Performance Evaluation of Amine-Infused Resin (AIR) for LNG and Process Optimization through Simulation

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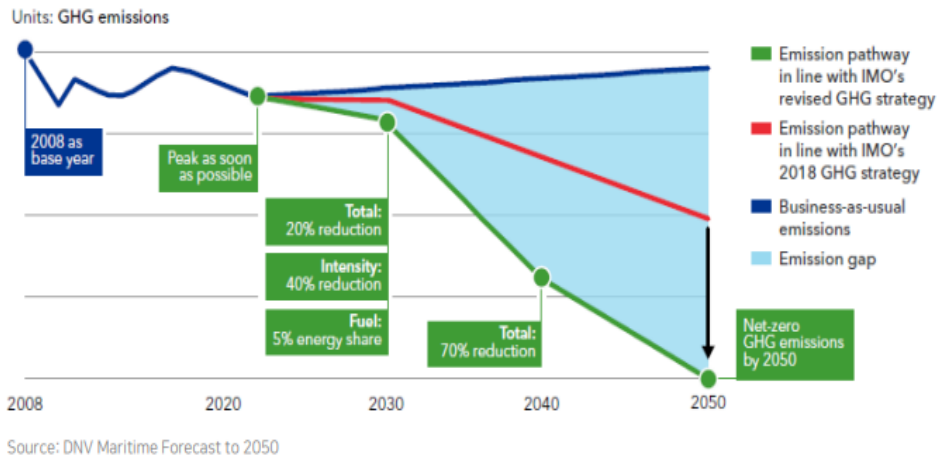
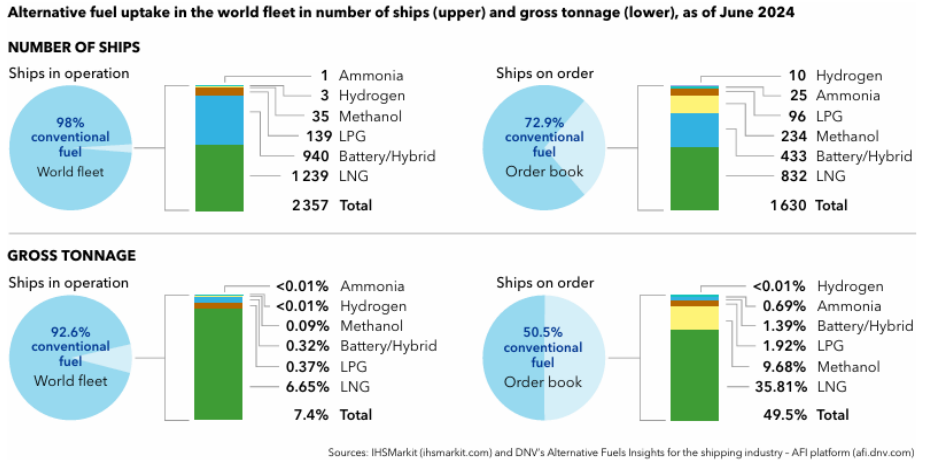
Background



Source: DNV Maritime Forecast to 2050



* Maritime Forecast to 2050, DNV(2024)

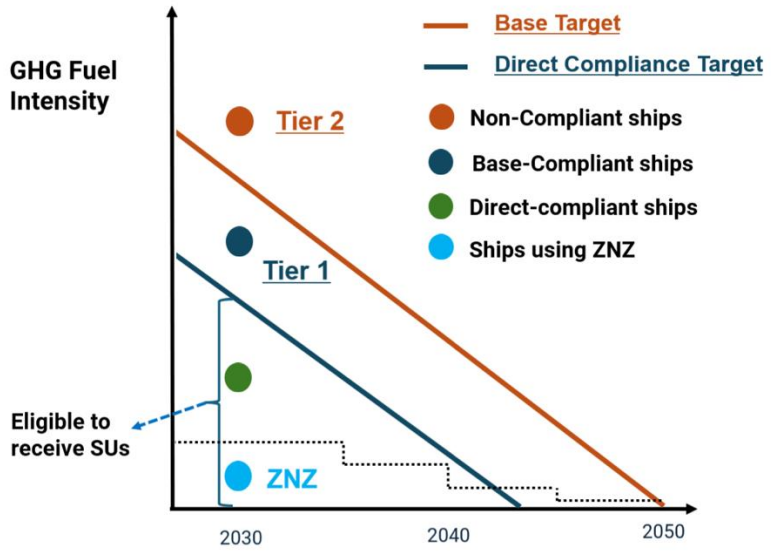
- Since the Industrial Revolution, the rapid increase in carbon dioxide emissions has accelerated global warming.
- Globally, there is a growing movement to reduce carbon emissions.
- In line with this trend, the shipping industry has set a target to achieve net-zero emissions by 2050.
- Accordingly, various studies are being conducted to reduce the use of fossil fuels, the primary source of carbon dioxide emissions.

- The use of low-carbon and carbon-free fuels is emerging as a promising alternative.
- Among orders for eco-friendly fuel-powered vessels, liquefied natural gas (LNG) accounts for approximately 50%, representing a significant proportion.

Introduction

Background

- LNG produces about 20% less CO_2 compared with conventional fossil fuels, which is why it is considered a relatively eco-friendly fuel.
- However, the shipping industry is now facing strict carbon emission regulations.
- At the 83rd session of the Marine Environment Protection Committee (MEPC), incentives for low-emission vessels were considered.



* Korean Register, IMO NEWS Flash(2025)

