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Work consumption reduction technology of gas centrifuge cascade with turbine

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1. Introduction

Liquid Air Energy Storage (LAES) is one of the energy storage systems that is drawing attention recently. During charging process of LAES, air is liquified to be used as energy storage source. When air is liquefied in low temperature, CO_2 freezes to dry ice before other components in air such as oxygen and nitrogen become liquid. Thus, CO_2 should be separated before charging process and gas centrifuge cascade can be used to separate CO_2 from air.

Since LAES requires large amount of air flow as feed, centrifuge cascades used for separating CO_2 from air for LAES system requires large energy consumption.

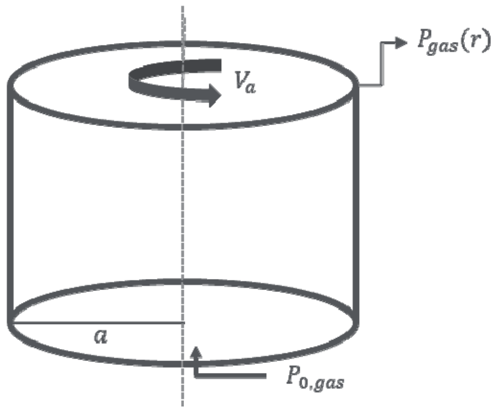
To minimize energy consumption of centrifuge cascade for CO_2 separation, a method to recover consumed work from the system can be devised. Considering high pressure of product in gas centrifuge, turbine can be used to recover work from product flow of gas centrifuge. Inspired by the previous studies on CO_2 separation process using gas centrifuge, the authors will be analyzing work recovery method using turbine for gas centrifuge cascade.

2. Theoretical background

Gas centrifuge is one of the material separation method that is commonly used to enrich uranium. Mass difference of molecules consisting each material of gaseous mixture causes materials to be separated in gas centrifuge.

Gas centrifuge enrichment facility generally uses multi-stage structure to get higher product flow concentration. Such multi-stage structure of gas centrifuge is called gas centrifuge cascade [1].

Outlet flow from centrifuge with higher concentration of target material is called product flow of centrifuge and outlet flow with lower concentration is called tail flow of centrifuge.

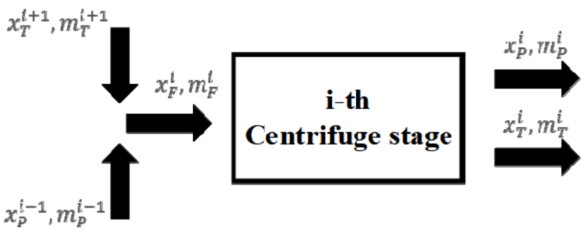


[Fig 1. Partial pressure diagram of gas centrifuge]

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

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

To calculate molar concentration of gas centrifuge product flow, partial pressure ratio of gaseous mixture should be calculated since molar concentration of gas components is proportional to partial pressure of gas in gaseous mixture. Partial pressure in gas centrifuge can be calculated with equations [1] and [2].



[Fig 2. i-th centrifuge cascade stage diagram]

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

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

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

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

Feed flow of certain centrifuge cascade stage is affected by product flow and tail flow of another cascade stages. Product flow from lower stage and tail flow from upper stage composes feed flow of certain cascade stage.

Mass flow rate of tail flow can be calculated with equation [5] and data about feed flow and product flow of certain cascade stage. Considering mass conversion of each centrifuge stage, a sum of tail mass flow rate and product mass flow rate is equal to feed mass flow rate and molar concentration of each flow can be calculated.

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

H: Centrifuge height (m) D: Diffusion coefficient

ρ: Density (kg/m³) R: Ideal gas constant

T: Temperature (K) ΔM: Mass difference between materials (g/mol)

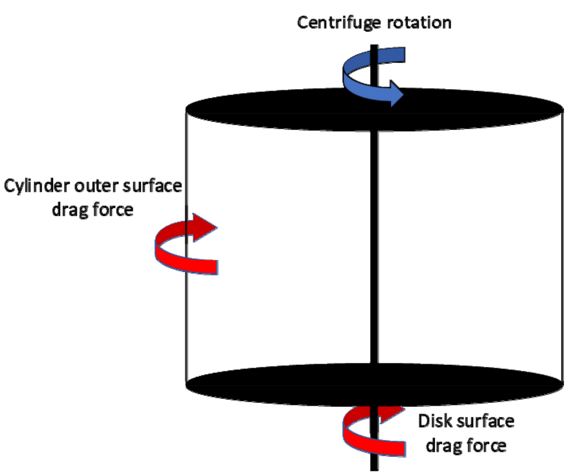
$$m_T = SWU\left(\left(\frac{x_F - x_T}{x_P - x_T}\right)v_P + v_T - \left(\frac{x_P - x_T}{x_P - x_F}\right)v_F\right)^{-1} \quad \cdots [8]$$

