China Steel Technical Report, No. 38, pp.84－90, (2025)

Development of Energy-Saving Absorbents for CO_2 Capture

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The Taiwanese government has announced a policy to achieve carbon neutrality by 2050. To mitigate CO_2 emissions, various decarbonization options have been proposed, such as improving energy efficiency, using hydrogen-based energy, replacing fossil fuels with biomass, and combining them with carbon capture and storage (CCS) processes. Among these options, CCS is a key strategy for China Steel's carbon-neutral pathway. The cost of carbon capture is most closely related to the regeneration energy consumption. The regeneration energy is strongly linked to the properties of the absorbent itself. Amine-based absorbents, including primary, secondary, and tertiary amines, are the most promising solutions for carbon capture because they generate bicarbonates after reacting with CO_2, which can reduce regeneration energy consumption. This study developed low-energy, high-efficiency absorbents through absorbent blending to reduce carbon capture costs. In this study, mixed absorbents were synthesized, and a performance screening method was established to identify an optimal formulation. Carbon capture experiments showed that, when the inlet CO_2 concentration and flow rate were 28% and 25 LPM, respectively, the newly developed absorbent reduced regeneration energy consumption by approximately 10-20% compared to the commercial absorbent at similar CO_2 recovery rates.

Keywords: CO_2, Chemical absorption, Energy consumption, Absorbent

1. INTRODUCTION

Anthropogenic emissions of CO_2 are one of the main causes of global warming. According to the Intergovernmental Panel on Climate Change (IPCC), global anthropogenic emissions of CO_2 should be reduced to net-zero by 2050 to avoid a temperature increase of greater than 1.5°C. The main sources of CO_2 emissions are the combustion of fossil fuels and industrial processes, particularly in cement production(1). Governments around the world have committed to developing carbon reduction regulations and technologies. Taiwan aims to achieve carbon neutrality by 2050.

To mitigate CO_2 emissions, various decarbonization options have been proposed, including measures to improve energy efficiency through hydrogen-based energy, replacing fossil fuels with biomass, and integrating carbon capture, utilization, and storage (CCUS) processes. CCUS refers to carbon capture, utilization, and storage technology, which is the process of separating CO_2 from industrial processes, energy use, or the atmosphere, and either utilizing it directly or injecting it into the ground to achieve a permanent reduction in the amount of carbon dioxide. Several technologies exist for capturing CO_2, including chemical absorption, cryogenic separation, removal with membranes, and adsorption with zeolites or metal–organic frameworks(2–7). Chemical absorption is a well-known process that has been proposed as the most dominant technology for CO_2 capture in the post-combustion process. The chemical absorption process can be divided into two phases: absorption and desorption. The flue gas enters the bottom of a packed column, flows upward, and contacts a CO_2-absorbing solvent circulated countercurrently. The CO_2-rich solution (rich solvent), leaving the bottom of the absorber, is then pumped to a cross heat-exchanger and then to a desorber column for its regeneration at high temperature. In the regeneration, the reactions between CO_2 and the solvent are reversed using heat, and gaseous CO_2 and water vapor are produced. The gases are sent to a condenser, where gas rich in CO_2 is obtained. The regenerated solvent, now with a low concentration of CO_2 (lean solvent), is returned to the absorber. In the regeneration, one of the main factors to consider for the process optimization is the energy input(8).

The cyclic chemical absorption and regeneration process based on common primary and secondary amines such as monoethanolamine (MEA) and diethanolamine (DEA) is the most mature in industrial applications(3,5). Unhindered primary and secondary amines react rapidly with CO_2 to form very stable carbamates. The amount of energy required for the regeneration of these solvents is large. Carbon capture applied to a coal-fired power plant may reduce the net output of the plant by 30%(6). With sterically hindered amines or tertiary amines, CO_2 is captured as bicarbonate, which has a much smaller heat of reaction than carbamate formation, resulting in regeneration energy savings(9). Moreover, their CO_2 absorption capacity is much higher. Tertiary amines are therefore increasingly used in the high-pressure natural gas treatment industry to remove acid gases like CO_2. However, in general, the rate of direct bicarbonate formation is much lower than that of carbamate formation, resulting in much slower CO_2 absorption rates with tertiary amines and thus in unacceptably large equipment for low-pressure, anthropogenic (flue gas), CO_2 capture applications(5,9). Another option, which is currently followed by the industry, is to prepare an absorbent with low regeneration energy consumption through absorbent blending, significantly taking into account both regeneration energy consumption and absorption rate. Therefore, the objective of this study is to prepare new absorbents to reduce regeneration energy consumption through absorbent blending.