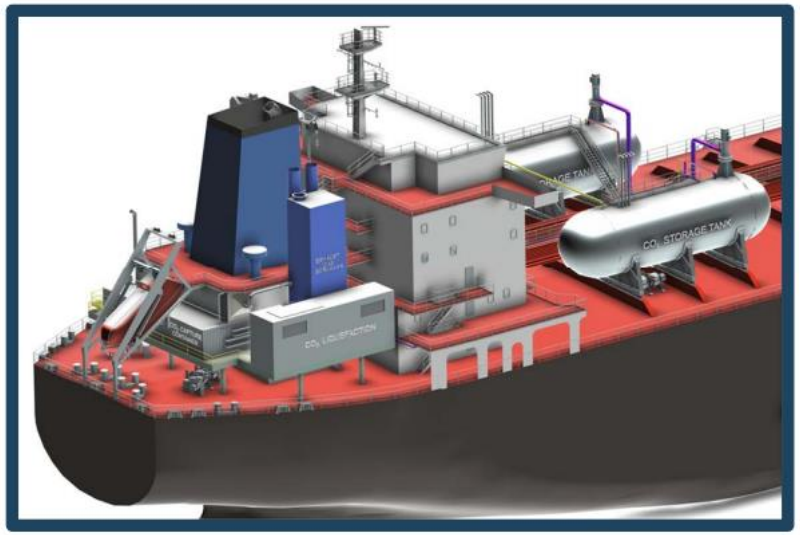


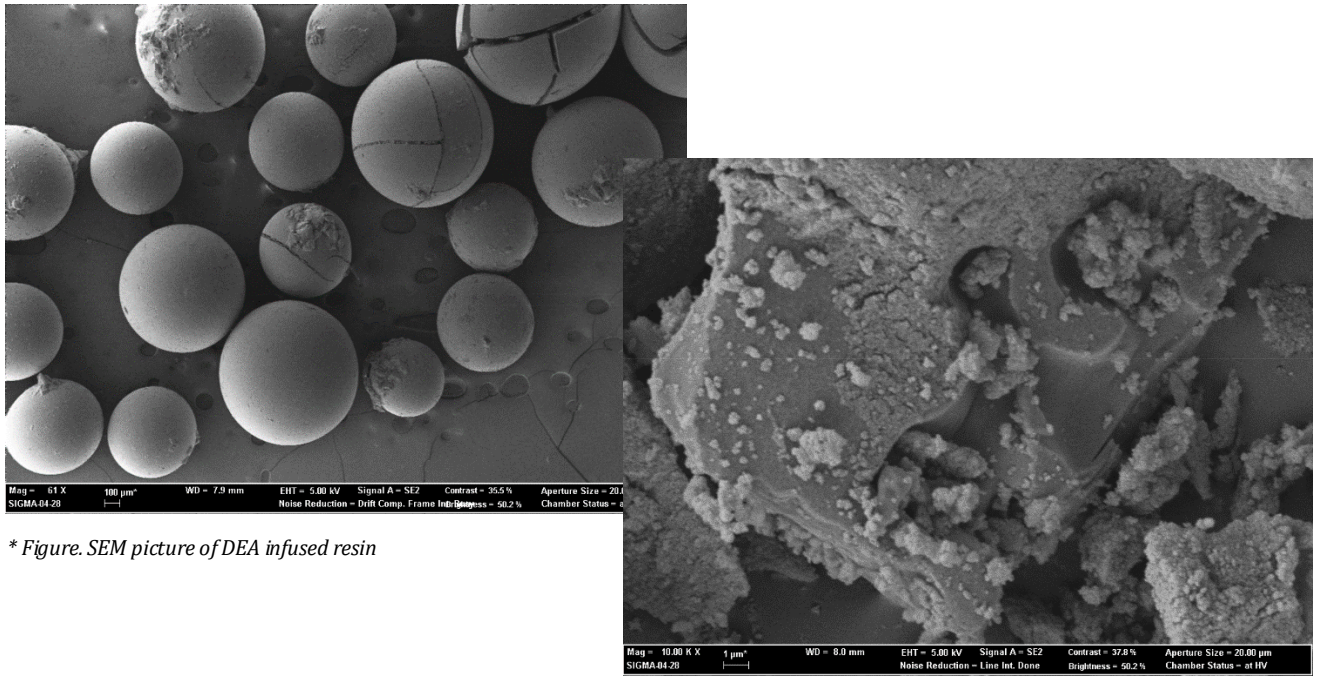
Figure 4. Conditioning and Capture equipment locations for 1 ton per hour capacity.

- Even small amounts of carbon dioxide generated during vessel operation need to be addressed.
- Consequently, the demand for on-board CO_2 capture is increasing.
- However, ships have limited space and energy, more research is required to develop practical solutions.

Introduction

Objective

** Figure. SHI's Ship with OCC system*



** Figure. SEM picture of DEA infused resin*

- SHI(Samsung Heavy Industries) successfully demonstrated the first amine-based onboard CO_2 capture technology in Korea.
- However, chemical absorbents have inherent challenges such as high regeneration energy requirements.
- To overcome these limitations, adsorbents are being considered as alternatives.
- Adsorbents offer lower regeneration energy demand and higher durability, making them more suitable for onboard CO_2 capture systems.
- In fact, Jung et al. (in progress, 2025) evaluated the performance of an amine infused resin, showing promising results under CO_2 15 % condition.
- Experiments were conducted using amine-infused resin capable of both chemical absorption and physical adsorption.

Find the optimal operating condition of Adsorbent for OCC and Optimization through Simulation

Experiment

MEA / DEA Infused Resin Experiment – Experimental Apparatus

** Figure. Experimental Apparatus*

** Table. Specification of Experimental Setting*

	Specification
Reactor	• Tubular • Size : ½” (id 13.1 mm) * 200 mmL • DP/DT : 5 bar/ 120 ℃ • Material : 316SS
Heat	• Range : ~ 150 ℃ • Band
Pressure	• Back Pressure Regulator
Mass Flow Controller	• Placed at inlet and outlet of the reactor • Range : ~500 sccm
Gas Chromatography	• Column : Porapak-N

Experiment

DEA Infused Resin Experiment

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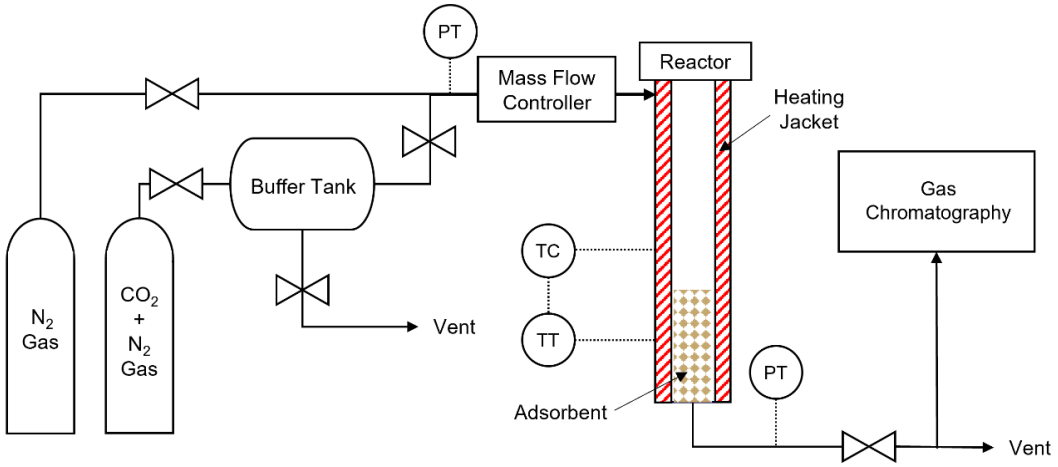
Experimental Procedure

- The reactor is packed with adsorbent.
- Reaction gas is stored in a buffer tank and controlled by an MFC before entering the reactor.
- The pressure of the reaction gas is regulated by a BPR located at the outlet of the reactor.
- After passing through the adsorbent, the reaction gas exits the reactor and is analyzed by GC.
- During regeneration, nitrogen controlled by the MFC is purged while the reactor temperature is increased.



