Application of Breakthrough Curve Analyzers in Liquid Absorbents for CO_2 Capture

1. Background

Reducing atmospheric CO_2 concentrations remains one of the most pressing challenges in climate science and industrial decarbonization. Carbon Capture and Storage (CCS) has emerged as one of the most effective approaches for mitigating CO_2 emissions, with several core technologies under active development: membrane separation, solid adsorption, and liquid absorption.(1)

Liquid absorption is particularly useful due to its high efficiency and capacity for CO_2 absorption. While legacy chemical solvents offer high capacity and fast absorption rates, several (e.g., KOH and ammonia) face challenges related to equipment corrosion, volatility, and safety. Today, amine-based absorbents are the most widely used due to their favorable balance of reactivity, efficiency, and scalability in industrial CO_2 capture.(2)

The CO_2 absorption sequence into liquid follows these steps:

1. CO_2 diffuses from the bulk gas phase to the gas film surface.
2. It then moves across the gas film by molecular diffusion.
3. At the gas–liquid interface, CO_2 dissolves into the liquid.
4. The dissolved CO_2 diffuses through the liquid film.
5. Finally, CO_2 enters bulk liquid phase where chemical reaction with solvent occurs

Monoethanolamine (MEA) is one of the most widely used absorbents for CO_2 capture.(3) As a primary amine, MEA exhibits strong basicity and a low molecular weight, resulting in:

- ✓ High reactivity
- ✓ Rapid absorption kinetics
- ✓ High CO_2 capacity per unit mass
- ✓ Relatively low solvent cost

Due to these advantages, MEA-based absorption systems are commercially established and extensively deployed in both industrial and pilot-scale applications.

However, MEA is not without drawbacks. It has a high heat of reaction with CO_2, which translates to greater energy consumption during regeneration. MEA also tends to form stable amine carbonates and is prone to degradation when exposed to CO, sulfur compounds, or oxygen-containing gases, contributing to solvent loss and reduced operational efficiency.

Studies have shown that increasing MEA concentration improves CO_2 removal efficiency, but higher concentrations come with trade-offs like corrosion and degradation.(4) For these reasons, MEA is most commonly used at ~30 wt% concentration, where performance and system stability are reasonably balanced.

Current research efforts are focused on enhancing thermal and oxidative stability, reducing energy consumption during MEA regeneration, and developing modified or blended amine formulations to optimize performance.(5-7)

2. Experiment

To study the CO_2 absorption behavior of monoethanolamine (MEA), we conducted a series of experiments using the **BTsorb 100** breakthrough curve and mass transfer analyzer on a commercially available MEA solution. The experimental parameters are described in Table 1.
To eliminate interference from MEA vapor during measurement, a condenser was installed at the outlet of the sample cell and maintained at 0 °C, and a desiccant was placed in the cold trap to remove residual moisture from the gas stream. Prior to each experiment, the system was purged with nitrogen (N_2) at 185 mL/min to ensure complete removal of residual CO_2 from the setup.

The experiment was first conducted with fresh MEA (denoted MEA_F). A repeated CO_2 absorption experiment (denoted MEA_{RA}) was performed after CO_2 desorption from spent sample. Regeneration was carried out by heating the sample cell to 120 °C. Once the CO_2 concentration at the outlet dropped below 0.5%, the absorption process was repeated under the same conditions. An additional test was performed by sampling fresh MEA solution under the same test conditions to assess repeatability (denoted MEA_F-2).

Sample ID	**Sample Volume (mL)**	**N_2 Flow Rate (mL/min)**	**CO_2 Flow Rate (mL/min)**	**Temperature (°C)**	**Pressure (bar)**
MEA_F	10	185	15	40	1
MEA_{RA}					
MEA_F - 2					

*Table 1: Experimental conditions for breakthrough curve analysis of CO_2 in MEA using the **BTsorb100** from **AMI***

3. Results

As shown in Figure 1, the breakthrough curves from the MEA_F and MEA_F-2tests are nearly identical, demonstrating excellent repeatability of the experimental setup. However, the MEA_{RA} curve exhibits a slightly shorter breakthrough time, indicating a marginal decrease in absorption capacity following the regeneration cycle.