2. EXPERIMENTAL METHOD

2.1 Construction of CO_2 Capture Pilot Plant

A self-designed CO_2 capture pilot plant with a capture capacity of approximately 10-20 kg of CO_2 per day has been constructed and tested. Figure 1 shows the carbon capture pilot plant. The carbon capture system is housed within a container-based structure, making it transportable and suitable for on-site testing across different industrial facilities. This setup allows for flexible adaptation to various flue gas compositions.

Figure 2 shows the flow sheet of the carbon capture process. The equipment is described as follows:

Column A: Pretreatment Column

The pretreatment column removes air pollutants from flue gas that may interfere with CO_2 absorption

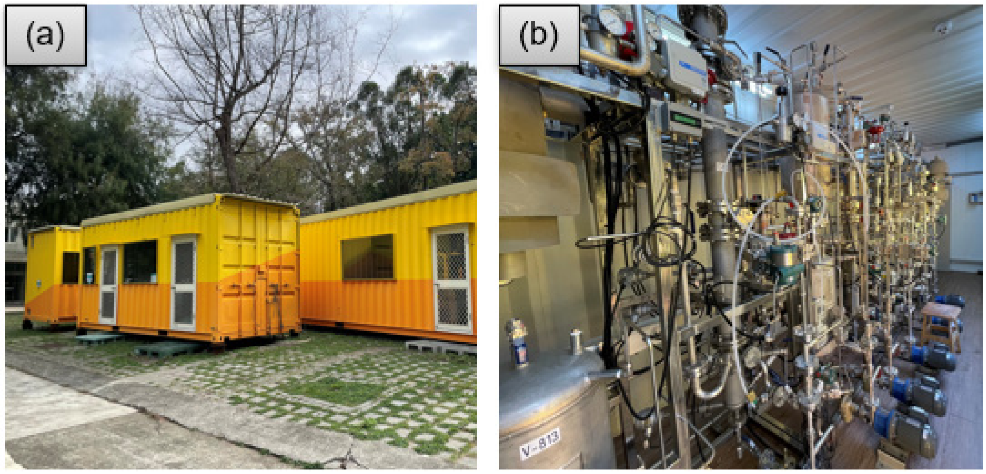

Fig.1. Carbon capture pilot plant. (a) Exterior view of the carbon capture pilot plant. (b) Equipment inside the pilot plant.

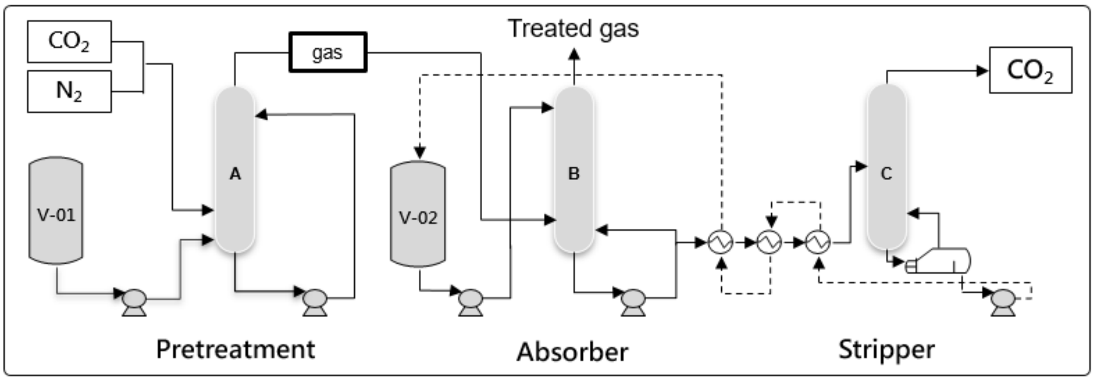

Fig.2. Schematic diagram of the carbon capture process.