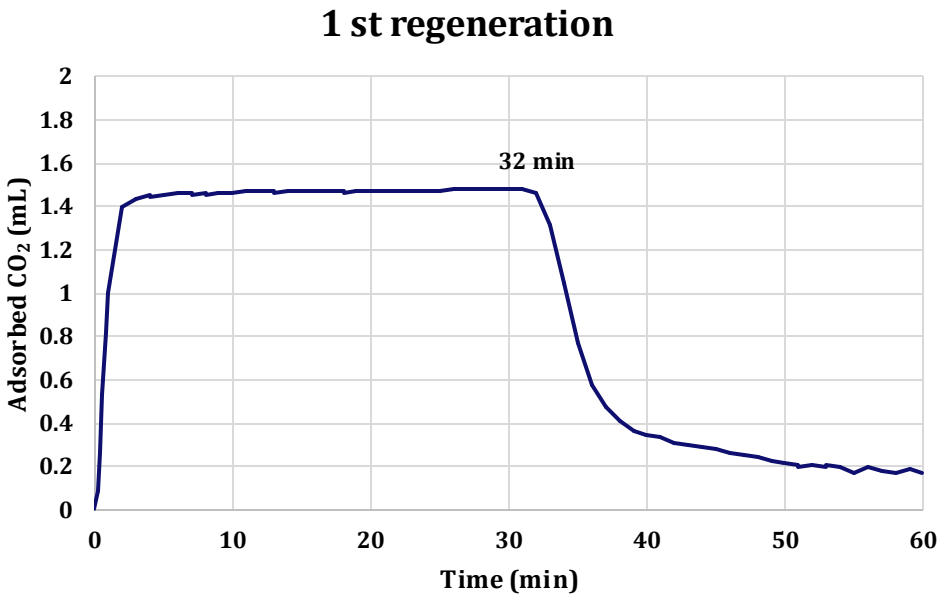
** Figure. Schematic of Experimental Setting*

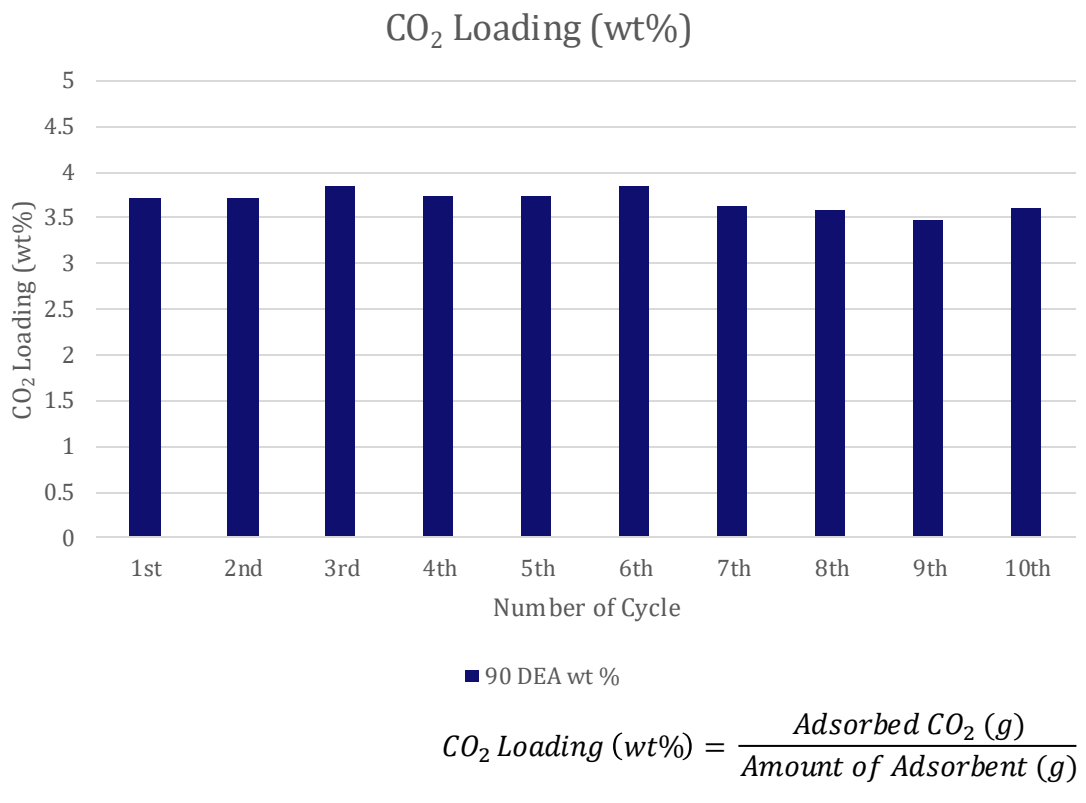
** Table. Detail of Experimental Condition*

	Composition of Flue gas	Pressure	Mass	Adsorption			Regeneration			# of Cycle
				Temperature	Flow rate	Adsorption Time	Temperature	Flow rate (N_2)	Regeneration Time	
DEA-Resin	CO_2 5 % N_2 Balance	3.5 bara	3 g	30 ℃	30 sccm	1 hour	90 ℃	100 sccm	2 hours	10

Experiment

DEA Infused Resin Experiment





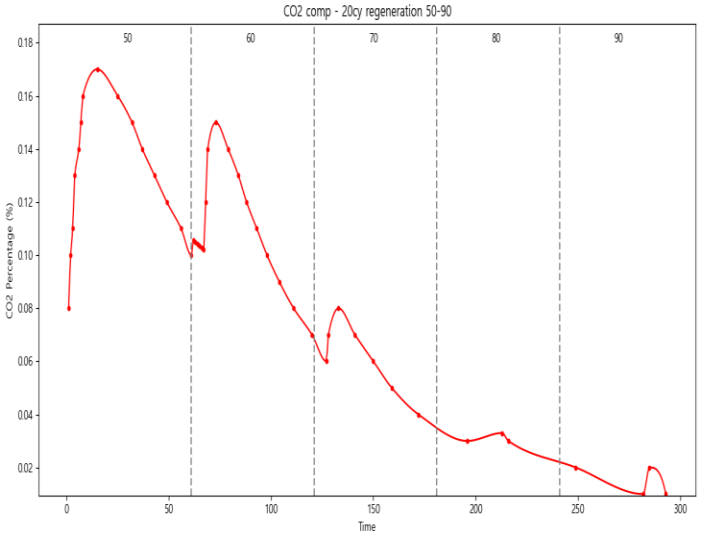
$$CO_2\ Loading\ (wt\%) = \frac{Adsorbed\ CO_2\ (g)}{Amount\ of\ Adsorbent\ (g)}$$

