Assessment of the Blended Amine Absorbents Targeting CO_2 Capture from Low CO_2 Content Flue Gas

Introduction

Aqueous amine absorption is one of the most mature and practical technologies for post-combustion CO_2 capture. Conventional amine solvents, such as monoethanolamine (MEA), have been widely used as benchmark absorbents because of their fast CO_2 absorption kinetics and relatively simple process applicability. However, the large-scale implementation of amine-based CO_2 capture is still limited by high regeneration energy demand, solvent degradation, corrosion, and process cost. These limitations become more critical when treating low-CO_2 flue gases, where the reduced CO_2 partial pressure decreases the gas–liquid driving force for absorption. Low-CO_2 exhaust streams from gas-fired or highly diluted power systems, such as NGCC- and SOFC-related processes, typically require more efficient solvent screening strategies than conventional coal-fired flue gas capture. Under these conditions, the solvent must maintain sufficient CO_2 absorption response despite the low CO_2 concentration. Therefore, evaluating the early-stage absorption behavior and outlet CO_2 response of candidate solvents is essential for identifying suitable absorbents for low-CO_2 flue-gas capture. Blended amine absorbents have been investigated as a practical strategy to overcome the limitations of single-component amine solvents. Primary and secondary amines generally provide rapid CO_2 absorption through carbamate formation, whereas tertiary and sterically hindered amines can offer higher theoretical loading and improved regeneration behavior through bicarbonate-based pathways. In addition, cyclic diamines such as piperazine (PZ) can act as kinetic promoters to enhance the absorption rate of slower amine systems. Although various blended amine systems have been reported, systematic dynamic screening under approximately 5 vol% CO_2 conditions remains important for low-partial-pressure flue-gas applications. In this study, a lab-scale NDIR-based screening approach is proposed to evaluate blended amine absorbents under low-CO_2 flue-gas conditions. The initial solvent set includes a benchmark primary amine, a tertiary amine platform, and promoter-containing blended amine systems. The objective of this work is to establish a practical screening protocol based on outlet CO_2 profiles, initial absorption response, CO_2 loading, and cyclic capacity.

Theory

The reaction pathway of CO_2 absorption depends on the amine structure. Primary and secondary amines react rapidly with CO_2 through a zwitterion mechanism, forming carbamate and protonated amine species. This pathway provides fast CO_2 uptake but generally limits the theoretical CO_2 loading because two amine molecules are involved in the formation of one carbamate species. The stable carbamate species can also increase the thermal energy required for solvent regeneration. Tertiary amines do not form carbamate directly because they lack an N–H bond. Instead, they act as bases that promote CO_2 hydration and bicarbonate formation in aqueous solution. This bicarbonate-based pathway can provide improved regeneration behavior and higher theoretical CO_2 loading, but the intrinsic absorption rate is typically lower than that of primary or secondary amines. Therefore, tertiary amines alone may show limited absorption response under low CO_2 partial pressure. Promoted blended amines are designed to compensate for this limitation. In these systems, a fast-reacting promoter can enhance the early-stage CO_2 absorption response, while the base amine contributes to working capacity and regeneration-related performance. This complementary behavior is particularly relevant under approximately 5 vol% CO_2 conditions, where rapid absorption at low driving force is required.

Method

The amine screening system consists of a simulated flue-gas supply, mass flow control unit, gas–liquid absorption reactor, temperature control unit, condenser or drying unit, and non-dispersive infrared (NDIR) CO_2 analyzer. A CO_2/N_2 gas mixture containing approximately 5 vol% CO_2 is introduced into the aqueous amine solution at a fixed flow rate and temperature. The outlet CO_2 concentration is continuously monitored using the NDIR analyzer, and the resulting time-resolved CO_2 profile is used

to compare the absorption behavior of each solvent. The screening focuses on three classes of amine absorbents: benchmark amines, regeneration-oriented amines, and promoted blended amines. A benchmark primary amine is used to provide a reference for rapid CO_2 absorption. A tertiary amine is selected as a platform solvent because of its favorable regeneration-related characteristics. A cyclic diamine promoter is introduced to improve the absorption response of the tertiary amine-based system. Depending on solvent availability, additional blended systems containing sterically hindered amines or alternative tertiary amines can be included to broaden the screening map. The absorbed amount of CO_2 is calculated from the difference between the inlet and outlet CO_2 flow rates. The CO_2 loading is defined as: CO_2 loading = n_{CO2} / n_{amine} where n_{CO2} is the amount of absorbed CO_2 and n_{amine} is the total amount of amine in the solution. The initial absorption rate is estimated from the initial slope of the CO_2 loading–time profile. The outlet CO_2 concentration profile is also used to evaluate the breakthrough response, CO_2 removal efficiency, and the time required for the outlet CO_2 concentration to approach the inlet concentration. For regeneration-related evaluation, cyclic capacity is used as a key screening parameter: Cyclic capacity = rich loading − lean loading where rich loading is the CO_2 loading after absorption and lean loading is the CO_2 loading after desorption. These parameters are combined to construct a screening index for low-CO_2 flue-gas capture.

