Original Research

Comparative Study of CO$_2$ Chemical Absorbents for the Exhaust Gas of a Ship Diesel Engine

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Abstract

The exhaust emissions from ship diesel engines contain a large amount of carbon dioxide, which is one of the main greenhouse gases. Currently, carbon capture and storage (CCS) technology is considered a promising means of reducing CO$_2$ emissions. In the process of carbon dioxide capture, the chemical absorption method is the most widely used. Based on the main characteristics of various absorbents at present, this article selects MEA and NaOH solutions as representative absorbents to compare the carbon dioxide capture effect, aiming to establish an efficient and low-cost absorption and desorption cycle system. This article uses Aspen Plus software to simulate the performance of common absorbents, MEA and NaOH solutions, in carbon dioxide capture systems. Comparative analysis of carbon dioxide capture efficiency from various aspects is performed, such as intake temperature, pressure, flow rate, carbon dioxide concentration, absorbent concentration, reflux ratio, etc. The research results show that the performance of NaOH solution in absorbing CO$_2$ is similar to that of MEA under the same capture environment. Under absorption conditions of 40ºC and 1.5 bar, the highest capture rate can reach about 76%. Combining the economic costs of the two types of absorbent solutions, the economic cost of using NaOH solution as the absorbent is only one-third of that of MEA solution. In contrast, using NaOH solution as an absorbent is more cost-effective and conducive to large-scale market promotion when the CO$_2$ capture effect is equivalent.

Introduction

The main reason for global warming and rising temperatures is the increase in greenhouse gas emissions, especially the increase in carbon dioxide (CO$_2$) emissions. In order to slow down the greenhouse effect, new technologies such as carbon capture and storage (CCS) are being used in the market to reduce carbon dioxide emissions.

Carbon capture and storage technology is a new means of capturing carbon dioxide and storing it in underground rock formations to prevent it from being emitted into the air and causing global warming and other issues. It can mainly reduce the emissions of greenhouse gases such as carbon dioxide [1, 2], thereby mitigating the impact of the greenhouse effect.

Carbon capture and storage technology also has its own disadvantages. Firstly, because its technology

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is still in the early stages of development, many aspects of implementation are not mature enough, resulting in high costs and significant expenses, including capture, transportation, and storage. In addition, compared with other current clean energy technologies, there are also some requirements for the selection of storage sites for carbon capture and storage technology.

Overall, carbon capture and storage technology is an important means of reducing greenhouse gas emissions and addressing climate change. It is hoped that through further research and innovation, this technology can gradually mature and play a broader role in the future, contributing to the achievement of global low-carbon goals.

Materials and Methods

Overview of CO_2 Capture Technology

CO_2 capture technology can be divided into three main types: pre-combustion capture, oxygen-enriched combustion capture, and post-combustion capture [3, 4].

Pre-combustion capture technology refers to the use of specialized equipment to separate carbon dioxide before fuel combustion. This method can be applied to various types of fuels such as coal, oil, and natural gas [5]. One important advantage of this method is that the pre-treated carbon dioxide gas has a relatively high purity, making it easier for subsequent processing and storage. But the disadvantage is that the operation is more complex and the cost is higher. Specialized capture equipment and additional process steps need to be prepared, and more energy will also be consumed during this process. In addition, pre-combustion capture technology also requires the use of a large amount of water for hydrogen production [6].

Oxygen-enriched combustion capture technology refers to the use of high-purity oxygen instead of air to participate in the reaction during fuel combustion [7], creating an oxygen-rich environmental atmosphere. Since there is no nitrogen involved in the combustion reaction, pure carbon dioxide can be obtained in the reaction result, which is convenient for subsequent separation and storage. Moreover, oxygen-enriched combustion technology can also reduce the emissions of other pollutants, such as nitrogen oxides (NOx). But the disadvantage is that the oxygen-enriched combustion capture method requires a large amount of pure oxygen to be provided, which increases the overall energy consumption. Moreover, due to the need for pure oxygen during the reaction process, the combustion temperature will increase, which may require higher requirements for the design and operation of the reaction equipment, increasing the cost of the equipment. This technology is particularly suitable for high-emission industries such as coal-fired power plants.

