Economic estimation of boron isotope production by gas diffusion method using BF$_3$ as processing gas

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Abstract. Natural occurring boron has two stable isotopes: boron-10 and boron-11. Boron-10 has high thermal neutron cross section in a wide range of energy and the product of boron-10’s neutron reaction contains alpha particles. So, it is a good material for neutron absorbing and neutron detecting. In order to enrich boron-10 from natural boron, several methods had been proven to be feasible: chemical exchange distillation, cryogenic distillation and ion exchange resin method. The market now places higher demands on the economics of the separation method, so study on production of boron-10 by gas diffusion method is carried out. Using BF$_3$ as processing gas, it is feasible to enrich high abundance of boron-10 by gas diffusion. The single stage separation effect and the hydraulic status of single stage was estimated. Binary gas diffusion cascades were designed and compared. Under given production requirements, the scale of the cascade was estimated and optimized. Finally, step cascade was picked for the production of 96% boron-10. Based on the cascade design, economic estimation of this separation method was conducted, and the target product cost was calculated. This study laid a good foundation for the expansion of boron isotope separation methods.

1. Introduction

Natural occurring boron has two stable isotopes: boron-10 and boron-11. The natural abundance of boron 10 is about 19.8%, and the natural abundance of boron 11 is about 80.2%. The thermal neutron cross section of boron 10 is 3837 barn, and the thermal neutron cross section of boron 11 is less than 0.1 barn[1]. Besides, the reaction between boron-10 and neutron has two main features which make it an important material in many fields. First, the cross section is high over a wide range of energy, unlike other isotopes that have significant absorbing resonance in a narrow energy range. Secondly, the reaction product contains alpha particles and does not contain gamma rays, so the products of the reaction are all ionizing radiation, which is easy to detect and easy to block[2]. Due to these features, boron-10 is widely used in nuclear reactors, radio-protection, neutron therapy, and neutron detector[3].

In order to enrich boron-10 from natural boron, several methods have been proven to be feasible: chemical exchange distillation, cryogenic distillation and ion exchange resin method. However, only chemical exchange distillation was applied to industrial production. The market now places higher demands on the economics of the separation method. The annual demand for enriched boron-10 as neutron shielder is nearly 250 kg/y and the annual demand as neutron...
detector is 15 kg/y in 2007[4]. The demand is increasing with time and add up to nearly 1000 kg/y now.

Preliminary experiment was carried out using CO₂ as processing gas and organic membrane made segregator in our lab. With suitable flow rate and pressure ratio, good stage separation effect was observed, and the efficiency of separating carbon isotopes by gas diffusion method was proved[5]. These experiments illustrate that gas diffusion method is a promising method for separating light isotopes. Considering the market’s higher demands on the economics of boron isotope separation, it maybe a good idea to bring gas diffusion method into the production of boron isotopes. So the feasibility of enriching boron-10 by gas diffusion method using BF₃ as processing gas is discussed and the economic estimation is made in this study.

2. Single Separator Status and Cascade Design
In order to estimate the economics of the method, suitable processing gas should be selected and single separator status should be analyzed. Then, cascade design is calculated and optimized.

2.1. Processing Gas Selection
BF₃ is chosen as the processing gas for separating boron isotope for its chemical and physical properties. BF₃ behaves as gas at normal temperature, and the saturated vapor pressure is relatively high. Besides, it is a common chemical raw material which is cheap and the chemical synthesis and conversion is easy and efficient[6]. From the perspective of gas separation, BF₃ has two kind of molecules with different molar mass, which makes the separation binary gas diffusion. Besides, the molar mass is nearly 68, which is not very high and leads to relatively large separation factor.

2.2. Single Separator Status
In order to study the separation of light isotopes by diffusion method, a preliminary experiment was carried out using CO₂ as processing gas to separate ¹³C from natural carbon[5]. The device is shown in Figure 1. Using tubular separator and multilayer organic membrane, good separation factor was obtained under certain flow and pressure conditions. According to the law of gas diffusion[7], the separation factor efficiency and hydraulic status of boron separation can be derived from carbon separation.