(e.g., acidic gases, particles). The simulated flue gas produced from the cylinders does not contain acidic gases. V-01 is filled with pure water in this study. The CO_2 concentration in the simulated flue gas diluted with nitrogen is about 28%.

Column B: Absorber

The pretreated gas entering the absorber contacts with the absorbent supplied from V-02 in a countercurrent way. The absorbent selectively absorbs CO_2. The treated (CO_2-lean) gas is released from the top of the absorber.

Column C: Stripper

Function: the regeneration of the absorbent.

V-01: Pretreatment Liquid Tank

The pretreatment liquid tank is used for storing alkaline solution to remove acidic gases (e.g., SO_2, HCl) of flue gas. In this study, pure water is used for the simulated flue gas washing and humidification.

V-02: Absorbent Storage Tank

The absorbent storage tank is used to store the chemical absorbent (e.g., amine solution). The regenerated absorbent from the stripper is pumped into the absorber.

2.2 Preparation of Absorbents

Before conducting carbon capture experiments, various absorbents are prepared in the laboratory and exposed to CO_2 to evaluate their absorption rates. In this study, 30 wt.% MEA (monoethanolamine), 30 wt.% SHA (sterically hindered amine), 20 wt.% SA (secondary amines), and the commercial benchmark (Comm) were tested. The absorbent formulation with the highest CO_2 absorption rate was selected and then introduced into the carbon capture system for further testing. In the system, V-01 is filled with water, and V-02 is filled with absorbent.

2.3 CO_2 Capture in Pilot Plant

This carbon capture system is divided into three main stages: Pretreatment, Absorption, and Regeneration (Stripping). In the pretreatment stage, a mixed gas composed of nitrogen and carbon dioxide is regulated using flow meters and then enters the pretreatment Column A. Since the system uses a simple CO_2/N_2 mixture without acidic gases, V-01 is filled with pure water instead of the alkaline solution commonly used in real flue gas treatments. The water serves to humidify and lightly clean the gas stream.

After pretreatment, the gas enters the absorber Column B, where it reacts with the absorbent supplied from tank V-02. V-02 typically contains an amine-based absorbent, which selectively captures CO_2 from the gas stream. The ratio of the absorbent circulation rate to inlet gas flow (L/G in L/m^3) affects the carbon capture efficiency and was investigated. The treated gas, with reduced CO_2 content, exits from the top of the absorber. The CO_2-rich absorbent (rich solvent) is then sent to the stripper, where heat and a reboiler system are used to release the absorbed CO_2. The purified CO_2 is collected from the top of the stripper, while the regenerated absorbent is cycled back to tank V-02 or directly returned to the absorber for reuse. The bottom temperature of the stripper influences the CO_2 capture efficiency. Different temperatures were tested to achieve various capture efficiencies, and the corresponding energy consumption was measured.

3. RESULTS AND DISCUSSION

3.1 Measurement of CO_2 Absorption Rates

The CO_2 absorption rates of SHA, SA, and MEA were tested in the laboratory. Figure 3 shows the CO_2 absorption rates of these three absorbents. Results indicate that SA reached absorption saturation first, achieving saturated CO_2 absorption within 60 minutes. MEA followed, reaching saturation at 90 minutes, while SHA exhibited the slowest absorption rate, taking up to 150 minutes to reach saturation due to its steric hindrance effect. Within the first 30 minutes of CO_2 introduction, the absorption rate order was observed as SA > MEA > SHA. However, after 90 minutes, SHA's absorption amount and rate surpassed those of MEA. As a result, the final CO_2 saturation capacities ranked as SA > SHA > MEA.

The reaction between CO_2 and alkanolamines involves the formation of carbamates and bicarbonates, as illustrated in Figure 4. Primary amines mainly react to form carbamates, requiring 2 moles of amine per mole of CO_2. In contrast, sterically hindered amines and secondary amines tend to form bicarbonates, which follow a 1:1 molar ratio with CO_2. The formation of bicarbonate is beneficial in the regeneration process within the stripper, as it helps reduce the energy required for CO_2 desorption. Based on these reaction mechanisms, SHA reacts with CO_2 to form both carbamates and bicarbonates. The formation of bicarbonate is advantageous as it helps reduce energy consumption. However, due to its slower CO_2 absorption rate, SHA needs to be blended with SA to enhance its overall absorption performance.