This result suggests that while MEA retains good performance after regeneration, some loss of absorption efficiency may occur, likely due to incomplete solvent recovery or minor thermal degradation during the desorption process.

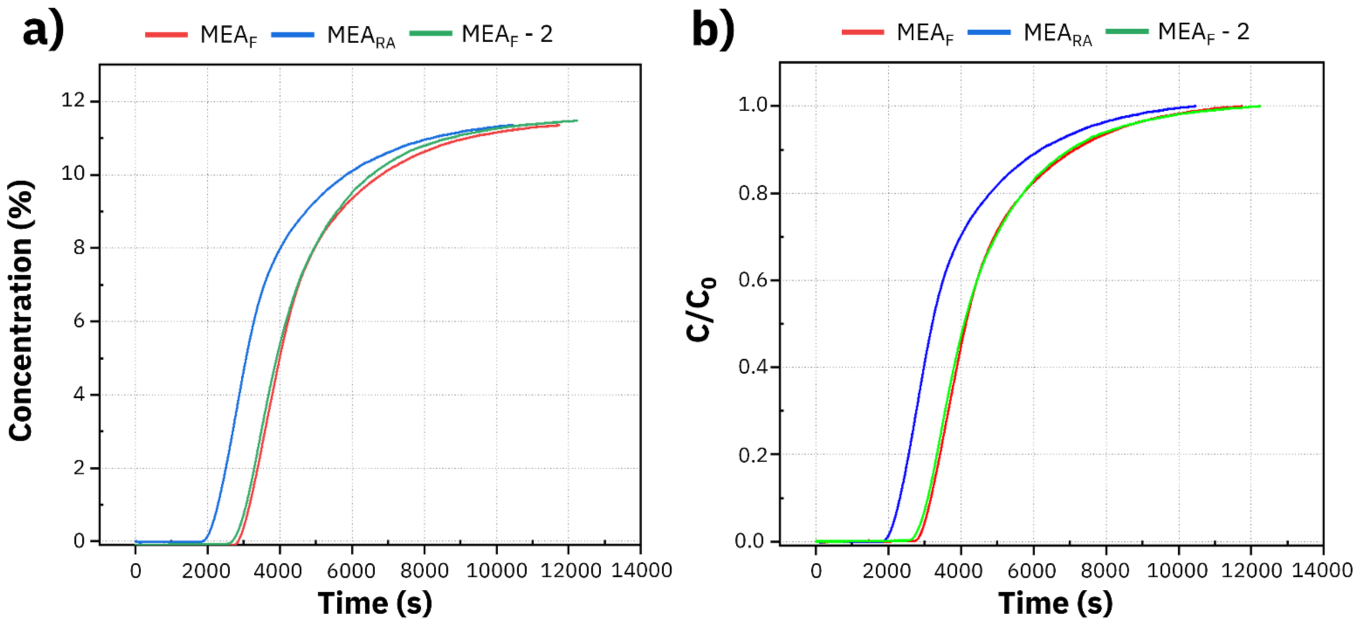

Figure 1: Breakthrough curves for CO_2 absorption in MEA displayed as time vs a) total CO_2 concentration and b) C/C_0

Sample ID	Absorption Capacity (mol CO_2/mol MEA)
MEA$_F$	0.4875
MEA$_{RA}$	0.3875
MEA$_F$ - 2	0.4822

Table 2: Calculated absorption capacities for CO_2 in fresh MEA (MEA$_F$), MEA after re-absorption (MEA$_{RA}$), and a second fresh MEA experiment (MEA$_F$ – 2)

Based on the calculated results presented in Table 2, the measured CO_2 absorption capacities for the two 10 mL monoethanolamine (MEA) samples were 0.4875 mol/mol and 0.4822 mol/mol, respectively. These values are consistent with the commonly reported commercial MEA capacity of approximately 0.5 mol CO_2 per mol amine, validating the reliability of the test conditions and measurement approach.(8)

Following desorption and re-absorption (MEA$_{RA}$), the measured absorption capacity decreased to 0.3875 mol/mol, indicating a notable decline in performance after regeneration. This reduction may be attributed to partial thermal degradation of MEA or incomplete recovery of active absorption sites during the desorption cycle.

