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Preliminary Analysis of SMR-DAC Integration System for Carbon Dioxide Removal Approach

Ju Hun Jung, In Cheol Bang*
Dept. of Nuclear Engr., Ulsan National Institute of Science and Technology (UNIST),
50 UNIST-gil., Ulju-gun., Ulsan., Republic of Korea
**Corresponding author: icbang@unist.ac.kr*

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1. Introduction

In recent years, various industries have proactively formulated strategies aimed at achieving carbon neutrality, with the overarching objective of mitigating the global climate crisis. Among these strategies, the adoption of nuclear power generation has garnered considerable attention due to its potential to significantly curtail carbon emissions while offering a stable and continuous supply of electrical power—a critical component in addressing the climate challenge. This trajectory is underscored by the escalating prominence of nuclear power as a pragmatic avenue toward carbon neutrality, a prevailing discourse on a global scale [1]. Notably, Nuclear Power Plants (NPPs) exhibit a distinct capacity for synergistic integration with a spectrum of non-electric power generation domains, an attribute attributed to its favorable economic viability relative to alternative energy sources. Within this context, the concept of Small Modular Reactors (SMRs) has emerged as a salient contender for harmonizing with diverse carbon-neutral and carbon-reduction technologies, a trend propelled by its inherent safety, public acceptability, and versatile operational framework [2]. Evidently, SMRs stand poised to facilitate symbiotic collaboration with a suite of technologies that advocate for carbon neutrality and reduction. This assemblage encompasses technologies geared toward hydrogen production, renewable energy utilization, and the comprehensive spectrum of Carbon Capture, Utilization, and Storage (CCUS) technologies. A particular emphasis is placed on the application of Direct Air Capture (DAC) technology—a pivotal avenue within the broader CCUS milieu focused on the carbon dioxide removal (CDR) approach. Despite its relatively nascent stage of development, DAC technology is rapidly gaining momentum, signifying an accelerated trajectory [3]. This momentum is further validated by the International Energy Agency (IEA), which duly recognizes and supports the burgeoning potential of DAC technology in advancing carbon neutrality ambitions. The IEA's endorsement is discernible through its sustained backing of DAC technology's evolution, with a delineated objective of effecting a 15% reduction in atmospheric carbon dioxide (CO_2) levels—a testament to its pivotal role in the carbon-neutral imperative [1].

The potential integration of DAC technology with various power generation sectors stems from its ability to provide a consistent and reliable supply of both electricity and thermal energy, qualities that are intrinsically requisite for energy sources characterized by low carbon emissions [3]. Historically, DAC technology has predominantly interfaced with coal power plants marked by high levels of carbon emissions, a pragmatic approach that, according to the IEA, inadvertently extends the operational lifespan of carbon-emitting technologies despite their classification as carbon-reduction measures [1]. Notably, the IEA has identified a conspicuous paradox wherein the coupling of DAC technology with carbon-intensive coal power generation inadvertently perpetuates carbon emissions, thereby challenging the fundamental tenets of carbon abatement strategies [1].

Given the recognized imperative to rely on energy sources with minimal carbon footprint, nuclear power generation has materialized as a preeminent selection by the IEA—an endorsement that solidifies its standing as a prospective cornerstone in the pursuit of carbon-neutral energy paradigms. This pivotal alignment has rendered nuclear power generation a pivotal contender as a pivotal energy provision mechanism for DAC technology, positioning it as a prospective driver of next-generation energy supply ecosystems oriented towards carbon neutrality [1]. This paradigmatic convergence accentuates the compelling prospects of SMRs as an alluring candidate for symbiotic coupling with DAC technology. The inherent attributes of SMRs, namely their capacity to furnish a reliable stream of low-carbon emission energy, underscore their viability in this integrated framework, an outlook buttressed by a plethora of preliminary investigations seeking to establish integration with SMR installations and DAC facilities.