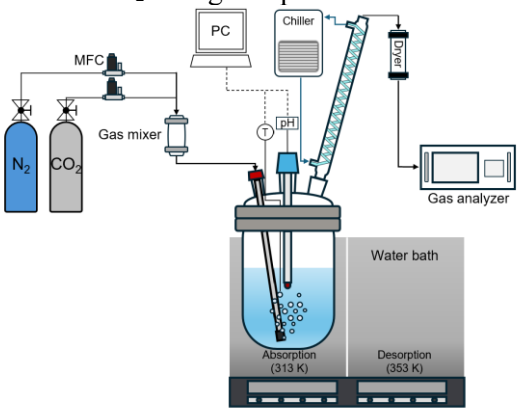

Figure 1. *Schematic illustration of the lab-scale NDIR-based amine screening system*

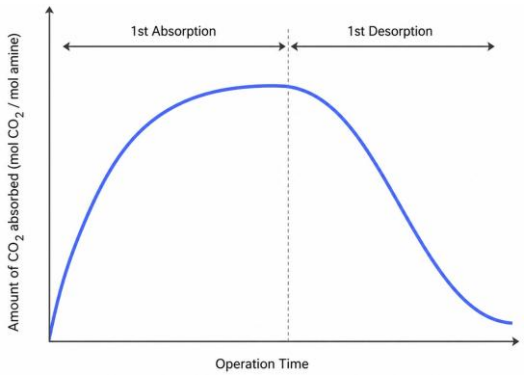

Figure 2. *Absorption–desorption profile of an amine absorbent*

Conclusions

This study proposes an NDIR-based screening approach for evaluating blended amine absorbents under low-CO_2 flue-gas conditions. Unlike conventional amine screening studies mainly focused on higher CO_2 concentrations, this work emphasizes dynamic outlet CO_2 response and early-stage absorption behavior at approximately 5 vol% CO_2. This condition is relevant to low-partial-pressure exhaust streams from NGCC- and SOFC-related processes. The proposed screening protocol enables direct comparison of benchmark amines, tertiary amine platforms, and promoter-containing blended amine systems under identical operating conditions. Time-resolved NDIR analysis provides quantitative information on CO_2 removal behavior, absorption rate, loading capacity, and cyclic capacity. These

parameters can be used to construct a practical solvent screening map for selecting promising absorbents for low-CO_2 flue-gas capture. The NDIR-based outlet CO_2 profiles and comparative screening indices is used to clarify how blended amine design influences CO_2 absorption behavior under low CO_2 partial pressure, providing a basis for further optimization of amine absorbents for CCUS applications.

Acknowledgements (Optional)

National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS2023-00280519)
Korea Basic Science Institute (National research Facilities and Equipment Center) grant funded by the Korea government (MSIT) (RS-2024-00404896)
Korea Planning & Evaluation Institute of Industrial Technology funded by the Korean government (Ministry of Trade, Industry, and Energy, MSIT, Ministry of the Interior and Safety, National Fire Agency, Project Title: Development of gas hydrate extinguishing agent and fire suppression technology for inaccessible fires, Project Number: 2760000002)
Global - Learning & Academic research institution for Master's·PhD students, and Postdocs (LAMP) Program of the NRFgrant funded by the Ministry of Education (RS-2025-25440216).
This research was supported by the Regional Innovation System & Education(RISE) program through the Institute for Regional Innovation System & Education in Busan Metropolitan City, funded by the Ministry of Education(MOE) and the Busan Metropolitan City, Republic of Korea.(2026-RISE-02-003)

References

Meng, F., Meng, Y., Ju, T., Han, S., Lin, L., and Jiang, J. Research progress of aqueous amine solution for CO2 capture: A review. Renewable and Sustainable Energy Reviews, 168, 112902, 2022.

Kim, J., Kim, K., Lim, H., Kang, J. H., Park, H. S., Park, J., and Song, H. Structural investigation of aqueous amine solutions for CO2 capture: CO2 loading, cyclic capacity, absorption–desorption rate, and pKa. Journal of Environmental Chemical Engineering, 12, 112664, 2024.

Mazari, S. A., Ghalib, L., Sattar, A., Bozdar, M. M., Qayoom, A., Ahmed, I., Muhammad, A., Abro, R., Abdulkareem, A., Nizamuddin, S., Baloch, H., and Mubarak, N. M. Review of modelling and simulation strategies for evaluating corrosive behavior of aqueous amine systems for CO2 capture. International Journal of Greenhouse Gas Control, 96, 103010, 2020.

Patil, M., Vaidya, P., and Kenig, E. Bench-scale study for CO2 capture using AMP/PZ/water mixtures. Chemical Engineering Transactions, 69, 163–168, 2018.

Zhou, X., Song, Q., Chen, J., Chen, C., Chen, Y., and Yang, F. N,N-diethylethanolamine-based blended amine systems enhance CO2 capture performance. Chemical Engineering Journal, 521, 166709, 2025.