Experimental Study on the Performance of An MEA Alcoholamine Absorber for Flue Gas CO₂ Capture

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Abstract. The chemical absorption method utilizing alcohol-amine solutions has found widespread application in flue gas CO_2 capture and recovery in power plants. However, the performance of the absorbent and energy consumption are pivotal factors that have hindered its large-scale implementation in power plants. To facilitate the broader adoption of the chemical absorption method using alcohol-amine solutions in flue gas CO_2 capture, we conducted a comprehensive investigation into the absorbent's performance through experimental methods. In this study, a typical MEA solution was chosen as the focus, and an indoor experimental setup was established to systematically examine the absorption and desorption performance of the MEA solution under various concentration and temperature conditions. Special attention was given to assessing energy consumption during the desorption process. The experimental findings revealed distinct performance characteristics of the MEA solutions under different operating conditions, providing essential data for the further optimization of absorbers. These experimental results are anticipated to offer robust support for enhancing the efficiency of the chemical absorption method using alcohol-amine solutions for CO_2 capture from flue gas in power plants. The goal is to encourage its widespread application in industrial practices.

Keywords: Carbon dioxide capture, Absorbent MEA, Desorption energy consumption, Absorption properties, regeneration rate.

1 Introduction

With the escalating impacts of global climate change, the imperative to control and diminish carbon dioxide emissions, a major greenhouse gas, has become a pressing global task. Carbon Capture, Utilization, and Storage (CCUS) technology stands out as a key strategy to confront this challenge. Within the CCUS technology chain, carbon capture represents the linchpin, with its efficiency and cost directly determining the overall feasibility and economics of the technology chain.

In recent years, post-combustion carbon capture technologies based on absorption mechanisms have garnered considerable attention. Miran Yoo et al. delved into the performance of KOH aqueous solution as a CO_2 absorber, revealing its effectiveness in capturing CO_2 through continuous chemical reactions. This underscores the potential

application of chemical absorbers in the realm of carbon capture [1]. Additionally, a study by S. Jane et al. centered on the design of a wetted ledge using hydrated ammonia as an absorbent, simulating CO_2 absorption from a simulated flue gas. This further validated the viability of carbon capture technology for industrial applications [2]

Another crucial aspect of carbon capture technology lies in optimizing absorber performance. M. Lee et al. explored the utilization of a fibrous alumina mat immobilized with a calcium oxide absorber for CO_2 capture at high temperatures. This study not only enhances the stability of the absorber but also provides innovative insights into high-temperature carbon capture technology [3]. San-Jun Han et al. investigated the use of $Ca(OH)_2$ aqueous solution as an absorbent to capture high-concentration CO_2 gas mixtures, with results crucial for improving carbon capture efficiency and reducing costs [4].

As carbon capture technology advances, research on novel absorbers progresses. Susmita Datta Peu et al. provided a comprehensive review of post-combustion carbon capture technologies based on absorption mechanisms, emphasizing chemical and physical absorption, as well as the performance of various solvents and absorbing materials [5]. Y. Ye et al. optimized the absorption performance of the NICE absorber developed by the China Clean and Low-Carbon Energy Research Institute (CLCERI) on a pilot platform, exploring the effects of liquid-gas ratio, regeneration pressure, rich-liquid diversion ratio, and intermediate cooling on absorption performance and regeneration energy consumption. This provides crucial data for the practical application of low-energy carbon capture technology [6].
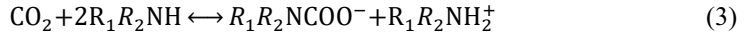
Furthermore, T. Westendorf et al. designed and constructed a laboratory-scale process based on a novel phase-change aminosilicone-based CO_2 capture solvent, aiming to validate the scalability, technical feasibility, and economic viability of post-combustion capture using a phase-change CO_2 capture absorbent [7]. M. Farhan's study focused on optimizing post-combustion carbon capture systems based on the chemisorption of MEA solvents. Through detailed process modeling and techno-economic analysis, this study demonstrated the potential of carbon capture technology in reducing costs and energy consumption [8]. In industrial production, CO_2 absorption and regeneration occur simultaneously, and the amount of solution regeneration energy consumption significantly determines the cost of CO_2 recovery. Therefore, measuring and analyzing the absorption and desorption performance of absorbents and regeneration energy consumption are crucial for evaluating absorbent performance.