![Figure 1. Schematic diagram of membrane separation device](image)

The inlet pressure, pre-membrane outlet pressure and the after-membrane pressure are estimated at 10000 Pa, 8000 Pa and 2000 Pa according to the previous experiment. Under these conditions, the separation efficiency is estimated at 0.5. The effective enrichment factor can be calculated by Equation 1 and 2.
\[ \alpha - 1 = E \cdot (\alpha_0 - 1) = E_B \cdot E_M \cdot E_S (\alpha_0 - 1) \]  \hspace{1cm} (1)

\[ \varepsilon = \alpha - 1 = 0.0037 \]  \hspace{1cm} (2)

2.3. Cascade Design and Optimization

After the single separator status is estimated, cascade can be designed to get the final product. Square cascade is used to estimate the price because it is simple and representative. Given the product requirements and the single stage separation effect, the number of stages \( N \) and the flow of each stage \( G \) can be calculated. With \( G \), the number of parallel separators required for each stage, as well as the volume flow and power of the compressors can be calculated.

The yield of our cascade is set to occupy 1/5 of the global market share, which is 200 kg/y. To obtain 200 kg \(^{10}\)B products with abundance of 96% each year, optimization is made to minimize the total flow \( NG \). The design goals are shown in Table 1.

| Parameter | Value |
|-----------|-------|
| \( C_F \) | 0.2 |
| \( C_P \) | 0.96 |
| \( C_W \) | 0.15 |
| \( P^{(10)B} \) | 200 kg/y |

Table 1. Design Goals of the Cascade

The total flow \( NG \) calculated as a function of stage flow \( G \) is shown in Figure 2.

Table 2. Optimized results of the Cascade

| Parameter \( G^{(10)B} \) | Value |
|--------------------------|-------|
| \( N_F \) | 954 stages |
| \( N_W \) | 102 stages |
| \( F^{(10)B} \) | 370 g/h |

As is shown in Figure 2, the total flow has minimum value, so optimized solution can be gotten from the calculation. The result of optimization is shown in Table 2. The abundance curve of the optimized cascade is shown in Figure 3.

Figure 2. Total flow \( NG \) calculated as a function of stage flow \( G \)
3. Economic Estimation

Based on the cascade calculation and single stage status, the cost of separation can be estimated. The component of enrichment cost consists mainly of four parts, depreciation of equipment, electricity cost, raw materials and maintenance cost.

3.1. Depreciation Cost

In order to calculate the depreciation expense of the equipment, it is necessary to calculate the total investment of the equipment. The initial investment mainly contains three parts, compressors, separators and auxiliary equipment.

The estimated stage flow $G$ is 35,500 grams of $^{10}$B per hour, which means the volume flow of the compressor is $29 \text{ m}^3/\text{min} \text{ BF}_3$. The compression ratio is estimated at 2. Based on previous study on magnetic bearing compressor and market research, high speed centrifugal compressor can meet demands, and the market price of the compressor is nearly 100,000 CNY per stage.

Calculated by processing gas, the stage flow is 240,000 grams of BF$_3$ per hour. In our previous experiment, the flow of one tube with nearly 0.0002 m$^3$ membrane is around 100 g/h. Therefore, the separator used for actual production should be larger in size and one stage should include multiple separators in parallel. Assuming each tube can provide flow of 1000 g/h and each separator consists of 10 tubes, each stage in the cascade will need 24 separators. Because the separation membrane is very cheap, the main cost of the separator is mainly used for sealed separator. The separator price can be estimated at 100,000 CNY per stage.

The auxiliary equipment cost can be estimated at 25% of the total investment. So, the total amount of initial investment $I_{total}$ can be calculated by Equation 3.

$$I_{total} = I_{comp} + I_{sep} + I_{aux} = N_{total} \frac{C_{comp} + C_{sep}}{1 - r_{aux}}$$  \hspace{1cm} (3)

The depreciation cost $S_{dep}$ can be calculated by Equation 4, where $r_{res}$ is the residual value rate of the fixed assets. $L$ is the estimated useful life.

$$S_{dep} = I_{total} \frac{1 - r_{res}}{L}$$  \hspace{1cm} (4)
3.2. Electricity Cost
Electricity cost is one of the main costs of producing boron isotope. The main energy consumption is spent on compressors. The compressors convert electrical energy into mechanical energy of compressed gas. As is known, the stage volume flow is 29 m$^3$/min and the compression ratio is 2. The compressor takes mixed gas of 2000 Pa and 8000 Pa in and turn it into 10000 Pa of compressed gas. The power of one compressor can be calculated by Equation 5[8].

