Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

CO_2 separation technology utilizing uranium centrifuge enrichment technique

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1. Introduction

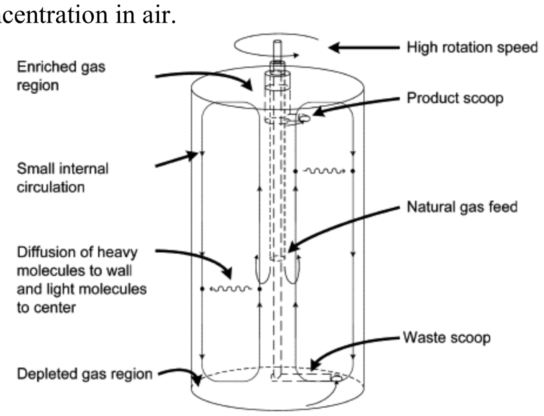
Recently, the demand for energy storage system has been growing in the energy industry. In order to cope with the varying power demand over time, it is inevitable to improve the load following capability of nuclear power plants. Since changing power of reactor core frequently is not encouraged, load following operation utilizing external energy storage system can be an alternative solution.

Liquid Air Energy Storage (LAES) is an energy storage system that is gaining attention recently. During the charging process of LAES, ambient air from atmosphere enters LAES cycle and air is liquefied. During the liquefaction process, freezing of CO_2 can cause problem because of its high sublimation temperature. To resolve this problem, CO_2 should be separated from air before liquefaction process.

To separate CO_2 from air, the authors propose using a gas centrifuge technique in this paper. Gas centrifuge technology is one of the technologies that have been commonly used for uranium enrichment process. Based on accumulated theoretical background of gas centrifuge technology, the authors are going to analyze CO_2 separation process using gas centrifuge.

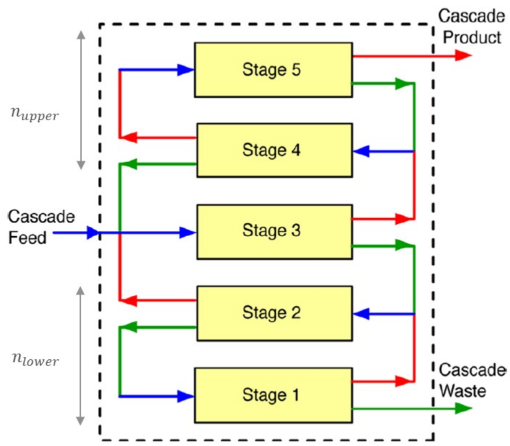
2. Theoretical background

Gas centrifuge is used in material separation by using mass difference of each elements composing mixture. Since molecular mass difference of CO_2 and air is much bigger than that of U_{235} and U_{238}, required energy consumption can be minimized during decreasing CO_2 concentration in air.



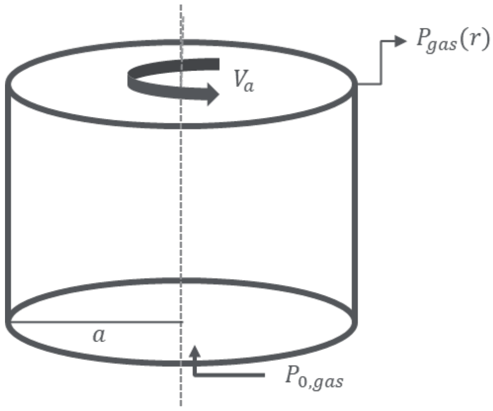
[Fig 1. Schematic diagram of gas centrifuge]

To achieve low CO_2 concentration, single centrifuge stage is not sufficient. Uranium enrichment facility using gas centrifuge has a structure of multiple layer which is called centrifuge cascade structure.



[Fig 2. Centrifuge cascades structure] [1]

Each centrifuge cascade stage separates feed flow into product flow with higher concentration of target material and tail flow with lower concentration of target material. Product flow proceeds to upper stage of centrifuge cascade and tail flow proceed to lower stage.



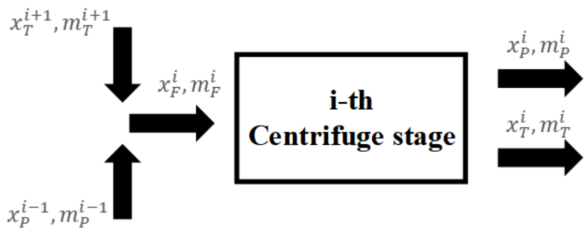
[Fig 3. Partial pressure diagram of gas centrifuge]

Partial pressure of gas in gaseous mixture is proportional to the ratio of molar concentration of gas components. By calculating the partial pressure distribution of product flow, we can get the ratio of concentration for each components in gas mixture.

$$P_{gas}(r) = P_{0,gas} \exp\left(\frac{M_{gas} V_a^2}{2RT}\left(\frac{r}{a}\right)^2\right) \quad \ldots [1]$$

$$x_{gas_k} = \frac{P_{gas_k}}{\sum P_{gas_i}} = x_{product_k} \cdots [2]$$

From equations [1] and [2], partial pressure ratio and molar concentration distribution of gas centrifuge product flow can be obtained.