DEA infused Resin Adsorption Performance

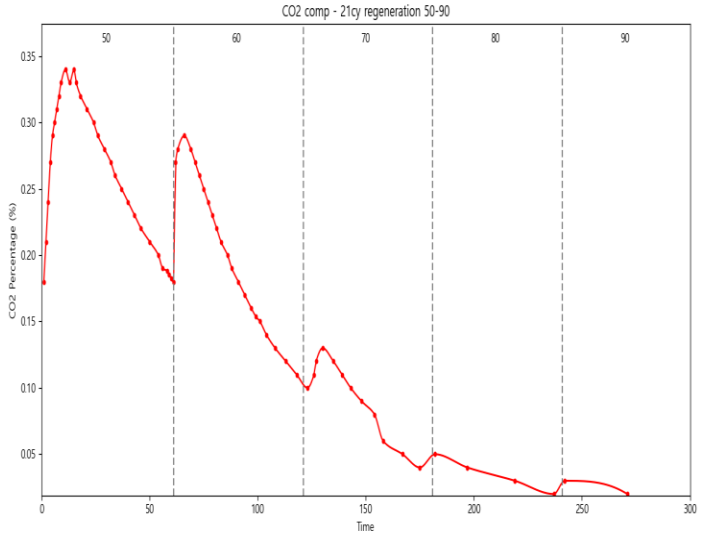
- Across all cycles, the maximum adsorption time remained similar, at approximately 30 minutes.
- CO_2 Loading (wt%) was calculated by adsorbed CO_2 which is accumulated by GC over amount of adsorbent.
- The average CO_2 Loading was 3.69 wt%.
- No significant performance degradation was observed.

Experiment

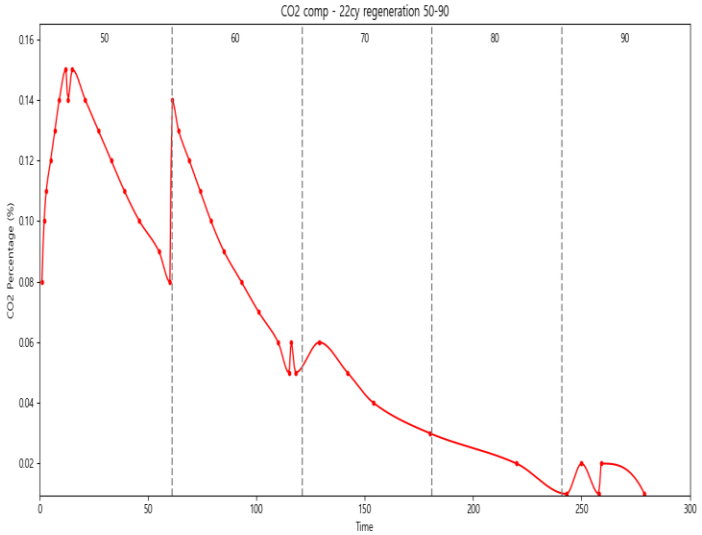
DEA Infused Resin Experiment - Regeneration Temperature Assessment for DEA Resin



CO_2 Desorption by Regeneration Temperature (20th Cycle)



CO_2 Desorption by Regeneration Temperature (21st Cycle)



CO_2 Desorption by Regeneration Temperature (22nd Cycle)

Experimental Procedure

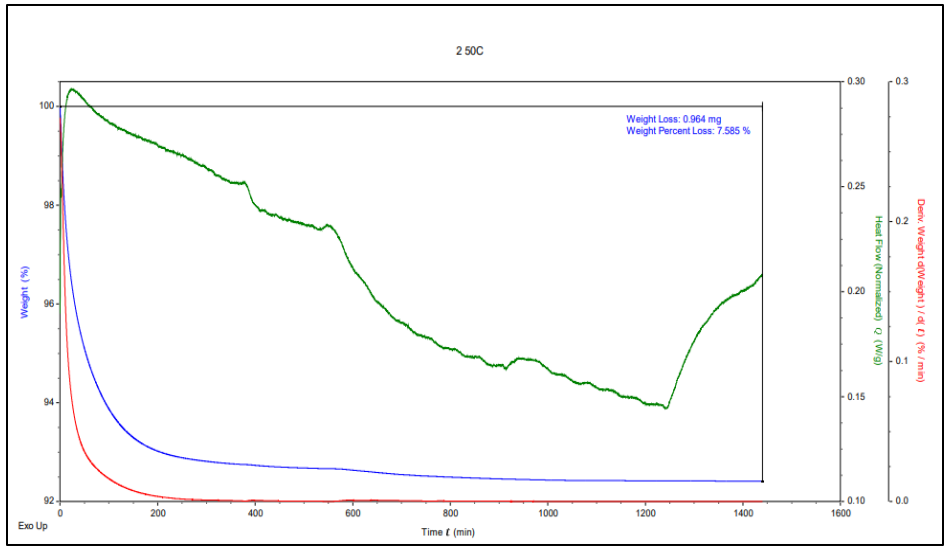
- To identify the optimal regeneration temperature for DEA.
- Purged with N_2 at 100 sccm, identical to the regeneration process.
- Measured the CO_2 released from the DEA resin as the temperature was increased from 50 to 90 °C, in increments of 10 °C per hour.

Results

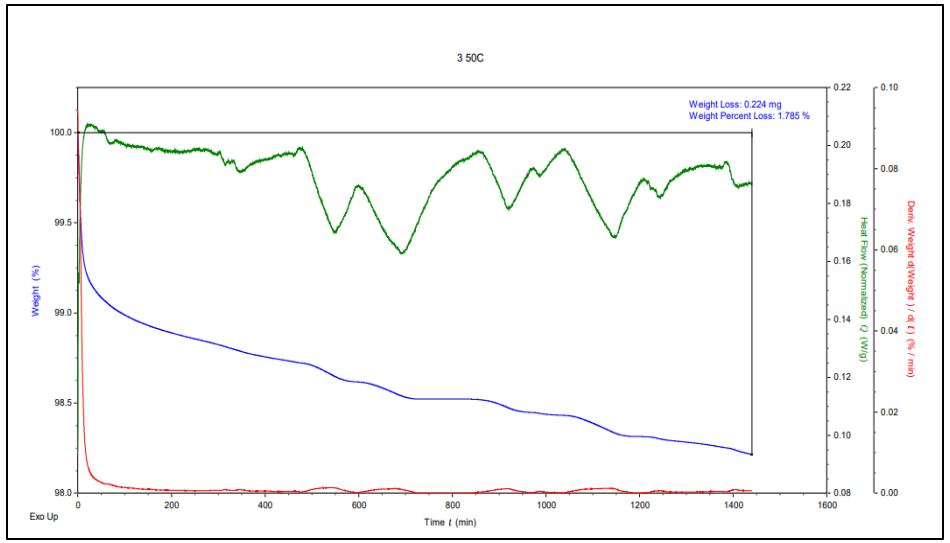
- The highest CO_2 desorption was observed at 50 °C and 60 °C, with an initial desorption peak also appearing at 70 °C.
- The highest CO_2 desorption was observed at 50 °C.