The pilot-scale post-combustion CO_2 capture (PCC) facility evaluated in the study conducted by Yuli Artantoa et al [10]. was located at Loy Yang Power Station in Victoria, Australia. It was designed to capture approximately 50 kg of CO_2 per hour from the flue gas of a brown-coal-fired power plant using chemical absorption. When operating with 30 wt.% MEA as the absorbent, the study showed that different CO_2 capture rates corresponded to varying lean and rich loadings. Specifically, the rich loading ranged from 0.41 to 0.46 mol CO_2/mol amine, while the lean loading ranged from 0.17

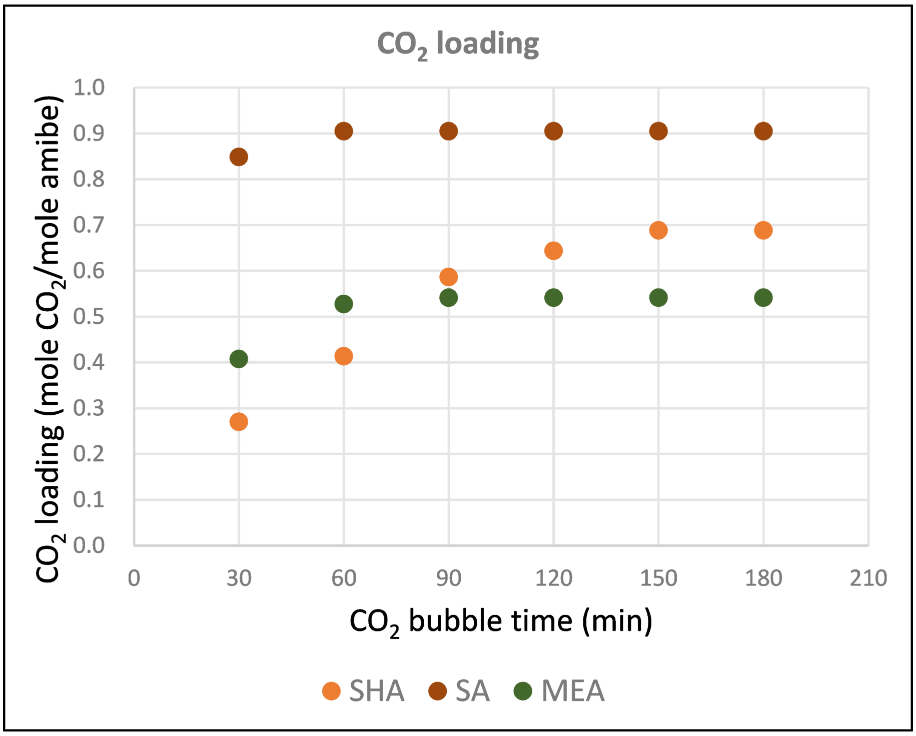

Fig.3. CO_2 absorption rates of SHA, SA, and MEA.

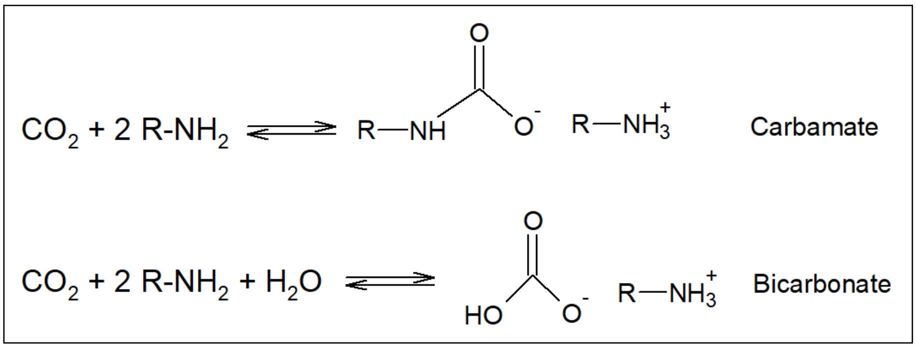

Fig.4. Reaction between CO_2 and alkanolamines, showing the formation of carbamates and bicarbonates.

to 0.27 mol CO_2/mol amine. As shown in Figure 3, the lean and rich CO_2 loadings for MEA were reached within the first 30 minutes of CO_2 bubbling. Consequently, to better compare the absorption performance of various solvent formulations, the CO_2 bubbling period within the initial 30 minutes was analyzed with finer time resolution.