[Fig 4. i-th centrifuge cascade stage diagram]

Product flow from lower cascade stage and tail flow from upper cascade stage compose feed flow of a centrifuge cascade stage.

$$M_{F,i}x_{F,i} = M_{P,i}x_{P,i} + M_{T,i}x_{T,i} \cdots [3]$$

$$M_{F,i} = M_{P,i} + M_{T,i} \cdots [4]$$

$$M_{T,i} = \frac{x_{F,i} - x_{P,i}}{x_{T,i} - x_{P,i}} M_{F,i} \cdots [5]$$

$$x_{T,i} = \frac{k}{1+k} \quad where\ k = \frac{\left(\frac{x_{F,i}}{1-x_{F,i}}\right)^2}{\left(\frac{x_{P,i}}{1-x_{P,i}}\right)} \cdots [6]$$

Mass flow rate distribution of each cascade stage can be calculated from the obtained concentration data. From equation [5], tail flow rate of cascade stage can be calculated from feed mass flow rate. Considering mass conversion of each centrifuge stage, sum of product mass flow rate and tail mass flow rate is equal to the feed mass flow rate.

$$SWU_{max} = \frac{\pi \rho D}{2}\left(\frac{\Delta M V_a^2}{2RT}\right)^2 H \quad (SWU\ per\ year) \cdots [7]\ [2]$$

H: Centrifuge height (m) D: Diffusion coefficient
ρ: Density (kg/m^3) R: Ideal gas constant
T: Temperature (K) ΔM: Mass difference between materials (g/mol)

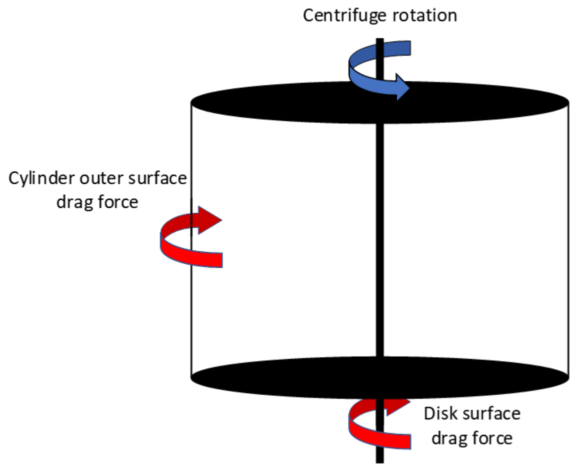
$$m_T = SWU\left(\left(\frac{x_F - x_T}{x_P - x_T}\right)v_P + v_T - \left(\frac{x_P - x_T}{x_P - x_F}\right)v_F\right)^{-1} \cdots [8]$$

$$m_F = m_T\frac{x_P - x_T}{x_P - x_F} \cdots [9]$$

$$v_i = (2x_i - 1)\ln\left(\frac{x_i}{1-x_i}\right) \cdots [10]$$

To calculate the required work for whole centrifuge cascade, the amount of mass flow rate that single gas centrifuge unit can process should be considered. Mass flow rate of single gas centrifuge can be calculated from separation work unit (SWU) of centrifuge. SWU is the amount of separation done by an enrichment process. SWU of certain centrifuge unit can be calculated by equation [7]. With calculated SWU, feed flow rate of unit centrifuge can be calculated from equations [8] and [9].

When the total feed mass flow rate is divided into unit centrifuge feed mass flow rate, the number of centrifuges required to process certain mass flow rate can be calculated.



[Fig 5. Centrifuge friction diagram]

$$Friction\ loss\ on\ horizontal\ disc\ surface\ P_{disc} = \frac{2}{5}c_f \rho w^3 \pi R^5$$
$\cdots$ [11] [3]

$$Friction\ loss\ on\ vertical\ cylinder\ surface\ P_{disc} = c_f \rho w^3 \pi H R^4$$
$\cdots$ [12] [3]

As centrifuge cylinder rotates, friction force works on the outside of the centrifuge cylinder. Friction force acts on the two parts of cylinder; disk surface friction force and outer surface friction force. Equations for friction forces are shown in equations [11] and [12], respectively. With the calculated centrifuge unit number of total centrifuge cascade, work consumption for whole centrifuge cascade can be calculated.

