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Proposal of Direct Air Capture and Electricity cogeneration system for Nuclear Applications

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1. Introduction

Direct Air Capture (DAC) as a pivotal technology for net-zero emissions due to its ability to capture atmospheric CO_2. However, it faces hurdles such as low technological maturity and high energy costs, making it less viable economically compared to other carbon capture methods. The paper proposes integrating DAC with the Open-Air Brayton Cycle (OABC) to enhance efficiency and reduce costs, leveraging the large air intake required by DAC and OABC's temperature variations. This innovative approach aims to make DAC more sustainable and economically feasible by optimizing overall system efficiency and energy consumption.

2. Methods and Results

2.1 DAC Model

The most suitable form of DAC system for integration with a power generation system utilizing a nuclear heat source is the Temperature Swing Adsorption system. The simplest configuration of this system is shown in Figure 1.

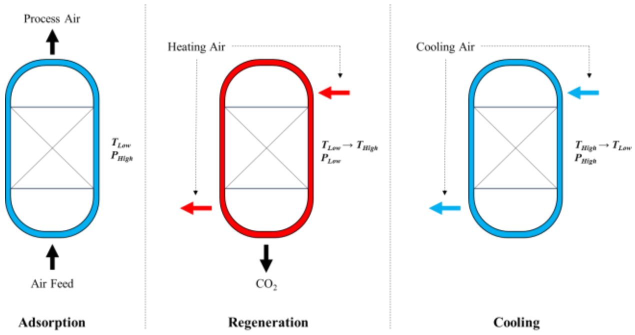

Figure 1. Schematic diagram of 3-step Temperature Swing Adsorption (TSA) process

Assuming that the process proceeds at a sufficiently slow pace, the TSA system can be simply modeled through equilibrium states. This approach is referred to as the Equilibrium short-cut model. Modeling of the TSA process using this model can be conducted using the equation below [1].

Adsorption step

$$q_{ads,i} = q^*(P_{ads}, y_{ads,i}, T_{ads})$$
$$y = y_{feed}$$

Regeneration step

$$q_{heat,i}^{k+1} = q^*(P_{heat}, y_{heat,i}^{k+1}, T_{heat}^{k+1})$$
$$y_{heat,i}^{k+1} = \frac{q_{heat,i}^{k} - q_{heat,i}^{k+1}}{\Sigma_i(q_{heat,i}^{k} - q_{heat,i}^{k+1})}$$

Cooling step

$$q_{cool,i}^{k+1} = q^*(P_{cool}, y_{cool,i}^{k+1}, T_{cool}^{k+1})$$
$$y_{feed}^{k+1} = \frac{q_{cool,i}^{k} - q_{cool,i}^{k+1}}{\Sigma_i(q_{cool,i}^{k} - q_{cool,i}^{k+1})}$$

The performance of the TSA process is primarily evaluated based on two factors: purity and recovery rate. The definitions of purity and recovery rate are as follows.

$$Purity = \frac{q_{ads,CO_2} - q_{heat,CO_2}}{\Sigma_i(q_{ads,i} - q_{heat,i})}$$
$$Recovery = \frac{q_{ads,CO_2} - q_{heat,CO_2}}{q_{out,CO_2} + (q_{ads,CO_2} - q_{heat,CO_2}) + (q_{ads,CO_2} - q_{cool,CO_2})}$$

2.2 OABC-DAC system layout

The most suitable method for integrating a TSA-type DAC system with a nuclear-linked OABC system involves performing adsorption at the compressor inlet and dividing the recuperator into two parts to perform regeneration at an appropriate intermediate temperature after the turbine. The layout of such a system is shown in Figure 2.

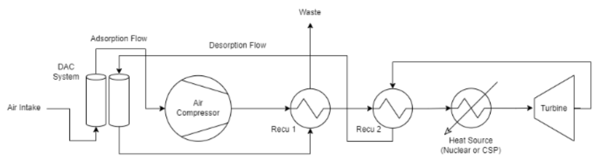

Figure 2. OABC-DAC system layout

To analyze this system, conditions for the OABC system applicable to nuclear power, as presented in Table 1 [2], were adopted as references.

Table 1. Open-Air Brayton Cycle Baseline [2]

Turbine Inlet Temperature	933 K
Turbine polytropic efficiency	90%
Compressor polytropic efficiency	90%
Compressor pressure ratio	Calculated
Main heater pressure ratios	0.99

Recuperator effectiveness	0.95
Recuperator pressure ratio on hot side	0.99
Atmospheric pressure	1 atm
Atmospheric temperature	288 K
Ratio of exhaust pressure to atmospheric	0.98

For the TSA, the adsorbent assumed for analysis Is mmen-Mg_2(dobpdc) [3,4], based on references from previous DAC-related studies [5]. Under the given conditions, the recovery rate and purity of the system as a function of regeneration temperature are illustrated in Figure 3.

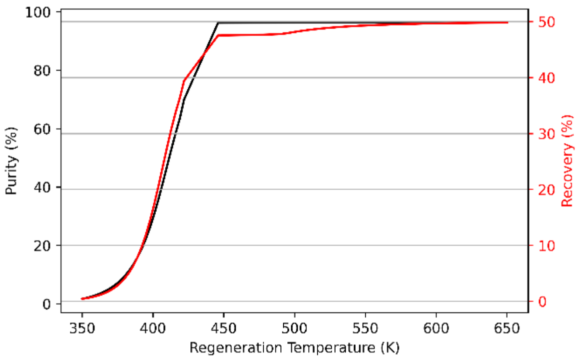

Figure 3. Recovery and purity of the system as a function of regeneration temperature

The results show convergence of both indices at a specific regeneration temperature (above 600K). At the convergence point, the adsorption diagram of the system is as illustrated in Figure 4.

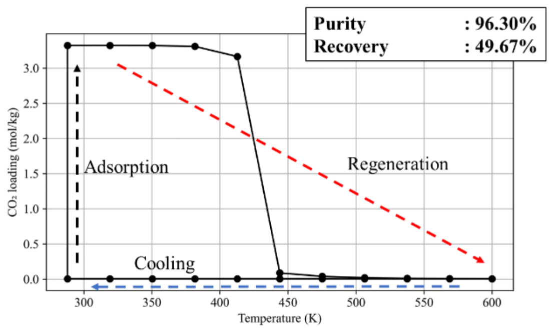

Figure 4. Adsorption diagram of the system

3. Conclusions

This study presents a system layout that combines a DAC system with an OABC power generation system utilizing a nuclear heat source. Consequently, it was found that by applying a suitable TSA-type DAC system, it is possible to capture carbon dioxide from the air with a purity of 96.3% at a recovery rate of approximately 50%. Further research on evaluating energy consumption for this process is planned.

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