selected cascades. As shown in Figure 7b, as the number of stages increases, the number of separation steps to reach the desired concentration decreases, which increases the recovery factor. Also, it is clear in Figure 7c that the amount of product increases with the number of stages over the one-year period. As shown in Figure 7a, doubling the number of stages from 45 to 90 increases the recovery factor by only 5%. The effect of increasing the stages decreases gradually. The 90- and 60-stage cascades have far more operational risk than the 45-stage cascade. For example, when a GC crashes in a 90-stage cascade, there will be only one active GC in that stage, and the cascade deviates from the design mode. There is a possibility that another GC will crash at that stage. Therefore, among the 60, 90, 45, 30 and 36 cascade options, a 36-stage cascade is selected. Figure 8 shows the concentration of isotopes along cascades at distinct steps. As seen, in the first step of the separation of ^{130}Xe, the concentration of adjacent isotopes, ^{131}Xe, ^{132}Xe and ^{129}Xe increases as well. Most of the ^{129}Xe and ^{130}Xe are in light side, and most of the ^{131}Xe and ^{132}Xe is in the heavy side. In the second step, ^{129}Xe increases in the light side which is the waste flow and removes from the desired composition. Similarly, in the third step, ^{131}Xe increases in the heavy side and be removed from the desired composition. By removing the adjacent isotopes, ^{130}Xe reach to the desired concentration at the fourth step.



A. The concentration distribution of isotopes in the first step.

B. The concentration distribution of isotopes in the second step.

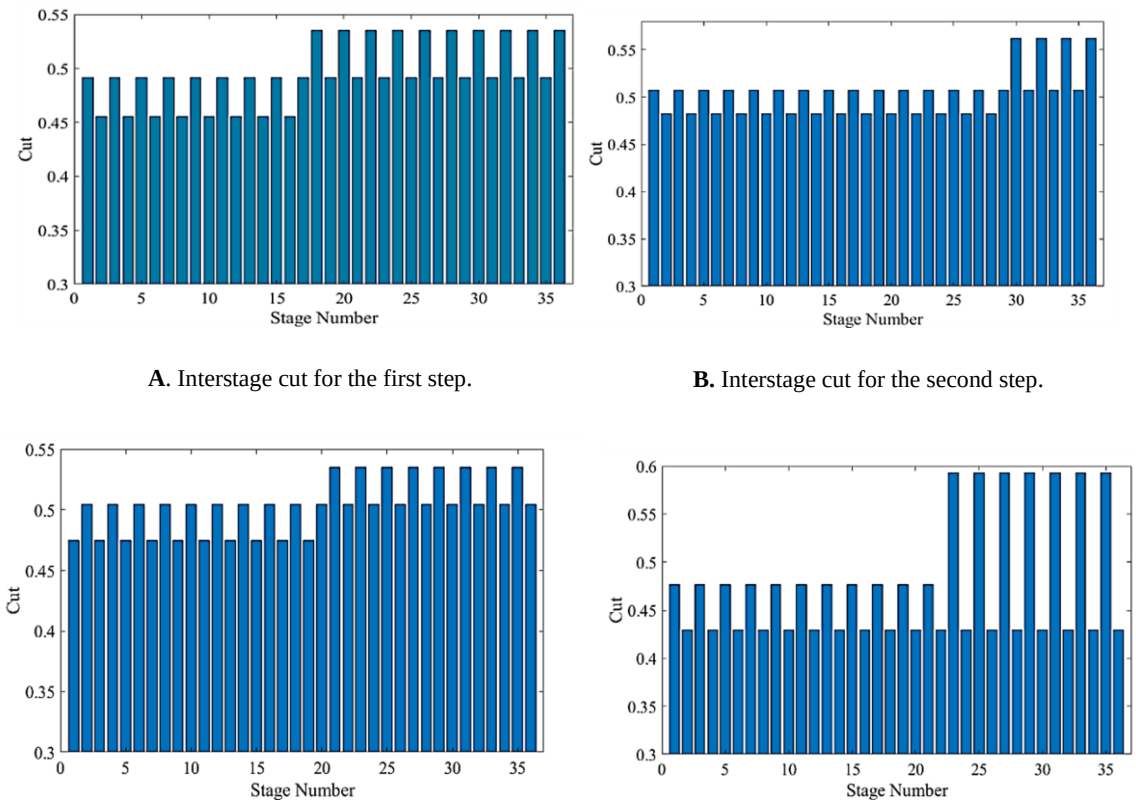
C. The concentration distribution of isotopes in the third step.

D. The concentration distribution of isotopes in the fourth step.

Fig. 8. Concentration distribution for a 36-step cascade during separation steps.

Figure 9 shows the changes in the inter-stage cut of the cascades in different steps. In fact, the output of the cascade design is the inter-stage cuts, and in the operation these cuts lead us to our desired concentration. To apply these cuts to the cascade, the control valves and pressure functions of the centrifuge can operate the cascade. These inter-stage cuts are between 0.4 to 0.6 which is an operational range for most of GCs. So, it can be concluded that these cascades are operational.

Table 6 presents the characteristics of an optimized 36-step cascade.



A. Interstage cut for the first step.

B. Interstage cut for the second step.

C. Interstage cut for the third step.

D. Interstage cut for the fourth step.

Fig. 9. Interstage cut changes for a 36-step cascade during that separation steps.

Table 6. Process characteristics of 36 optimized square cascades.

Step	NF	Feed (mg/s)	$\boldsymbol{\theta_1}$	$\boldsymbol{SF}$ **(mg/s)**	$\boldsymbol{\theta_{cas}}$
1	17	1.00	0.491	2.5	0.337
2	29	1.00	0.507	2.5	0.871
3	20	1.00	0.474	3.3	0.654
4	22	1.54	0.477	2.6	0.195

Conclusion

To provide a method for separation of the intermediate isotopes of the xenon element, 130Xe enrichment was presented as an intermediate isotope using a square cascade. At each separation step, the cascade process parameters, including the cascade cut, cascade feed flow rate, feed location, feed flow of stages, and cut of the first stage, were optimized by the Grey Wolf algorithm. According to the results, with increasing the number of stages, fewer separation steps were required to reach the desired concentration, and with decreasing the number of separation steps, in a certain period, the amount of product also increased. As the number of stages increased, the recovery factor increased as well. The amount of increase in the recovery factor did not follow the linear rate as the number of stages increased such that by doubling the number of stages, the recovery factor increased by only 5%. The separation path for all square cascades was one step from light flow and in the next step was from heavy flow. Finally, a 36-stage cascade was selected to separate ^{130}Xe. Using this cascade, ^{130}Xe reached 80% concentration in four steps. The recovery factor of this cascade is 41%, and in one year, by consuming 22 kg of natural xenon gas, 514 g of the xenon gas with 80% enrichment of ^{130}Xe isotope was obtained.

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