Pumping CO_2 from Air: Feasibility of Moisture-Driven Membrane Direct Air Capture (MD-DAC)

Introduction

The continuous rise in atmospheric CO_2 concentrations has intensified the urgency for large-scale deployment of negative emission technologies. According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming to 1.5 °C will require the removal of approximately 5 to 20 gigatons of CO_2 per year [1]. Achieving this target through low-carbon energy systems and conventional carbon capture technologies alone is likely to be insufficient.

Direct air capture (DAC) has emerged as a leading negative emissions strategy. Its principal advantage lies in its geographical flexibility, as it can be deployed virtually anywhere. However, DAC faces significant challenges related to high energy demand and cost compared with point-source capture, primarily due to the low atmospheric CO_2 concentration (~400 ppm). Coupling DAC with renewable energy sources and CO_2 utilization pathways could help lower overall costs and enhance its role within a broader carbon management portfolio [2].

Liquid-based DAC systems capture CO_2 using aqueous alkaline solutions and subsequently release it through high-temperature regeneration, resulting in substantial energy consumption [3]. Solid sorbent-based DAC (S-DAC) relies on porous materials to adsorb CO_2, which is then released via temperature or pressure swings typically between 80 °C and 100 °C. When physisorbents are used, pre-drying of air is necessary to minimize moisture interference, further increasing energy requirements [3]. Chemisorbents, such as solid amines, eliminate the need for pre-drying but demand considerable regeneration energy. For example, the Mammoth plant operated by Climeworks—currently the world's largest S-DAC facility—has yet to meet the ambitious cost reduction targets initially envisioned [4,5].

Membrane-based direct air capture offers a continuous approach for removing CO_2 from the atmosphere without the need for a separate regeneration step. However, conventional membranes typically rely on a CO_2 partial pressure gradient as the driving force for transport, which limits their effectiveness at the very low CO_2 concentrations found in ambient air (~400 ppm) [6].

Moisture-driven DAC (MD-DAC) exploits the moisture-swing (MS) mechanism, whereby specific materials absorb CO_2 under dry conditions and release it upon hydration, thereby eliminating the need for high temperatures or vacuum, as depicted in **Figure 1** [7]. In this process, CO_2 is captured at the relatively low relative humidity (RH) of ambient air and released at higher humidity levels due to competition from water vapor. The required energy is supplied by water evaporation at ambient temperature, enabling potential integration with waste heat streams or renewable energy sources [8].

Moisture-swing materials exhibit a humidity-dependent affinity for CO_2. Commercially available options include anion exchange membranes (AEMs), commonly used in fuel cells and electrolysers, as well as newly developed functional polymers [9]. MD-DAC systems can operate in a discontinuous mode, typically using particulate sorbents, which may present scalability challenges, or in a continuous mode using a membrane subjected to a humidity gradient. In the latter case, the membrane acts as a continuous CO_2 pump, eliminating the need for cyclic regeneration and improving process efficiency and scalability. When a moisture gradient is maintained across the membrane, MS chemistry induces a CO_2 flux opposite to the direction of water transport, enabling CO_2 pumping from a dry to a wet side—even against an opposing external CO_2 concentration gradient [10].

A CO_2 membrane pump based on Fumasep FAA-3, operated with 50% RH on the capture side and 100% RH on the release side, was estimated to achieve CO_2 capture rates exceeding those of tropical leaves, with an enrichment factor of 10:1 (from 400 to 4000 ppm). Although sorbent-based systems may attain higher capture rates, they are associated with substantial thermal energy requirements [10].

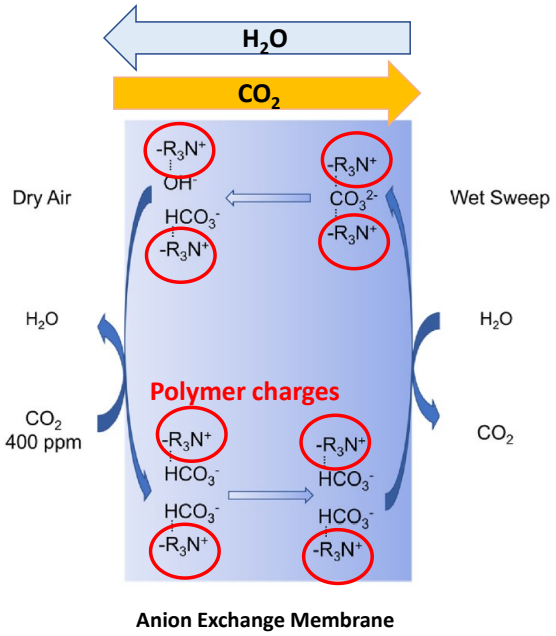

Figure 1 *A schematic of the moisture gradient-driven direct air capture (MD-DAC) process across an anion exchange membrane.*

A thorough understanding of dry-state CO_2 transport parameters is essential for assessing membrane performance in moisture-driven air capture. Under operating conditions, CO_2 enrichment on the downstream (wet) side may generate an opposing CO_2 partial pressure gradient within the membrane. Therefore, membranes with lower dry-state CO_2 permeability are advantageous, as they reduce undesired CO_2 back-diffusion and enhance net capture efficiency.