CO_2 gas was introduced into the system to identify solvent formulations with lower energy consumption compared to Comm. The tested formulations included Comm, A, B, and C. Absorbents A, B, and C are composed of SA, SHA, and water mixed in different proportions. The CO_2 loading results are summarized in Figure 5. When comparing the CO_2 absorption capacity at saturation, it is evident that C > B > Comm > A. However, in practical carbon capture applications, most of the CO_2 absorption and desorption loading occurs within the first 30 minutes of laboratory CO_2 bubbling tests. Figure 6 further presents the CO_2 loading results for A, B, and Comm, segmented into finer time intervals within the initial 30 minutes of CO_2 bubbling. Among the tested formulations, absorbent B demonstrated superior performance compared to Comm, while absorbent A showed slightly lower CO_2 loading. Absorbents B and Comm will be used in the carbon capture pilot plant for further CO_2 capture testing.

3.2 Absorbent Evaluation for CO_2 Capture in the Carbon Capture Pilot Plant

3.2.1 Absorbent Comm

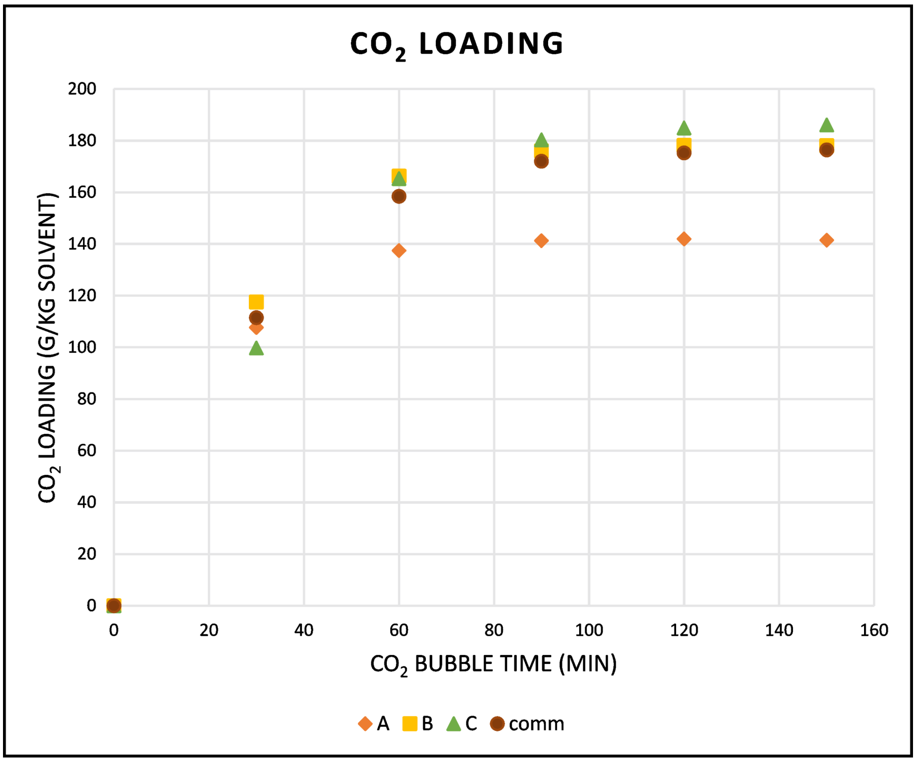

Fig.5. CO_2 loading of different absorbent Formulations.