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

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

Separation work unit (SWU) is the amount of separation done by an enrichment process. SWU is a function of molar concentration and mass flow rate of feed, product and tail flow of gas centrifuge. Since we have mass flow data and molar concentration data of feed flow and product flow, tail flow data can be determined and required SWU for centrifuge can also be calculated.

With calculated SWU, feed flow rate for single centrifuge unit can be calculated using equations [8] and [9]. When the total feed mass flow rate of certain cascade stage is divided by mass flow rate of single centrifuge unit, the total number of required centrifuge unit can be calculated.

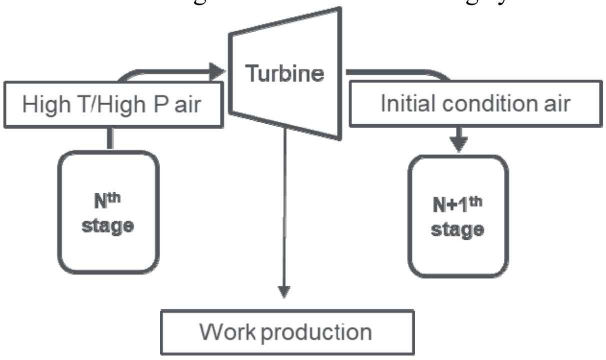


[Fig 3. Centrifuge friction diagram]

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

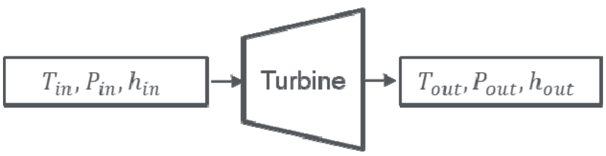
$$Friction\ loss\ on\ vertical\ cylinder\ surface\ P_{disc} = c_f \rho w^3 \pi H R^4 \quad \cdots [12]$$ [3]

Work loss for gas centrifuge occurs due to frictional loss of centrifuge cylinder and momentum loss by centrifuge outlet flow. Gas centrifuge is assumed to be a simple rotating cylinder. For the rotating cylinder, friction forces act on two parts of cylinder; top / bottom surfaces and outer surface. Equations [11] and [12] are used for estimating frictional loss of rotating cylinder.



[Fig 4. Turbine work recovery cascade model]

Since work consumption is high in centrifuge cascade, there should be a method to recover energy. After each stage of centrifuge cascade, pressure and temperature of gas increases. To recover energy between each cascade stage, the authors designed a cascade structure model with turbine between each stage.



[Fig 5. Turbine work production diagram]

$$W_{turbine} = \dot{m}(h_{in} - h_{out}) = \dot{m}E_{turbine}(h_{in} - h_{out}^{isentropic}) \quad \cdots [13]$$

It is assumed that after gas flow from Nth stage passes through turbine, air returns to ambient condition and proceed to N+1th stage. During the process, turbine recovers work and recovered work returns to cascade. Recovered work can be calculated by equation [13].

3. Results

[Table 1. Centrifuge cascade dimensions] [4]

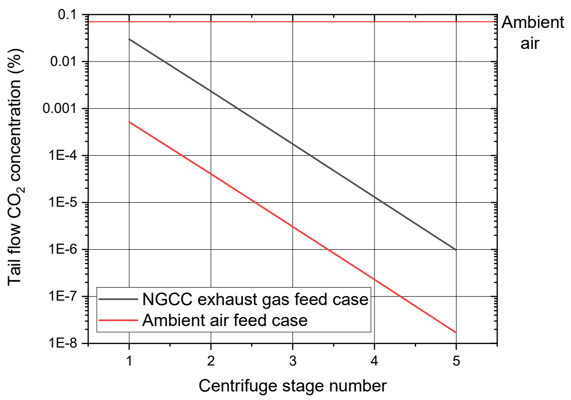
$V_{surface}$	900m/s
$H_{centrifuge}$	12m
$r_{centrifuge}$	0.3m
$E_{turbine}$	0.9