3. Results

[Table 1. Centrifuge cascade dimensions] [4]

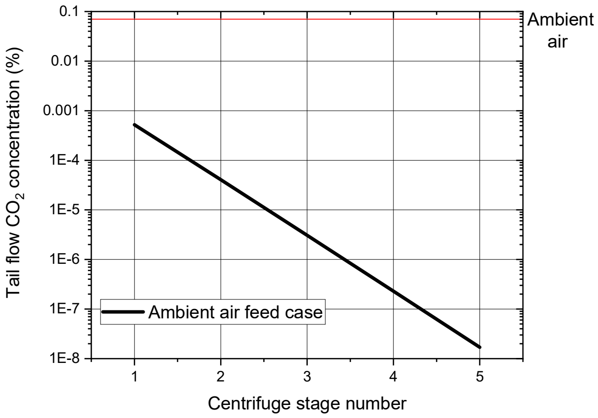
$V_{surface}$	900m/s
$H_{centrifuge}$	12m
$r_{centrifuge}$	0.3m
$E_{turbine}$	0.9

[Table 2. Air components mole fraction]

	Atmospheric air
N_2	77.99%
O_2	21.01%
Ar	0.93%
CO_2	0.07%

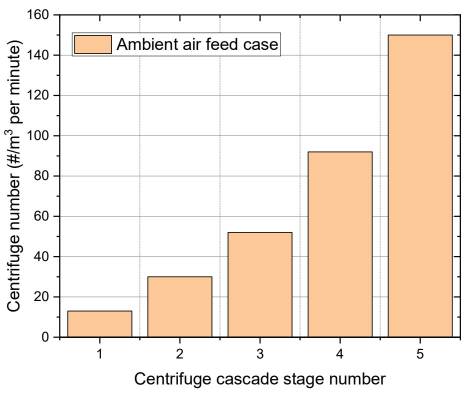
Assumed centrifuge dimension is shown in Table 1. The information is based on AC-100 centrifuge, which is one of the biggest centrifuges that is in commercial operation for the uranium enrichment.

In this study, feed flow of centrifuge cascade is assumed as ambient air. Mole fraction of inlet flow is shown in Table 2.



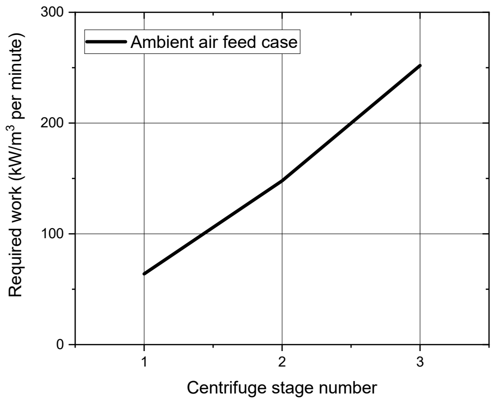
[Fig 6. Tail flow CO_2 concentration of centrifuge cascade]

As centrifuge cascade stage number increases, CO_2 concentration of CO_2 depleted flow decreases.



[Fig 7. Required centrifuge number per unit feed flow]

SWU of unit centrifuge determines the mass flow rate of feed flow and the total required unit number for the whole cascade. 13 centrifuge units per unit feed flow(m^3/min) are required for 1 stage centrifuge cascade and it increases as the stage number increases. For LAES with 300MW scale, 13917m^3/min feed flow rate is needed.



[Fig 8. Required work consumption for centrifuge cascade]

Work consumption by friction force of outer surface of centrifuge cylinder for total centrifuge cascade is plotted on Fig. 11. 63.83MW of work is needed for CO_2 separation of 1m^3 feed air for 1 stage cascade. As cascade stage number increases, required work increases.

4. Conclusions

Gas centrifuge can be one of the answers for CO_2 separation process needed for LAES. Compared to membrane CO_2 separation method, gas centrifuge does not have contamination issue of membrane surface and complicated structure that can deteriorate productivity.

However, utilizing centrifuge cascade requires large amount of energy to separate CO_2 from feed air flow. To lower CO_2 concentration of ambient air under 0.001%, 13 unit centrifuges and 63.83kW work consumption per 1m^3/min feed flow rate are expected. Considering that 300MW LAES requires 13,917m^3/min feed flow rate of air, substantial amount of energy can be required.

For more efficient CO_2 separation, determining upper limit of CO_2 concentration to prevent freezing of CO_2 and minimizing work consumption of centrifuge cascade system are considered future works.

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