Experiment

DEA Infused Resin Experiment - TGA/DTA Analysis at 50°C



** CO_2 Loaded DEA Resin*



** DEA Resin*

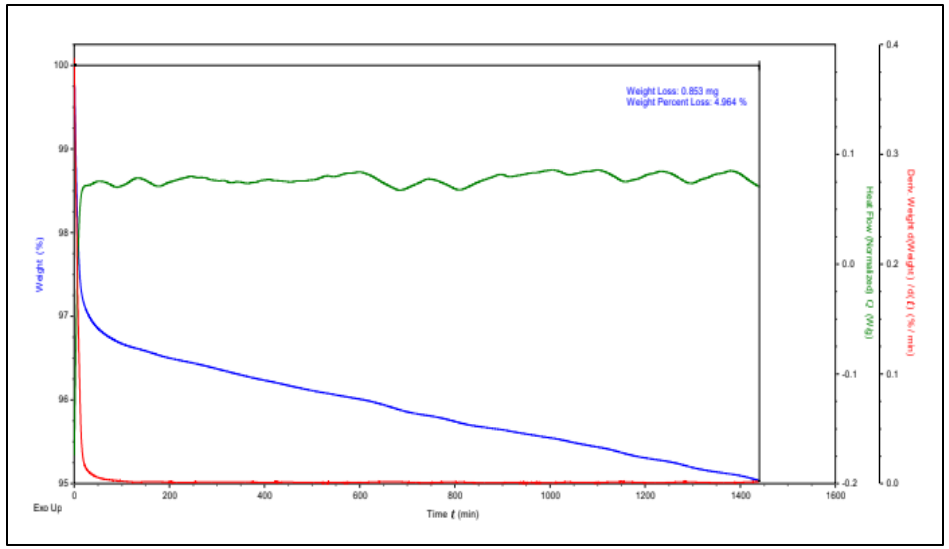
	CO_2 Loaded DEA Resin	DEA Resin
Heat Flow	Exo up	
Derivation of Weight	7.585 %	1.785 %
Weight Loss	0.964 mg	0.224 mg

Time-Dependent SDT Results at 50 °C

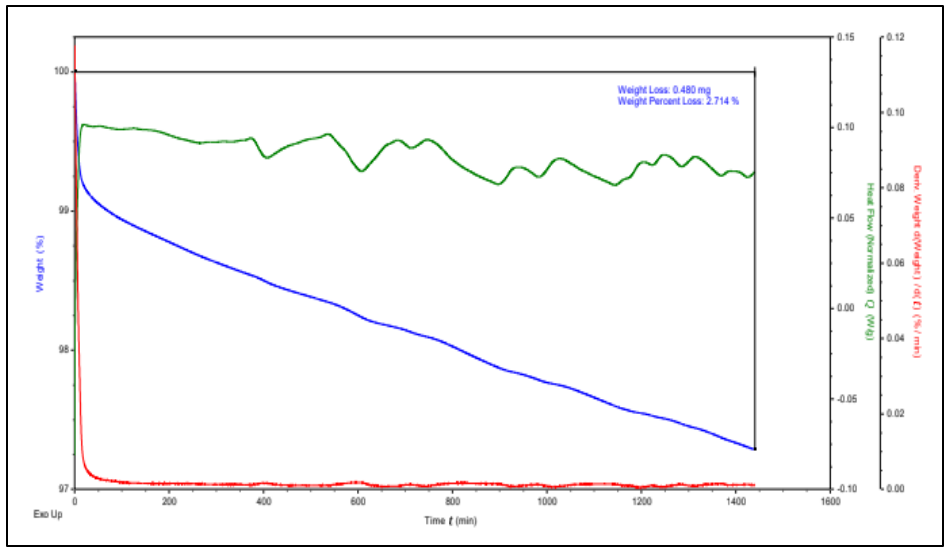
- The sample were kept at 50 °C for 24 hours resulted in substantially greater weight loss in CO_2 loaded DEA resin than in the unloaded sample, due to CO_2 desorption.
- The optimal regeneration time was approximately 30 minutes.

Experiment

DEA Infused Resin Experiment - TGA/DTA Analysis at 60°C



** CO_2 Loaded DEA Resin*



** DEA Resin*

	CO_2 Loaded DEA Resin	DEA Resin
Heat Flow	Exo up	
Derivation of Weight	4.963 %	2.714 %
Weight Loss	0.853 mg	0.480 mg

Time-Dependent SDT Results at 60 °C

- Both CO_2 loaded and unloaded samples showed rapid initial weight loss, followed by a gradual decrease.
- As observed at 50 °C, CO_2 loaded DEA resin exhibited greater weight loss than the unloaded resin.
- At 60 °C, DEA resin showed even higher weight loss compared to 50 °C.

Experiment

DEA Infused Resin Experiment - Regeneration Temperature as an Operational Variable

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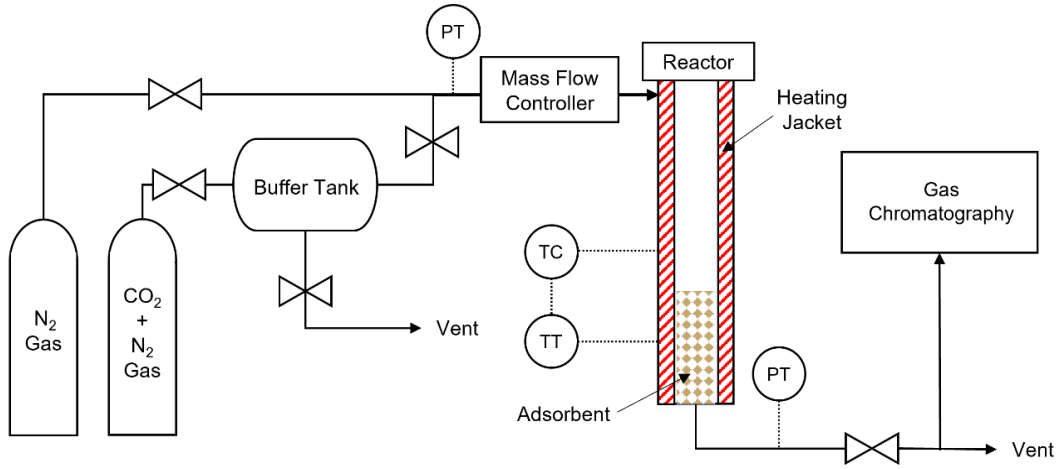
Experimental Procedure

- Adsorption method applied consistently across experiments.
- Regeneration experiments conducted at 50°C, 60°C, and 90°C.