Slesinski and Litzelman undertook a comprehensive investigation to assess the economic viability inherent in the integration of SMRs with DAC systems. Their study rigorously examined the financial feasibility of a co-generation scenario involving an integrated SMR-DAC system, culminating in the substantiation of a reduction in Capital Expenditures (CAPEX) for this unified configuration as gauged by the Levelized Cost of Electricity (LCOE) metric [4]. Popov et al. are dedicated to the development of an integrated NPP-DAC amalgamation. This undertaking employs Dymola, a potent multi-domain system analysis simulation tool founded upon the Modelica language, to comprehensively model and scrutinize the synergistic NPP-DAC system [5]. Sircar et al. are engaged in the formulation of an intricate descriptive economic analysis appertaining to the NPP-DAC paradigm. Consequently, an expanded research initiative is presently underway, striving to expound upon and augment the existing knowledge landscape in this domain [6].

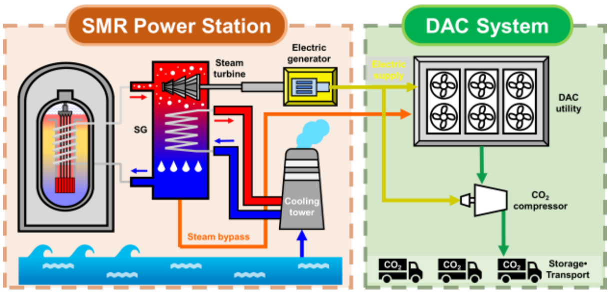

Fig. 1. Schematic of an integration system a SMR (Orange box) and a DAC facility (Green box), integrated SMR-DAC system.

Hence, this present study endeavors to conjoin carbon-neutral to establish SMR-DAC integration (Figure 1)—an innovative paradigm distinguished by its operational flexibility and interconnectivity. To facilitate a comprehensive preliminary assessment of the potential for this amalgamation, we have harnessed the capabilities of a multi-domain analysis simulation language, namely Modelica. This instrumental framework serves as the bedrock for evaluating the feasibility and viability of effecting the proposed linkage. The ensuing outcomes engendered by this investigation are seamlessly juxtaposed with a detailed exposition of a systemic strategy. This strategic delineation is underpinned by a meticulous dissection of the intrinsic attributes characterizing each constituent system, thereby providing the fundamental base of an integrated framework poised to redefine the landscape of carbon-neutral energy solutions.

2. Analytical Methodology

2.1 Applicability of the DAC System with SMR

The fundamental objective of DAC technology centers upon the direct retrieval of carbon dioxide molecules dispersed within the atmospheric milieu. This process is underpinned by a systematic mechanism wherein atmospheric air is drawn into the system using a fan. Subsequently, during the adsorption phase, the contained CO_2 molecules are selectively absorbed by an adsorbent material, concomitant with the absorption of thermal energy by the CO_2 molecules themselves. This adsorption phase is succeeded by a distinct desorption and regeneration sequence, wherein the CO_2 molecules are segregated from water molecules (H_2O). This isolation is achieved through their introduction to absorbents. The water molecules that have successfully traversed the regeneration phase are channeled back to the condenser, while the extracted CO_2 molecules are stored within a designated storage medium via compression processes [7]. The heat energy requisites of the DAC unit hinge upon the nature of the sorbent material employed. Depending on the sorbent category, the energy demands within the DAC system can exhibit variance. Generally categorized into solid sorbents and liquid sorbents, the sorbent types distinctly influence the energy dynamics of the DAC process. In the purview of this investigation, the steam derivable from the SMR is focused on this study, with particular emphasis on the DAC technology predicated on solid sorbents.

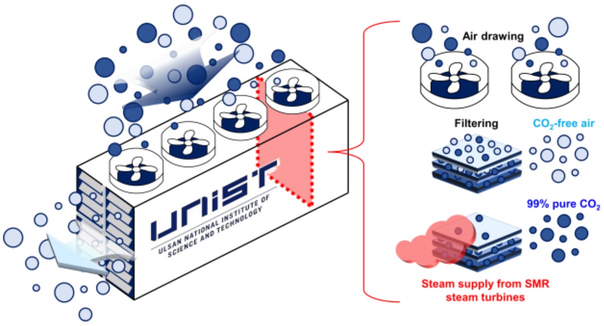

Fig. 2. Example of DAC process with a low temperature solid sorbent.