2   Experimental principle and device

2.1   Experimental principle

The organic amine method for CO_2 absorption operates on a reversible process, involving the interaction of a weak acid with a weak base, resulting in the formation of water-soluble salts. The reaction equation for CO_2 absorption by MEA solution is outlined below.

$$2H_2O \longleftrightarrow H_3O^+ + OH^- \tag{1}$$

$$CO_2 + OH^- \longleftrightarrow HCO_3^- \tag{2}$$

$$CO_2 + 2R_1R_2NH \longleftrightarrow R_1R_2NCOO^- + R_1R_2NH_2^+ \tag{3}$$

Each of the aforementioned three reactions is reversible. When the temperature rises, carbamate in the solution undergoes thermal decomposition, causing the reaction to proceed in the opposite direction, leading to the release of CO_2 from the solution. This constitutes the mechanism underlying the regeneration reaction.

2.2 Experimental device

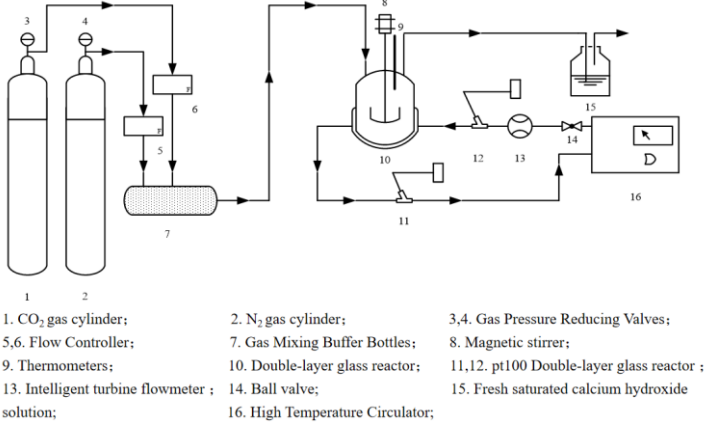The setup used in this experiment is shown in Table 1:

Table 1. Experimental setup

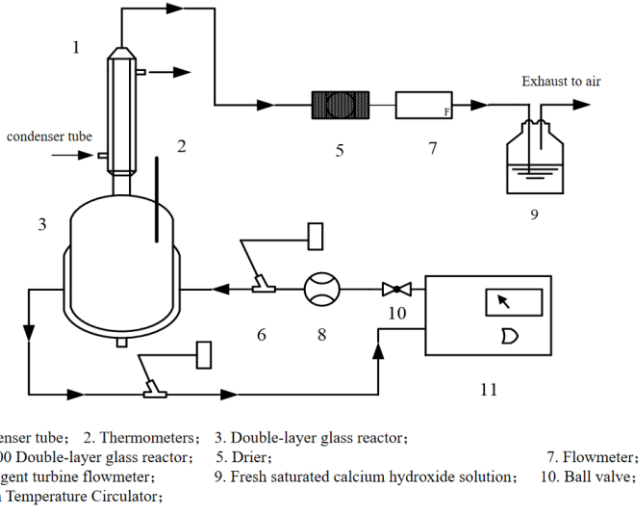| Experimental device	Models	Factory
High Temperature Circulator	GX $-$ 2015	Guangzhou Yisheng Experimental Instrument Co.
Intelligent Turbine Flow Meter	LWGY	Yantai Wushen Instrumentation Co.
Portable Acidity Meter	pH 315i	WTW Germany
Magnetic Stirring Reactor	-	-
Intelligent Temperature Display	XMTG 308	Yuyao Changjiang Temperature Instrument Factory
flow rate calculator	D08 $-$ 8C	Beijing Seven Stars Huachuang Electronics Co.
Mass Flow Controllers	D07 $-$ 19B	Beijing Seven Stars Huachuang Electronics Co.

2.3 Experimental methods

Flue gas simulation employed a gas mixture consisting of CO_2 and N_2. The volume fractions of N_2 and CO_2 were 85% and 15%, respectively. The flow of the gas mixture was precisely regulated using a mass flow controller, and the experimental setup is illustrated in Fig. 1. The double-layer glass reactor was filled with the appropriately proportioned MEA solution and agitated by a magnetic stirrer operating at a predetermined speed of 300 r/min. Subsequently, the gas mixture was introduced into the reactor. The timer was initiated, data collection occurred every 5 minutes, and 1 mL samples were extracted. CO_2 content analysis was performed using the acid digestion method. The absorption experiment concluded when the CO_2 content in the sample stabilized, signifying reaction saturation. Upon completion of the absorption experiment, extract the absorbent liquid from the reactor and seal it. Open the high-temperature circulator of the desorption device, heat synthetic heat transfer oil, stabilize the inlet and outlet oil temperature indicators, and introduce the absorbent liquid into the desorption kettle for the absorbent desorption experiment. Fig. 2 illustrates the desorption experimental apparatus. Record data every 5 minutes, extracting 1 mL of solution each time for CO_2

content analysis using the acid digestion method. The desorption experiment concludes when the CO_2 content in the solution stabilizes.