[Table 2. Air components mole fraction]

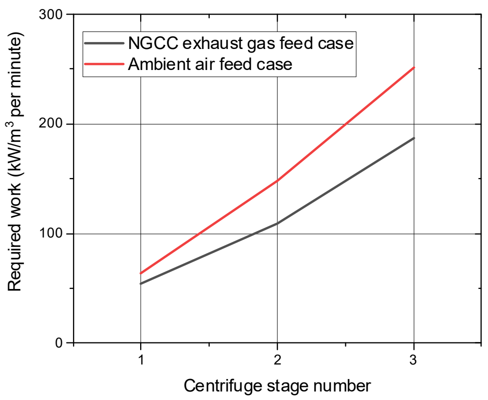
	Atmospheric air	NGCC exhaust gas
N_2	77.99%	74.32%
O_2	21.01%	12.09%
Ar	0.93%	0.89%
CO_2	0.07%	4.04%

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

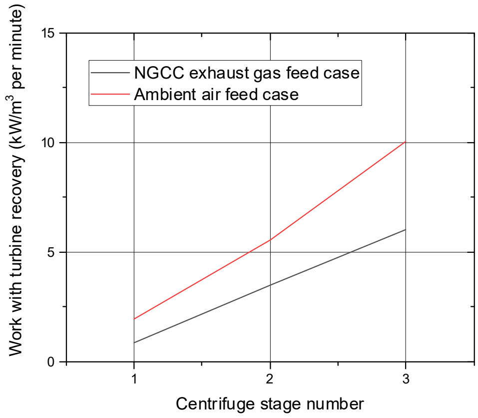
In this study, two cases of centrifuge cascade inlet gas are assumed. One is air with atmospheric condition and the other is exhaust gas produced from Natural Gas Combustion Cycle (NGCC). Mole fraction of each inlet gas is shown in Table 2.



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



[Fig 7. Required work consumption without turbine production]



[Fig 8. Required work consumption with turbine production]

Work consumption due to friction force of outer surface of centrifuge cylinder for the total centrifuge cascade is plotted on Fig. 7 without turbine and Fig. 8 with turbine.

As centrifuge cascade stage number increases, centrifuge tail flow concentration decreases, which means that CO_2 separation ability increases. However, increasing the number of centrifuge cascade stage costs more work consumption of the total facility.

The recovered work is determined by the condition of inlet flow to turbine and turbine efficiency which is shown in Fig.8.

For 3 cascade stage requires over 180kW work consumption for CO_2 separation if feed air flow is $1m^3$/min. LAES with 300MW scale requires $13{,}917m^3$/min feed flow rate is needed. In contrast, when turbine is installed to the centrifuge cascade, only about 6kW of net-work is consumed for $1m^3$/min air feed flow. Over 90% of work is recovered from turbine between each cascade stage.

4. Conclusions

CO_2 separation utilizing gas centrifuge cascade technique can be an answer for removing CO_2 from LAES charging process. However, gas centrifuge cascade consumes huge amount of work. To solve this problem, a work recovery method is newly suggested which utilizes turbine.

When turbine is installed to a centrifuge cascade, 90~97% of work is recovered by turbine. The recovery ratio of consumed work is determined by centrifuge cascade dimensions, but it is obvious that most of consumed work is recovered with turbine.

However, even though installation of turbine to centrifuge cascade can reduce energy cost, capital cost of enrichment facility will increase inevitably. As for the future study, an economic analysis considering capital cost change due to turbine installation and energy cost change will be conducted next.

Acknowledgements

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REFERENCES

[1] J.M.Whitaker, Uranium enrichment plant characteristics-A training manual for the IAEA
[2] Sergey Bogovalov, Vladimir Borman, Separative power of an optimized concurrent gas centrifuge, Nuclear engineering and technology, 2016, 48, 719-726
[3] Stefan Szepessy, Peter Thorwid, Low energy consumption of high speed centrifuges, Chemical engineering technology
[4] Alexander Glaser, Characteristics of the gas centrifuge for uranium enrichment and their relevance for nuclear weapon proliferation