Illustrated in Figure 2, the utilization of solid sorbents within the DAC framework necessitates the provision of heat energy at relatively modest levels of pressure and temperature, as delineated in previous research findings [8]. This requisite heat energy is predominantly furnished in the form of superheated steam. Notably, building upon the architectural configuration of the SMR, a notable correlation emerges between the thermal energy inherent in the steam channeled through the high-pressure steam turbine and the heat energy demanded by the DAC process. Specifically, this superheated steam, akin to that harnessed in the SMR operations, holds the potential to be seamlessly diverted to the interior of the DAC unit. This orchestrated coupling offers the prospect of expending the superheated steam resource to fulfill the stipulated steam demands of the DAC apparatus. The outcome of this steam utilization within the DAC unit culminates in the release of waste heat at a consistent temperature. This waste heat reservoir, in turn, presents an avenue to partially offset the heat energy prerequisites intrinsic to the DAC process, thereby fostering a more efficient energy utilization framework [9]. Nevertheless, it is paramount to acknowledge that this integration of waste heat remains entrenched within a conceptual realm, warranting further substantive development and practical validation.

Elaborated in Table I are the distinct heat and electrical energy prerequisites requisite for DAC facilities founded upon solid sorbents, as elucidated by Climeworks—an emblematic player within the DAC development landscape.

Table I: Thermal and Electrical Energy Demand for Climeworks DAC Facilities [9]

	With waste heat recovery	Without waste heat recovery
Cyclic capacity	1 mmol/g	
Steam mass	1.0 tH_2O/tCO_2	
Steam flow rate	64 kg/h	
Sensible heat	619 kWh/tCO_2	
Heat of H_2O desorption	0	890 kWh/tCO_2
Heat of CO_2 desorption	441 kWh/tCO_2	
Heat steam generation	0	628 kWh/tCO_2
Electricity heat pump	190 kWh/tCO_2	0
Total thermal energy demand	1060 kWh/tCO_2	2578 kWh/tCO_2
Total electrical energy demand	190 kWh/tCO_2	0

2.2 Modelica Simulation of the DAC System

Within the purview of this investigation, the analysis of the integrated SMR-DAC system was executed through the employment of Modelica language. Utilizing Modelica, a preliminary analysis of the DAC object model was conducted, culminating in a comprehensive evaluation of the inherent characteristics of each model and their potential compatibility with the SMR framework. It is noteworthy that a visual representation of these findings is anticipated in the form of Figure 3—a graphic depiction slated to elucidate the Modelica-based object model encapsulating the DAC system. This embedded DAC object model is seamlessly assimilated within the expansive Thermal Power Library developed by Modelon, an exemplar of versatile modeling frameworks within the field.

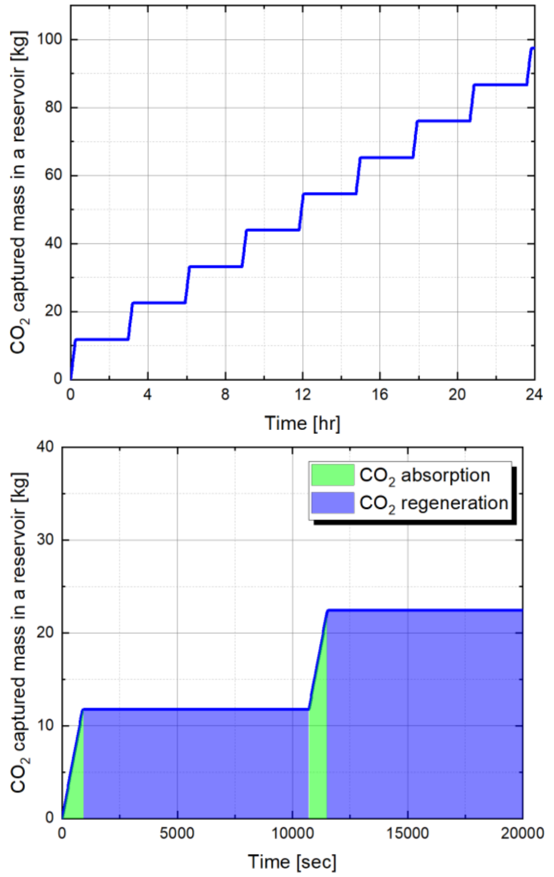

Fig. 4. Simulation result of captured CO_2 mass by DAC one module for (above) 24 hours, and (below) 20000 sec.