1. CO_2 gas cylinder;   2. N_2 gas cylinder;   3,4. Gas Pressure Reducing Valves;
5,6. Flow Controller;   7. Gas Mixing Buffer Bottles;   8. Magnetic stirrer;
9. Thermometers;   10. Double-layer glass reactor;   11,12. pt100 Double-layer glass reactor ;
13. Intelligent turbine flowmeter ;   14. Ball valve;   15. Fresh saturated calcium hydroxide
solution;   16. High Temperature Circulator;

Fig. 1. Absorption experiment device.

1. Condenser tube;   2. Thermometers;   3. Double-layer glass reactor;
4,6. Pt100 Double-layer glass reactor;   5. Drier;   7. Flowmeter;
8. Intelligent turbine flowmeter;   9. Fresh saturated calcium hydroxide solution;   10. Ball valve;
11. High Temperature Circulator;

Fig. 2. Desorption experiment device.

3   Experimental results and analysis and discussion

3.1   CO₂ Absorption Properties of MEA Absorbent

(1)Absorption rate of MEA solution as a function of time.

At room temperature, MEA solutions with mass fractions of 10 wt%, 15 wt%, and 20 wt% were individually prepared, with a CO_2 gas pressure of 1atm. The relationship between the CO_2 absorption rate of the solution and absorption time, as well as

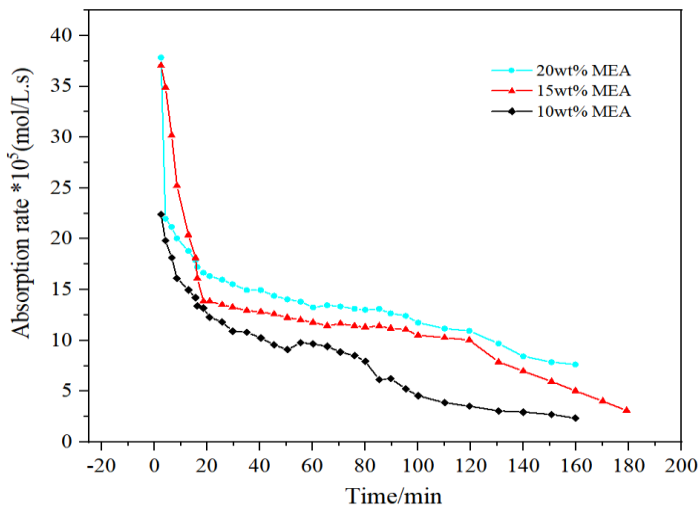absorption quantity, was investigated. pH values during the solution reaction process were measured and analyzed.

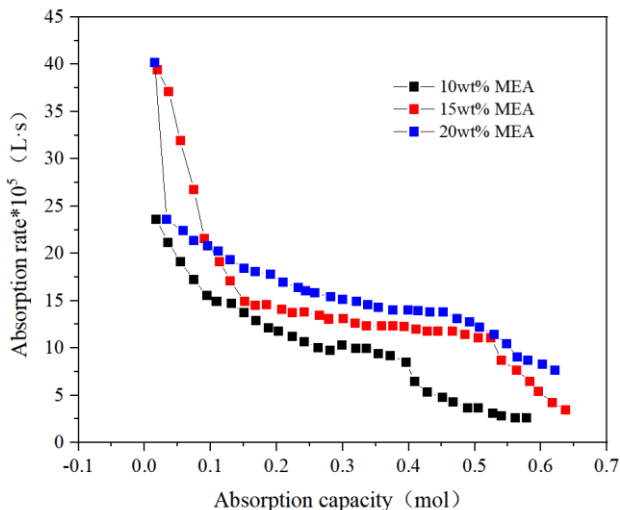

Fig. 3. DAbsorption rate vs time.