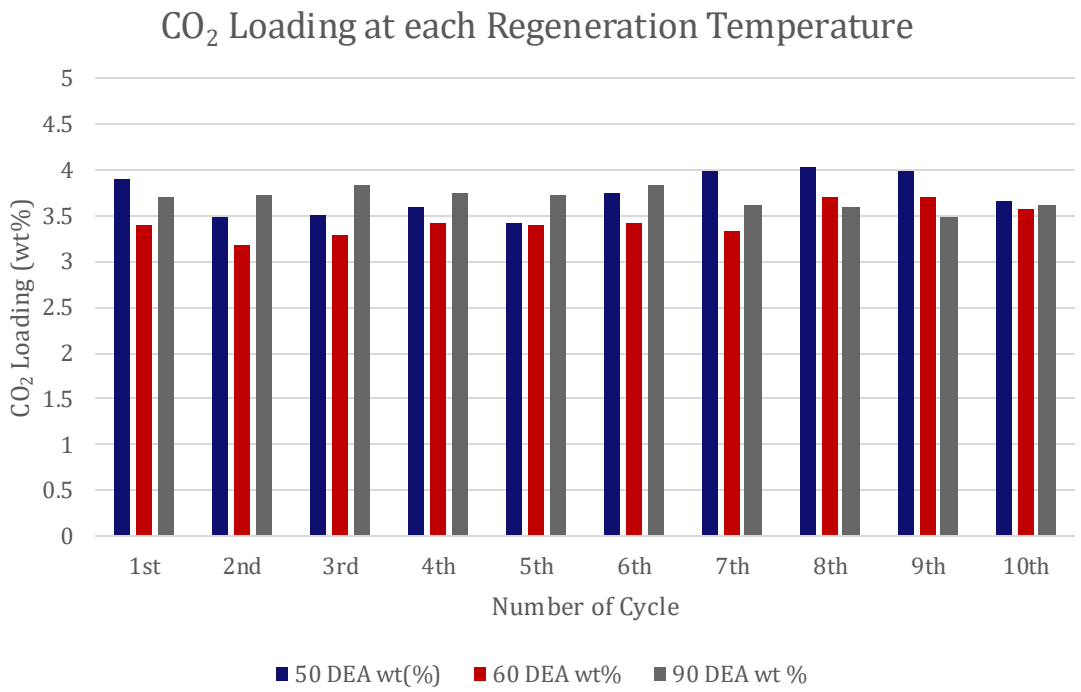


** Figure. Schematic of Experimental Setting*

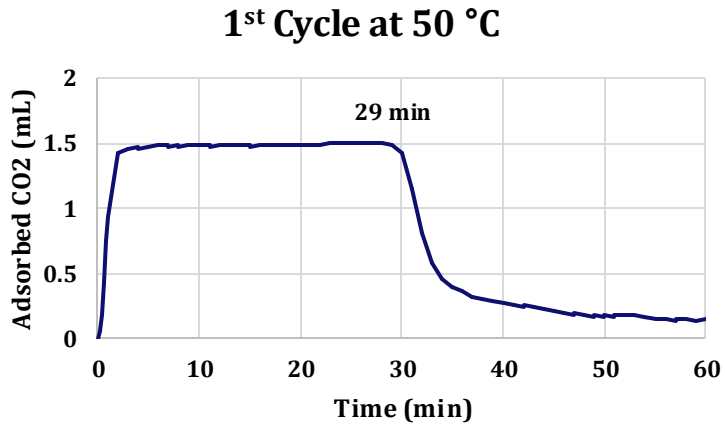
	Composition of Flue gas	Pressure	Mass	Adsorption			Regeneration			# of Cycle
				Temperature	Flow rate	Adsorption Time	Temperature	Flow rate (N_2)	Regeneration Time	
DEA-Resin	CO_2 5 % N_2 Balance	3.5 bara	3 g	30 ℃	30 sccm	1 hour	90 ℃	100 sccm	2 hours	10
							60 ℃			
							50 ℃			

Experiment

DEA Infused Resin Experiment - Adsorption Performance by Regeneration Temperature



Regeneration Temperature	Average CO_2 Loading (wt %)
50 °C	3.73
60 °C	3.45
90 °C	3.69



Adsorption Performance by Regeneration Temperature

- Among the three regeneration temperatures, 50 °C yielded the highest average adsorption capacity.
- Across all cycles, the maximum adsorption time remained similar, at approximately 30 minutes.
- No significant performance degradation was observed at any regeneration temperature.

Experiment

DEA Infused Resin Experiment – Adsorption Pressure as an Operational Variable

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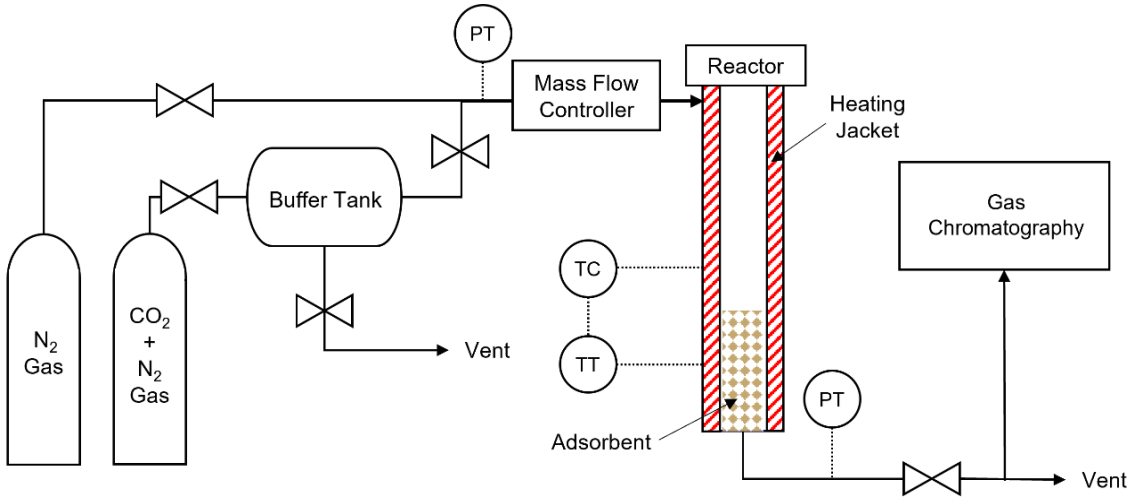
Adsorption Pressure as an Operational Variable

- Adsorption method applied consistently across experiments except the pressure.
- The experiments were conducted under 3.5 bar and 1.3 bar.