4. Conclusions

This study demonstrates the viability of using monoethanolamine (MEA) as a chemical absorbent for CO_2 capture under ambient conditions. Through a combination of theoretical review and experimental validation using the **BTsorb 100** breakthrough analyzer, MEA was shown to achieve CO_2 absorption capacities consistent with commercial expectations (~0.5 mol/mol).(8) While regeneration was successful, a decline in absorption performance after the desorption cycle suggests some loss in efficiency, likely due to thermal degradation or incomplete solvent recovery. The data confirms that MEA remains a strong candidate for CO_2 absorption systems, especially when optimized with temperature control and proper regeneration protocols.

- ✓ Versatile and comprehensive dynamic sorption analyzer designed for:
  - ✓ Breakthrough curve analysis
  - ✓ Competitive adsorption
  - ✓ Kinetic analysis
- ✓ Ideal for adsorption and separation analysis of porous materials like MOFs and zeolites

*Figure 2: Highlighted features of **BTsorb 100** dynamic sorption analyzer from **AMI***

For dynamic transport and process-relevant validation, the **AMI BTsorb 100**, shown in Figure 2, is ideal for these experiments. Its breakthrough-curve architecture couples precise mass-flow control with fast, low-noise detection to quantify real-time uptake, breakthrough times, and dynamic capacities under user-defined gas compositions, temperatures, and humidities. This enables direct observation of front propagation, mass-transfer resistances, and competitive adsorption—parameters that static sorption alone cannot resolve. The **BTsorb 100** workflow supports condensers, cold traps, and in-line conditioning, allowing accurate testing of challenging streams (e.g., moisture-bearing or reactive gases) while maintaining instrument stability and repeatability. Because **BTsorb** results correlate cleanly with static/gravimetric datasets (e.g., **Micro 300C**, **RuboSorp MSB**) and high-pressure capacity measurements (**RuboSorp MPA**), teams can link mechanistic sorption to process-scale performance in a single, coherent platform, making **BTsorb 100** the preferred tool for adsorption capacity, kinetic screening, and cycle-design.

5. References

(1) Osman, A. I.; Hefny, M.; Abdel Maksoud, M. I. A.; Elgarahy, A. M.; Rooney, D. W. Recent advances in carbon capture storage and utilisation technologies: A review. *Env. Chem. Lett.* **2021**, *19*, 797-849.
(2) Chowdhury, F. A.; Yamada, H.; Higashii, T.; Goto, K.; Onada, M. CO_2 capture by tertiary amine absorbents: A performance study. *Ind. Eng. Chem. Res.* **2013**, *52*, 8323-8331.
(3) Rao, A. B. and Rubin, E. S. A technical, economic, and environmental assessment of amine-based CO_2 capture technology for power plant greenhouse gas control. *Environ. Sci. Technol.* **2022**, *36*, 4467-4475.
(4) Wang, N.; Wang, D.; Krook-Riekkola, A.; Ji, X. MEA-based CO_2 capture: A study focuses on MEA concentrations and process parameters. *Front. Energy Res.* **2023**, *11*, 1230743.
(5) de Ávila, S. G.; Logli, M. A.; Matos, J. R. Kinetic study of the thermal decomposition of monoethanolamine (MEA), diethanolamine (DEA), triethanolamine (TEA), and methyldiethanolamine (MDEA). *Int. J. Greenhouse Gas Control*, 2015, *42*, 666-671.
(6) Ge, Y.; Zhang, Z.; Yang, L.; Liu, F.; Yang, X.; Liu, K. Surfactant-modified monoethanolamine for better foaming to enhance CO_2 removal efficiency. *Chem. Eng. J.* **2024**, *498*, 155440.
(7) Wang, Y.; Cheng, F.; Li, J.; Liu, Y.; Wang, H.; Li, Z.; Yang, X. Development of MEA-based and AEP-based CO_2 phase change absorbent. *Processes*, **2016**, *13*, 92.
(8) Dugas, R. and Rochelle, G. Absorption and desorption rates of carbon dioxide with monoethanolamine and piperazine. *Energy Procedia*, **2009**, *1*, 1163-1169.