In this study, we evaluate the suitability of two commercial membranes, Fumasep and Sustainion, for direct air capture applications. Specifically, we:

a. Conduct a preliminary characterization of CO_2 sorption and diffusion properties in the dry state as a function of pressure.
b. Assess the sorption and diffusion of water vapor at different humidities in the membranes
c. Use the measured parameters to evaluate numerically the flux of CO2 across the membranes, thus finding the optimal membrane properties and operating conditions
d. Use thermodynamic models to support and explain the observed findings.

Materials

Two commercially available anion exchange membranes (AEMs) bearing covalently bonded nitrogen-based cationic functional groups were investigated in this study: Fumasep FAA-3-50 and Sustainion X37-50 Grade RT.

Fumasep® features a proprietary polymer backbone functionalized with covalently attached quaternary ammonium groups. In contrast, Sustainion® incorporates imidazolium cations within its structure, rather than the more commonly used quaternary ammonium functionality.

Prior to testing, both membranes were converted to the hydroxide (OH^-) form by immersion in a 1 M KOH solution for 24 hours at room temperature [11]. The dry-state thickness was measured as 50.5 ± 1.4 µm for Fumasep® and 50.0 ± 1.5 µm for Sustainion®.

Results

Comprehensive sorption and diffusion measurements were performed to determine solubility, diffusivity, and permeability coefficients. Both Fumasep FAA-3-50 and Sustainion X37-50 Grade RT were tested with light gases (N_2, O_2, and CH_4) as well as with CO_2 and H_2O due to their specific relevance to the moisture-driven capture process. This structured analysis allows for a clear separation of thermodynamic and kinetic factors governing gas transport in the membranes.
The resulting permeability coefficients reveal that, across the entire pressure range investigated, Fumasep® exhibited higher CO_2 permeability than Sustainion®. While CO_2 solubility was greater in Sustainion®, diffusivity was higher in Fumasep®, leading to the observed permeability trend. The CO_2 permeability values of both membranes are comparable to those reported for other commercially available ion exchange membranes, such as Nafion®.

Building on the experimental dataset, a thermodynamic modeling framework based on PC-SAFT (Perturbed-Chain Statistical Associating Fluid Theory) was developed. Model parameters were determined through a weighted least-squares (WLS) minimization procedure, ensuring robust fitting across the entire pressure range. The calibrated model was then used to reproduce the experimental solubility isotherms as a function of sorbate partial pressure and to extract physically meaningful polymer parameters. This modeling effort provides predictive capability and establishes a link between molecular-level interactions and macroscopic sorption behavior.

Finally, we applied a species-wise mass balance was formulated and solved to describe coupled CO_2 and H_2O transport through the membrane under a humidity gradient. This transport model enabled identification of the key material properties governing carbon flux, including solubility selectivity, diffusivity ratios, and overall permeability. A parametric analysis was conducted to determine the optimal combination of membrane properties required to maximize net CO_2 transport while minimizing back-diffusion.

Using these optimized parameters, the transport equation was solved to predict steady-state CO_2 and H_2O fluxes under representative operating conditions.

This combined experimental–modeling approach provides both fundamental insight and a quantitative evaluation of membrane performance for moisture-driven direct air capture applications.

Conclusions

This work investigates two anion-exchange membranes, Fumasep FAA-3-50 and Sustainion X37-50 Grade RT, to better understand their suitability for the moisture gradient-driven direct air capture process.

First, their gas transport properties were experimentally characterized. Solubility, diffusivity, and permeability were determined from sorption tests. Both membranes were tested with light gases (N_2, O_2, CH_4), while Fumasep® was additionally evaluated with CO_2 and H_2O. Results were presented as solubility isotherms versus pressure, diffusivity versus concentration, and permeability versus pressure, allowing separation of thermodynamic and kinetic contributions to transport.

Second, a thermodynamic model was developed and fitted to the experimental data using a weighted least-squares procedure. The model reproduced the solubility behavior and provided polymer-specific parameters, enabling predictive capability.

Finally, the moisture-swing mechanism was analyzed by solving a species-wise transport equation for coupled CO_2 and H_2O fluxes. A parametric study identified the key membrane properties required to maximize CO_2 transport and minimize back-diffusion. Simulations using both optimized parameters

and experimental data were performed to assess the practical feasibility of implementing the moisture-driven process with Fumasep® membranes.

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