Fig. 4. Absorption rate vs absorption capacity

According to Fig. 3, the mass fraction of the solution significantly influences the absorption rate, with the absorption rate increasing correspondingly as the solution's mass fraction rises. In the first 20 minutes, the absorption rate is relatively high but decreases rapidly, especially for the 15 wt% MEA solution, where the decline in absorption rate is more pronounced. This phenomenon is not only related to the size of

the solution's mass fraction but also associated with the diffusion of CO_2 gas in the solution. In the initial stage, due to the relatively large mass fraction of the solution, alcohol amine molecules rapidly react with CO_2 to generate stable carbamate, and simultaneously, the solution contains a substantial amount of OH^-, maintaining a relatively high absorption rate in the early period. As the reaction progresses, the OH^- content in the solution decreases, the mass fraction of the solution reduces, viscosity decreases, and absorption gradually tends to saturation, ultimately reaching an absorption rate close to 0.

(2)Relationship between the rate of absorption of MEA solution and the amount of absorption.

Examination of Fig. 4 reveals the correlation between the absorption rate of the MEA solution and the CO_2 content in the solution as follows: for CO_2 content in the solution below 0.1 mol, the 15 wt% MEA solution demonstrates a superior absorption rate with an equivalent amount of CO_2 uptake, while the 10 wt% MEA solution registers the lowest absorption rate, with the order being 15 wt% > 20 wt% > 10 wt%. In the CO_2 content range of 0.15-0.6 mol, the absorption rate diminishes progressively with escalating solution concentration, with the hierarchy being 20 wt% > 15 wt% > 10 wt%. The overall absorption process curve indicates that the absorption rate undergoes more pronounced changes at the onset and culmination of the reaction, while the alterations in the middle phase of the reaction are comparatively gradual. This is primarily influenced by two factors: firstly, in the initial phase of the reaction, the solution is more alkaline and exhibits robust absorption capability, enabling rapid reaction with CO_2 to swiftly form carbamate, resulting in a rapid alteration of the absorption rate. As the absorption progresses, the solution attains a relatively equilibrium state, leading to a gradual decline in the absorption rate. Secondly, as the absorption advances, the water content in the solution rises, promoting the diffusion of carbamate within the solution and facilitating the CO_2 absorption reaction.

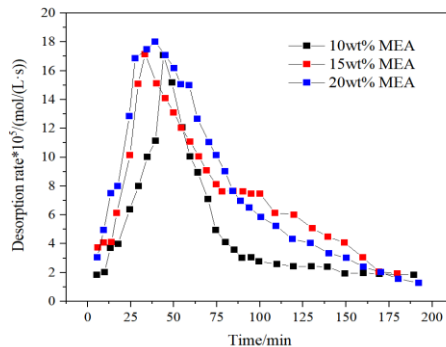## 3.2   Desorption performance of MEA absorbent for CO_2

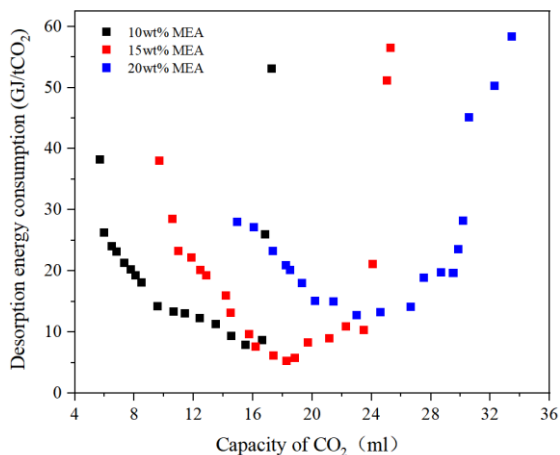**Fig. 5.** Desorption rate vs time

Fig. 6. Desorption energy consumption vs capacity of CO_2

Fig. 5 depicts the relationship curves between the desorption rates of MEA-rich solutions at different concentrations and time. Analyzing the curves reveals that, within the first 40 minutes of the desorption reaction, the desorption rates of MEA-rich solutions at various concentrations rapidly reach their peak values, with the three curves exhibiting similar trends. As time progresses, the desorption rates sharply decline, reaching a plateau around 200 minutes, indicating a gradual completion of the desorption process. The order of desorption rates for MEA-rich solutions at different concentrations is 20 wt% > 15 wt% > 10 wt%. The reason for this phenomenon is that, within the first 40 minutes, as the solution heats up and approaches the optimal desorption conditions, the desorption rate rapidly rises to its maximum. As the solution temperature continues to increase, CO_2 continuously desorbs and escapes, resulting in a reduction of CO_2 content in the solution. Desorption kinetics weaken, leading to a decline in the rate, ultimately concluding the reaction.