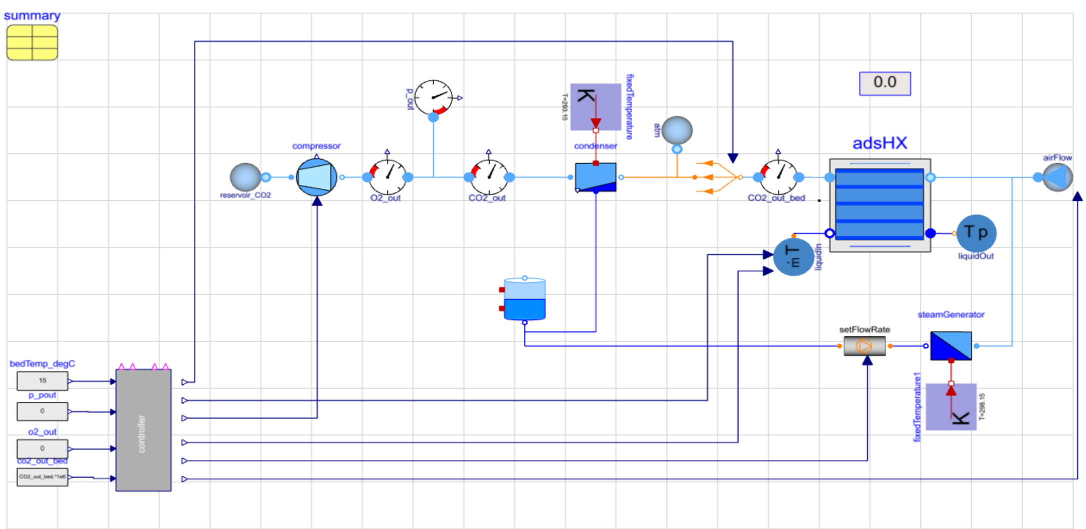

Fig. 3. A Modelica model of CO_2 capture process in a DAC module developed by Modelon.

Figure 4 presents the outcomes of a simulation encompassing the CO_2 capture process, conducted over a span of 24 hours and 20000 sec, utilizing the DAC object model realized through the Modelica framework. Within this simulation, the DAC module effectively isolated approximately 94.7 kg of CO_2 throughout the course of 24 hours. This quantitative metric corresponds to approximately 6.17% of the daily air capture rate, specifically calibrated at 64 kg/h. The architecture of the DAC module, as elucidated in section 2.1 and represented in Figure 2, adheres to a cyclic sequence. In this context, the module initiates with a 1080 sec absorption phase, followed by a subsequent desorption process that primes the module for the ensuing absorption cycle, persisting until the 10800 sec. Consequently, the formulated DAC module, as demonstrated in this study, necessitates a replication of its structure tenfold to ensure a continuous supply of thermal energy without SMR load-following operation.

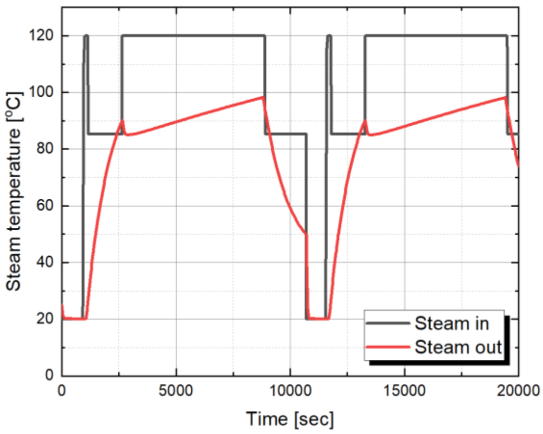

Fig. 5. Steam temperature at the inlet/outlet of solid sorbents.

Turning attention to Figure 5, a portrayal of the simulation outcomes encompassing two cycles, equivalent to 20000 sec, encapsulates the inlet/outlet temperature dynamics of the steam dispensed to solid sorbents. This visualization underscores the supply of superheated steam at 120°C to the adsorbent following a 1080 sec CO_2 absorption phase, followed by the subsequent desorption procedure. Cumulatively, the DAC module necessitates a total thermal energy amounting to 2578 kWh per ton of CO_2, which notably incorporates the specific thermal energy demand of the CO_2 desorption process—an energy requirement fixed at 441 kWh per ton of CO_2. It is of pertinence to note that this energy demand can be effectively met by diverting the secondary steam generated through the operations of the SMR, thereby conferring upon the integrated system a self-sustaining energy supply mechanism.