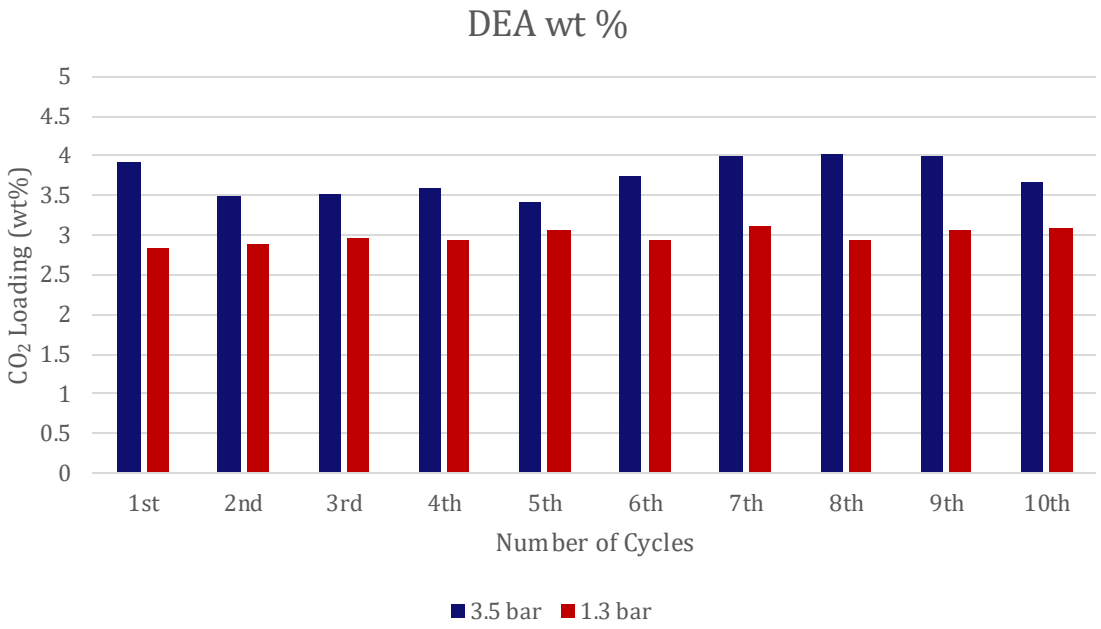


** Figure. Schematic of Experimental Setting*

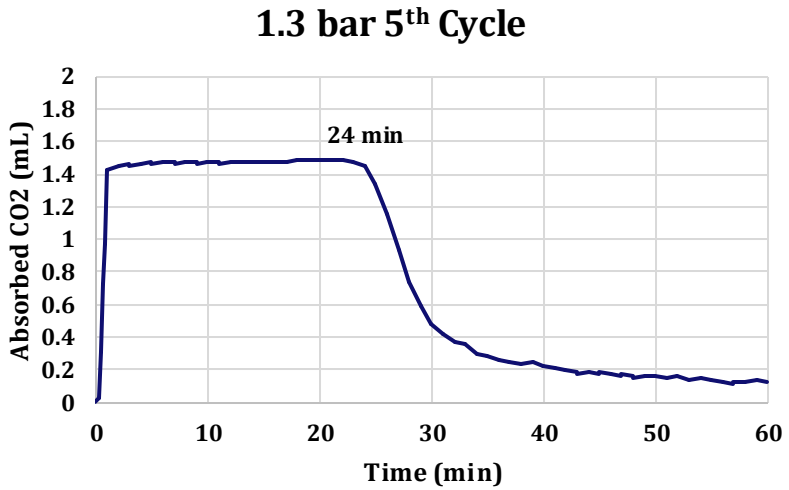
	Composition of Flue gas	Pressure	Mass	Adsorption			Regeneration			# of Cycle
				Temperature	Flow rate	Adsorption Time	Temperature	Flow rate (N_2)	Regeneration Time	
DEA-Resin	CO_2 5 % N_2 Balance	3.5 bar	3 g	30 ℃	30 sccm	1 hour	50 ℃	100 sccm	2 hours	10
		1.3 bar								

Experiment

DEA Infused Resin Experiment - Adsorption Performance by Adsorption Pressure



Adsorption Pressure	Average CO_2 Loading (wt %)
1.3 bar	2.98
3.5 bar	3.45



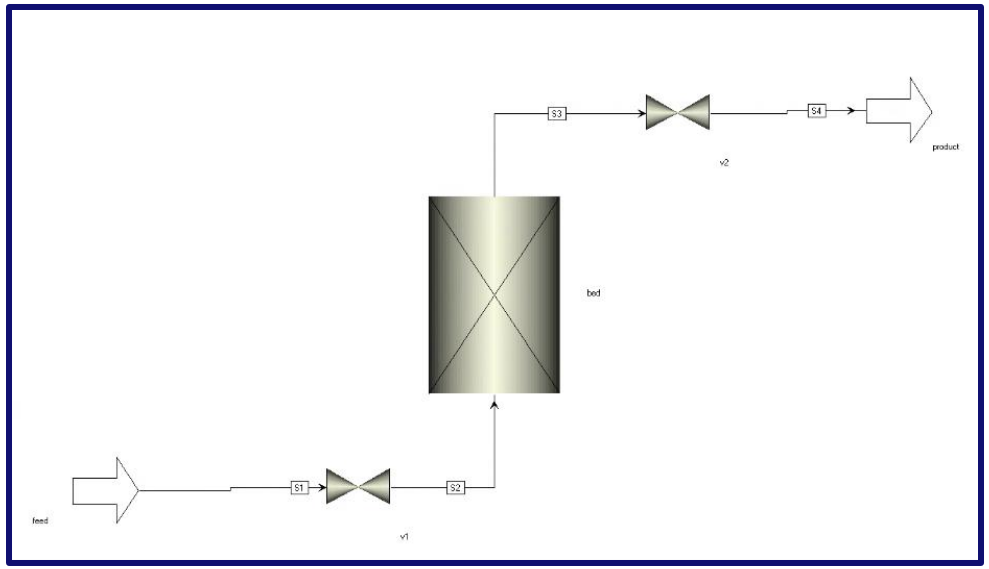
Adsorption Performance under different pressure

- Compared to 3.5 bar, the adsorption performance at 1.3 bar was about 0.5 points lower.
- The maximum adsorption time also decreased from 30 minutes to 24 minutes.
- Similar to the case at 3.5 bar, no noticeable degradation was observed.

Process Simulation

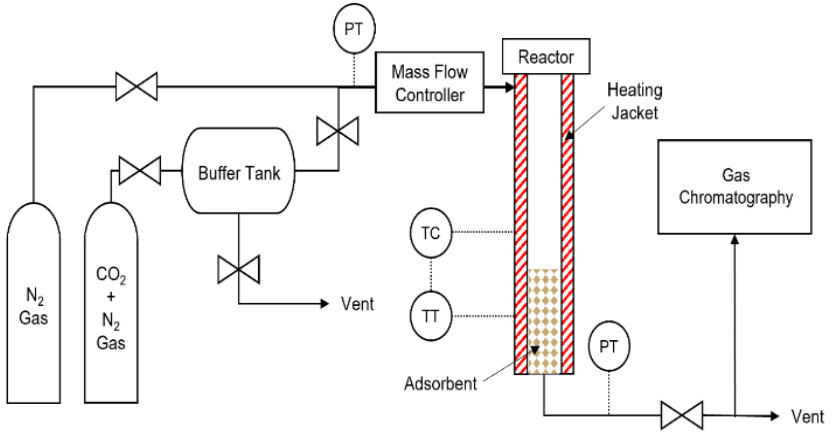
Model description

- Process simulation was performed using Aspen Adsorption, an adsorption process modeling tool.
- The simulation was based on the lab scale model.
- Only the adsorption phase of the adsorption–regeneration cycle was simulated.
- Model fitting was carried out using experimental conditions and parameters obtained from the experiments.