3.3   Analysis of energy consumption for CO_2 desorption from MEA absorber rich liquid

The extent of desorption can be indirectly evaluated by measuring the CO_2 content of the enriched solution and analyzed through the correlation between desorption energy consumption and CO_2 content. This analysis serves as a guide for assessing the energy consumption during the desorption process of solutions at various stages in industrial production. The Fig. 6 illustrates the correlation between desorption energy consumption and CO_2 content. In the initial stage, despite the high CO_2 content and potent desorption power, the unit desorption energy consumption is elevated owing to the low solution temperature. As the CO_2 content decreases to approximately 20 ml, the solution temperature rises, resulting in improved desorption kinetics and a reduction in unit desorption energy consumption. The 15 wt% MEA solution demonstrated lower desorption energy consumption under comparable CO_2 content conditions. Hence, the

CO_2 content in the MEA solution can serve as an indicator of the desorption energy consumption level at that moment. In industrial production, selecting suitable operating conditions to commence and conclude the desorption process holds paramount importance in minimizing energy consumption.

3.4   MEA absorber rich liquid regeneration degree analysis

It can be seen in Fig. 7 that in the initial 40 minutes of the desorption reaction, due to the relatively low solution temperature, incomplete desorption occurs, resulting in a low regeneration degree but with a rapid growth trend, aligning with the peak desorption rate around 40 minutes. As the desorption process progresses, the solution temperature rises, CO_2 content decreases, and the desorption rate decreases, leading to a slowing down of the growth trend in the regeneration degree of the solution. In the initial 35 minutes of desorption, the regeneration degree of 20 wt% MEA-rich solution shows a relatively rapid increase. However, after 50 minutes of desorption, the ranking of regeneration degree is 10 wt% > 15 wt% > 20 wt%, with the 10 wt% MEA solution exhibiting a stronger regeneration capability. After 125 minutes of desorption, the regeneration trends of the three solutions are essentially the same, and the differences tend to stabilize.
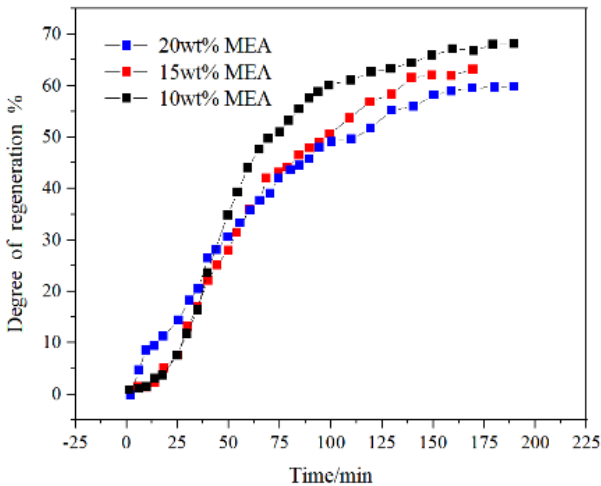

Fig. 7. Degree of regeneration

4   Conclusion

(1) The affluent solution can undergo regeneration through the application of heat, while the desorbed solution stands amenable to recycling.

(2) The interdependence between desorption temperature and desorption rate is unequivocal. Upon heating the solution for 30 minutes, a significant desorption rate is

attained, resulting in a temperature elevation to approximately 75 °C. However, with the ongoing desorption, the CO_2 content in the affluent liquid progressively diminishes, leading to a diminishing desorption power and a subsequent decline in the desorption rate. Therefore, the industry is urged to judiciously select the appropriate desorption temperature.

(3) Within the initial 30 minutes, the MEA-rich liquid experiences the foremost influences on desorption energy consumption attributable to the solution's temperature. When the solution temperature is low, the reaction encounters suboptimal progress. After 30 minutes of heating, the temperature attains the requisite operational condition, leading to a shift in the primary factor influencing desorption energy consumption to the CO2 content in the solution.

(4) The pinnacle desorption rate for MEA solutions of diverse concentrations is achieved at the 50-minute mark. At this juncture, the solution temperature hovers around 80°C, although a considerable duration is required to attain the utmost desorption rate. Specifically, a 15 wt% MEA solution exhibits a minimal desorption energy consumption of 5 GJ/t CO_2 after a 75-minute desorption period. Nevertheless, its regeneration efficacy remains modest, approximately 60%, notwithstanding its commendable overall performance.

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