2.3 Energy Transport from SMR to DAC system

Ongoing worldwide endeavors encompass diverse research and development initiatives focused on SMRs, this study pursues an exploration into the potential harmonization between SMRs and the DAC system. To this end, reference is drawn to the NuScale SMR, advanced and renowned for its safety attributes, emanating from the pioneering efforts of NuScale Power incorporation. The intricate thermal framework of NuScale SMR is complemented by the sequential progression of steam through a series of eight steam turbines, encompassing both high and low-pressure variants, to facilitate efficient heat transference. Pertinent details pertaining to the inlet and outlet parameters of each turbine are meticulously documented in Table II.

To harness the generated steam from the secondary side of the NuScale SMR, the establishment of a bypass conduit becomes imperative, diverting the steam from the steam turbine's conventional route. This diversion necessitates existing bypass lines that interface seamlessly with the existing NuScale steam turbines. Situated within the bypass path, between the outlet of steam generator No. 3 and the inlet of steam generator No. 4, the steam acquires a temperature of 127.1 °C at 3.5 bar. Given that this steam is intended for utilization within the solid sorbent-based DAC system, its elevated temperature requires direct supply. Consequently, the incorporation of an additional heat exchanger emerges as a requisite measure to facilitate the removal and redistribution of surplus heat energy. This vital intervention is critical to attaining the requisite thermal conditions essential for the desorption phase of the solid sorbent within the DAC system.

Table II: Steam Thermal Values at the Inlet/Outlet of Steam Turbines in NuScale SMR Module [10]

		Order of Steam turbine inlet/outlet								
TH value	**Unit**	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**
Pressure	bar	32.7	26.6	6.1	2.5	2.4	1.6	1.5	1.3	1.1
Temperature	℃	303.7	282.8	152.8	127.2	108.3	86.8	82.2	66.4	41.7
Steam mass flow	kg/s	241.5	240.7	228.7	210.4	206.9	192.5	188.2	68.8	48.6
Heat transfer	kJ/s	1360.5	1345.1	1212.8	1162.6	1136.0	1089.8	1096.4	1081.1	1025.2
Bypass line	-	No	No	Yes	Yes	No	Yes	No	No	No

3. Summary and Future Works

Within the realm of this investigation, set against the backdrop of the overarching aspiration for carbon neutrality, a comprehensive evaluation was undertaken to gauge the preliminary viability of integrating SMRs as a low-carbon emission energy source with carbon reduction technology, specifically, the DAC system. Aided by the utilization of Modelica, the DAC object system was meticulously modeled. This entailed a thorough exploration of the foundational principles governing the DAC apparatus, encompassing its carbon capture efficacy and the requisite thermal energy demand in the form of superheated steam. Integral to the mechanism of atmospheric carbon capture within the DAC system was the requisite infusion of thermal energy, primarily furnished via superheated steam. The establishment of a pragmatic range for this thermal was ascertained through a comparative assessment of the value of saturated steam, as gleaned from the steam bypass path of steam turbines of the NuScale SMR. Collectively, this study offers invaluable insights into the fundamental implementation of an integrated system, forging a synergistic connection between the SMR and the DAC system, a stalwart in the repertoire of direct carbon reduction methodologies.

Recognizing the incipient stage of the SMR-DAC research and development trajectory, it is evident that an array of subsequent research avenues necessitate exploration. As the DAC object system has been successfully modeled and its performance elucidated, the ensuing stage necessitates a comprehensive analysis focusing on the implementation of the SMR object model utilizing the Modelica framework, followed by an in-depth examination of the SMR-DAC linkage. Furthermore, given the representative role of DAC technology in realizing carbon neutrality aspirations, it remains incumbent to channel substantial efforts toward its research and development. To this end, the imperative entails the economic analysis and optimization of the integrated SMR-DAC system, encompassing a holistic exploration of its techno-economic feasibility and potential optimization strategies.

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