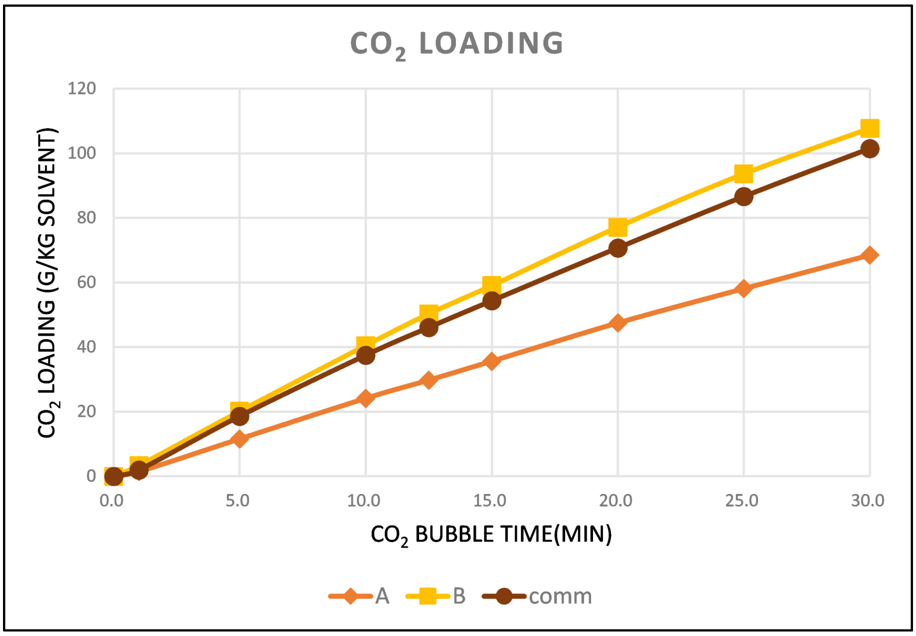

Fig.6. CO_2 loading of different absorbent Formulations within the first 30 minutes of CO_2 introduction.

The absorbent Comm was introduced into V-02 to conduct carbon capture experiments. At a gas inlet flow rate of 25 LPM with a CO_2 concentration of 28%, experiments were conducted by varying the absorbent circulation rate to achieve different L/G (liquid-to-gas) ratios of 14, 10, 9, and 6.67. During these tests, the external temperature of the stripper reboiler was fixed at 125°C. Under the condition where the heat transfer oil temperature was kept constant, it was observed that the carbon capture efficiency could be effectively adjusted by changing the absorbent flow rate. Table 1 shows that as the L/G ratio increased, the CO_2 recovery rate also increased. However, this improvement in efficiency was accompanied by a corresponding increase in energy consumption.

Subsequently, the absorbent circulation rate was fixed to maintain an L/G ratio of 9, while the external temperature of the stripper reboiler's heat transfer oil was varied at 120°C, 122°C, 124°C, 125°C, and 127°C. The objective was to evaluate the effects on the CO_2 recovery rate and energy consumption. The results are summarized in Table 2. It was observed that changes in the reboiler external temperature directly influenced the bottom temperature of the stripper, which in turn affected both the CO_2 recovery rate and the associated energy consumption.

Both the variation of the L/G ratio and the adjustment of the reboiler external temperature were found to influence the stripper bottom temperature. These changes ultimately impacted the CO_2 recovery rate, while energy consumption increased proportionally with the higher CO_2 recovery rate.

3.2.2 Absorbent B

The absorbent in the carbon capture system was replaced with absorbent B, while maintaining the same inlet gas flow rate of 25 LPM and a CO_2 concentration of 28%. The L/G ratio was fixed at 9, and carbon capture experiments were conducted by varying the external temperature of the stripper reboiler. The results were summarized in Table 3 and further compared with Comm., as illustrated in Figure 7. Under a similar CO_2 recovery rate, absorbent B demonstrated a 10–20% lower energy consumption compared to Comm.

Table 1 Effect of L/G ratio on carbon capture performance of absorbent Comm.

L/G (L/m^3)	CO_2 Purity (v%)	CO_2 recovery rate (%)	Energy consumption (GJ/tCO_2)	Stripper bottom temperature (°C)
14	>99	96.95	5.0	103.7
10	>99	92.65	3.92	102.3
9	>99	84.2	3.51	101.6
6.67	>99	58.91	2.92	101.2

(CO_2 inlet concentration: 28 v%, gas inlet flow rate: 25 LPM)

Table 2 Effect of stripper reboiler temperature on carbon capture performance of absorbent Comm.

Stripper reboiler Temperature (°C)	CO_2 Purity (v%)	CO_2 recovery rate (%)	Energy consumption (GJ/tCO_2)	Stripper bottom Temperature (°C)
120	>99	64.55	2.8	99.4
122	>99	80.85	3.23	101
124	>99	82.7	3.37	101.3
125	>99	84.2	3.51	101.6
127	>99	91.55	4.05	102.9

(CO_2 inlet concentration: 28 v%, gas inlet flow rate: 25 LPM, L/G: 9 L/m^3)

Table 3 Carbon capture performance of absorbent B.