$$P_w = \frac{1}{\eta_{motor} \cdot \eta_{comp}} \cdot p_{inlet} \cdot Q \cdot ln \frac{p_{outlet}}{p_{inlet}}$$  \hspace{1cm} (5)

In this equation, $\eta_{comp}$ is the efficiency of compressor and $\eta_{motor}$ is the efficiency of the electrical motor. $Q$ is the volume flow and $p_{inlet}$ and $p_{outlet}$ is the pressure of the flow through the compressor. With $P_w$ and electricity price $E_p$, the electricity fee $S_{elec}$ can be calculated by Equation 6. $T$ here is the total working time.

$$S_{elec} = P_w \cdot T \cdot E_p$$  \hspace{1cm} (6)

3.3. Raw Material Cost and Maintenance Cost
The material cost mainly consists of BF$_3$ supply into the cascade. Converting the $^{10}$B flow $F$($^{10}$B) into BF$_3$ flow and multiplying the unit price $M_p$, the raw material cost $S_{raw}$ is calculated by Equation 7.

$$S_{raw} = F \cdot T \cdot M_p$$  \hspace{1cm} (7)

The maintenance of the equipment is necessary for the separators and the compressors. The cost $S_{maint}$ is calculated by Equation 8, where $r_{maint}$ is the maintenance ratio and the $I_{total}$ is the total equipment investment.

$$S_{maint} = r_{maint} \cdot I_{total}$$  \hspace{1cm} (8)

3.4. Unit Enrichment Cost
Taking all the above factors into consideration, unit enrichment cost can be calculated by Equation 9.

$$C_{product} = \frac{S_{dep} + S_{elec} + S_{raw} + S_{maint}}{P}$$ \hspace{1cm} (9)

| Table 3. Related Parameter Estimates |
|-------------------------------------|
| Parameter                         | Symbol | Value            |
|-----------------------------------|--------|-----------------|
| Electricity Price                 | $E_p$  | 0.78 CNY/kWh    |
| BF$_3$ Price                      | $M_p$  | 200,000 CNY/t   |
| Membrane Price                    | /      | 3 CNY/m$^3$     |
| Life Span                         | $L$    | 20 years        |
| Motor Efficiency                  | $\eta_{motor}$ | 0.8           |
| Compress Efficiency               | $\eta_{comp}$ | 0.6            |
| Residual rate                     | $r_{res}$ | 5%             |
| Maintenance rate                  | $r_{maint}$ | 1%            |
| Auxiliary rate                    | $r_{aux}$ | 25%            |
The parameters in Table 3 is based on actual conditions. With these parameters, the enrichment cost can be estimated by Equation 9 at 228 CNY per gram of $^{10}$B, which is 33 USD per gram of $^{10}$B.

As is shown in Figure 4, the cost of electricity is relatively large in the production process. The equipment depreciation accounts for about 1/3 of the total cost.

| Product   | Abundance | Price     |
|-----------|-----------|-----------|
| $^{10}$B$_4$C | >96%      | 14.5 USD/g |
| $^{10}$B   | >96%      | 45 USD/g   |
| H$_3^{10}$BO$_3$ | 96%       | 50 CNY/g   |
| H$_3^{10}$BO$_3$ | 99%       | 279 CNY/g  |

In comparison to the market price in Table 4, the enrichment cost of gas diffusion method is a bit lower than the market price of $^{10}$B, which is nearly 300 CNY/g, but taking chemical conversion price and other cost into consideration, the final price may be a little higher than the market price.

Several improvements can be applied to cut costs in the following research. First of all, the form of the cascade can be optimized using step cascade to reduce the total flow. Then, processing gas with higher boron proportion can be tried, which may make the separating progress more efficient.
4. Conclusion
In this work, the single separator and cascade status are determined to separate $^{10}$B by gas diffusion method. Based on the calculation, the enrichment cost is estimated at a relatively reasonable level, which shows that gas diffusion is a promising method in separating boron isotope. Further verification and optimization are to be continued to finally implement this method. This study laid a good foundation for the expansion of boron isotope separation methods.

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