** Figure. Aspen Adsorption*

	Composition of Flue gas	Pressure	Mass	Adsorption		
				Temperature	Flow rate	Adsorption Time
DEA-Resin	CO_2 5 % N_2 Balance	3.5 bara	3 g	30 ℃	30 sccm	1 hour



Process Simulation

Model description

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** Table. Key Models in Simulation*

Model	Method	Equation
Adsorption isotherm model	Langmuir 1	$w_i = \frac{IP_1P_i}{1+IP_2P_i}$
Mass transfer model	Lumped resistance with a linear driving force	$\frac{\partial w_i}{\partial t} = MTC_{si}(w_i^* - w_i)$
Energy Balance	Non-isothermal with Gas & Solid Conduction	$\left(\varepsilon_i\rho_g C_{p,g} + \rho_s C_{p,s}\right)\frac{\partial T}{\partial t} = \varepsilon_i \frac{\partial(v_g\rho_g C_{p,g}T)}{\partial z} - \rho_s \Delta H_{ads}\frac{dq}{dt}$
Pressure drop, Gas velocity within the bed	Ergun equation	$\frac{\partial p}{\partial z} = -(\frac{1.5\times10^{-3}(1-\varepsilon_i)^2}{\left(2r_p\psi\right)^2\varepsilon_i^3}\mu v_g + 1.75\times10^{-5}\rho_g\frac{(1-\varepsilon_i)}{2r_p\psi\varepsilon_i^3}v_g^2)$

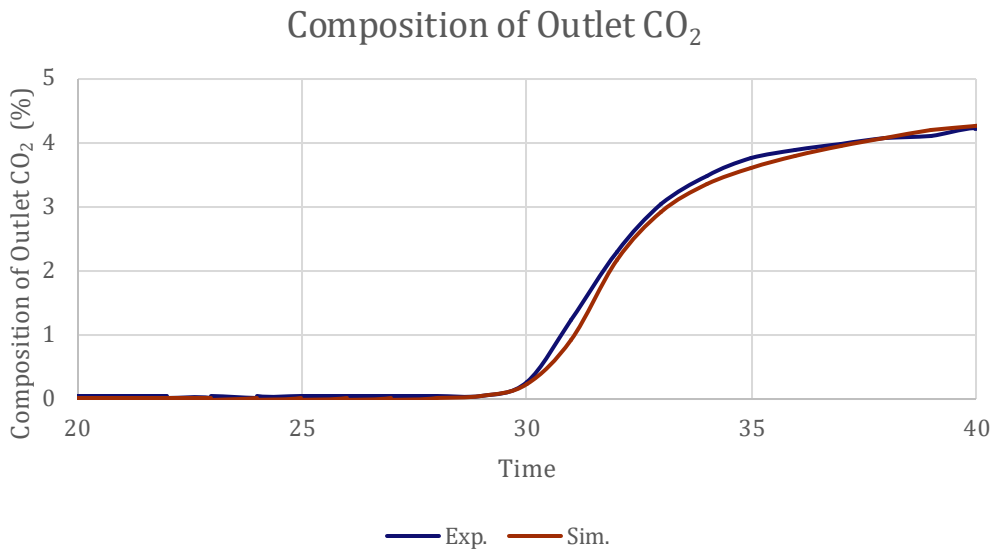
w_i : Adsorption capacity of adsorbent (mmol CO_2 / g of adsorbent)

ε_i : Inter-particle voidage
$C_{p,(g,s)}$: Heat Capacity of gas and solid

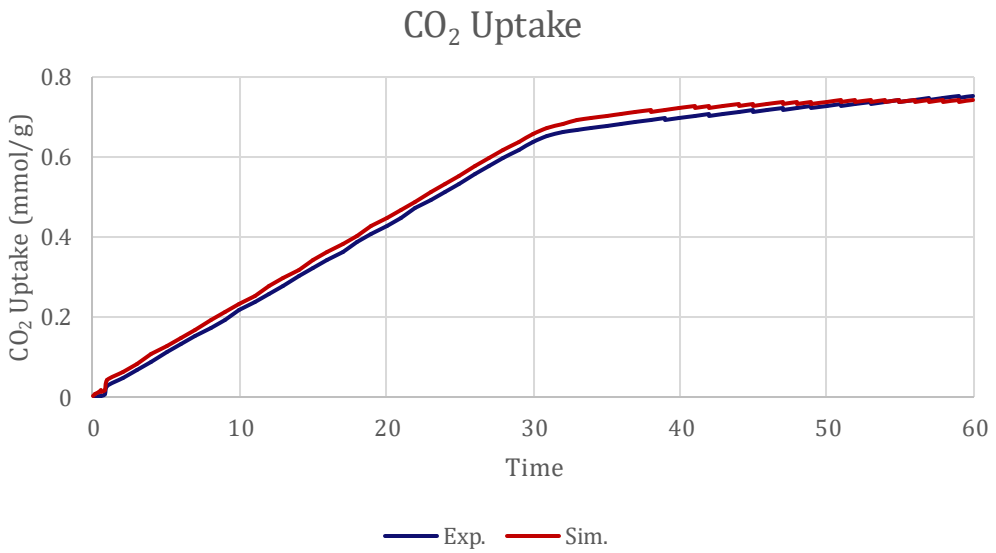
r_p : Particle radius
ψ : Sphericity
v_g : Gas Velocity

Process Simulation

Simulation Results



** Figure. Outlet CO_2 Concentration of Exp. and Sim.*



** Figure. CO_2 Hold up in bed of Exp. and Sim.*

- The breakthrough point and overall adsorption behavior were well simulated.
- Differences in adsorption rate were attributed to bed hold-up.

	Composition of Outlet CO_2	CO_2 Uptake
RMSE	0.1	0.017

Conclusion & Future Work

1. The adsorption performance of DEA infused resin was evaluated
    1. When regenerated at 90 , the resin showed 3.69 wt% adsorption performance, and no degradation was observed even after 10 cycles.
2. Regeneration temperature experiments were conducted from 50 °C to 90 °C, with 1-hour increments..
    1. The highest desorption was observed at 50 °C and 60 °C.
    2. At 50 °C, the resin exhibited the highest adsorption performance, with no degradation after 10 cycles.
3. Pressure experiments indicated that adsorption performance decreased by about 0.5 wt% compared to near-atmospheric pressure. It did not affect stability.
4. Aspen Adsorption simulations were carried out, successfully reproducing the adsorption process.

Future Work

- Further characterization of DEA-infused resins
- Economic evaluation of the process
- Desorption simulations
- Bed sizing and process design through simulation

Reference

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Thank you