Stripper reboiler Temperature (°C)	CO_2 Purity (v%)	CO_2 recovery rate (%)	Energy consumption (GJ/tCO_2)	Stripper bottom Temperature (°C)
120	>99	66.00	2.52	98.4
122	>99	81.49	2.75	98.9
124	>99	85.52	2.87	100.3
125	>99	91.43	3.51	102.1
126	>99	95.62	3.96	103.4

(CO_2 inlet concentration: 28 v%, gas inlet flow rate: 25 LPM, L/G: 9 L/m^3)

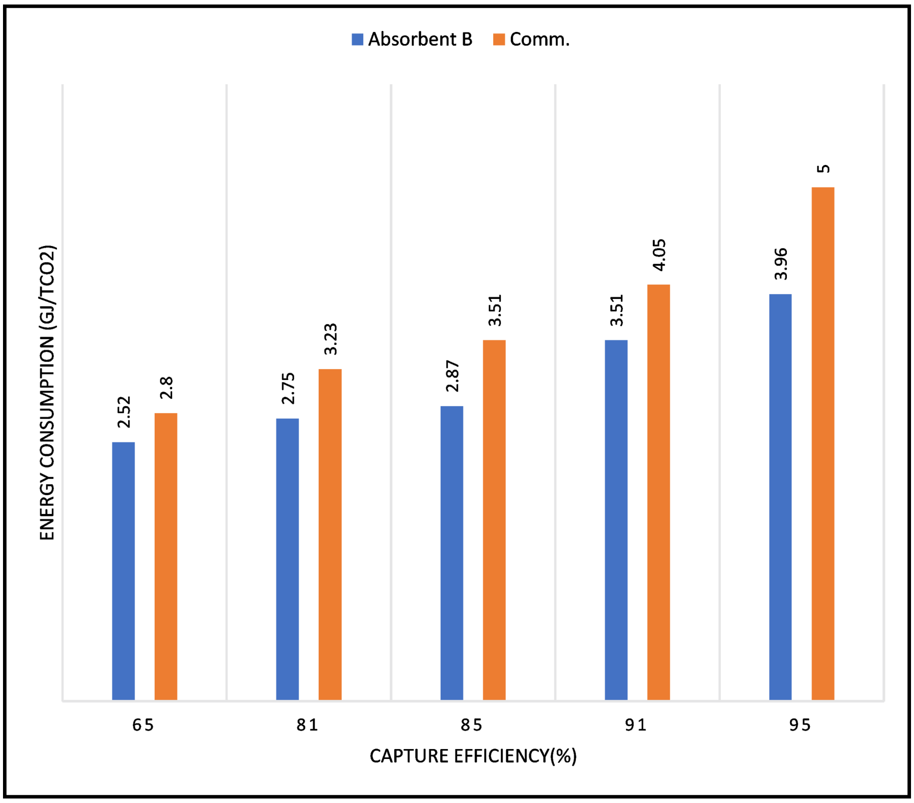

Fig.7. Carbon capture efficiency and energy consumption of absorbents Comm and B.

Additionally, the bottom temperature of the stripper using absorbent B was approximately 0.8–1.5°C lower, indicating its potential for energy savings in regeneration processes.

4. CONCLUSIONS

To ensure the effectiveness of the absorbents used in the carbon capture system, a laboratory-scale screening methodology was first established. This approach involved evaluating candidate formulations based on CO_2 absorption rate and loading capacity. Among the tested absorbents, absorbent B demonstrated promising performance in lab-scale tests and was therefore selected for further pilot-scale evaluation.

The subsequent carbon capture experiments revealed that both the L/G ratio and the stripper reboiler temperature significantly influenced system performance. Increasing the L/G ratio led to higher CO_2 capture efficiency, though it also resulted in greater energy consumption. When comparing absorbent B with the commercial absorbent (Comm), absorbent B achieved comparable capture efficiencies while reducing energy consumption by approximately 10–20% and lowering the stripper bottom temperature by 0.8–1.5°C. These results suggest that absorbent B is a more energy-efficient alternative for post-combustion CO_2 capture applications.

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