Post-combustion capture technology refers to capturing carbon dioxide after the fuel combustion process. It captures carbon dioxide by separating it from the exhaust gas after production is completed [8]. This method is widely used and can be applied to existing industrial power plants and factories because it can be combined with existing equipment and production processes. Moreover, compared to the above two technologies, post-combustion capture technology is more mature and has been applied in some commercial projects. The disadvantage is that post-combustion capture technology requires complex treatment and separation processes for exhaust gases, as it needs to be carried out in high-temperature and high-pressure environments, with high equipment requirements [9]. Another drawback of post-combustion capture technology is its high energy consumption and cost. Moreover, due to the presence of many gas components in the exhaust gas, among which the concentration of CO_2 is relatively low, and the capture efficiency is relatively low, more equipment and resources are needed to deal with the interfering gases [10].

Table 1. Methods and characteristics of post-combustion CO_2 capture.

Capture technology	Advantage	Disadvantage	Reference
Chemical absorption method	High absorption efficiency; High-purity carbon dioxide capture can be achieved.	High energy consumption, requiring treatment of waste liquid and regeneration solution; other by-products may be produced.	[12, 13]
Physical Adsorption method	Easy to operate, suitable for small-scale devices; renewable utilization of adsorbents.	The selection and regeneration of adsorbents need to consider cost and efficiency; adsorbents are prone to saturation and blockage.	[14, 15]
Membrane separation method	Low energy consumption and simple operation; suitable for small-scale devices, capable of achieving continuous separation.	Limited selectivity for carbon dioxide; the cost of membrane materials is relatively high.	[16, 17]
Low-temperature separation	Suitable for capturing high-concentration carbon dioxide; high-purity carbon dioxide extraction can be achieved.	High energy consumption, requiring low-temperature treatment; high requirements for equipment and materials.	[18]

As the most widespread method of carbon dioxide capture, post-combustion capture technology is mainly divided into chemical absorption method, physical adsorption method, membrane separation method, and low-temperature separation method according to different principles and methods of carbon dioxide capture [11]. Please refer to Table 1 for details.

According to literature records, chemical absorption and physical adsorption are currently the most mature and widely used carbon dioxide capture technologies. This article selects the chemical absorption method as the research object.

The advantages of the chemical absorption method include high capture efficiency, low cost, and simple operation, making it suitable for small and medium-sized industrial carbon dioxide exhaust gas treatment systems. However, the chemical absorption methods also have some drawbacks. The regeneration and recycling of chemical absorbents require additional energy consumption, and some absorbents have limited cycles and high consumption, requiring regular replacement. In addition, in some cases, absorbents may also have problems such as corrosion and environmental pollution due to their corrosiveness. Therefore, further research and technological innovation are needed to overcome these limitations and challenges and make it more widely applicable.

Research Status of the Chemical Absorption Method

The chemical absorption method is the use of appropriate chemicals to react with carbon dioxide in exhaust gas, converting it into harmless gas for emission or easily captured substances for subsequent collection. In the chemical absorption method, commonly used absorbents include ammonia water, alkaline solution, ethanolamine solution [19], etc.

Taking ethanolamine as an example absorbent, the principle is that carbon dioxide dissolves in water to form carbonic acid, which is a weak acid; ethanolamine dissolves in water to produce alkalinity, forming hydroxide ions. Both undergo acid-base neutralization reactions to generate carbonate ions, which absorb carbon dioxide from the gas and complete the carbon dioxide capture process. The most widely used chemical absorbents currently are organic amine solutions such as monoethanolamine (MEA), diethanolamine (DEA), and N-methyldiethanolamine (MDEA) [20].

The widely used chemical absorption process in the industry includes pre-treatment of flue gas, absorption and desorption of carbon dioxide, and regeneration steps [21]. In the absorption step, the flue gas enters from the bottom of the absorption tower after pre-treatment and forms counter-current contact with the absorbent from the top of the absorption tower. The flue gas after chemical reaction is discharged from the top of the absorption tower, while the rich liquid in carbon dioxide flows out from the bottom of the tower after the reaction is completed and enters the desorption tower. In the desorption and regeneration steps, the desorbed carbon dioxide is discharged from the top of the desorption tower together with water vapor. After being cooled by a cooler, the water is removed to obtain high-purity carbon dioxide gas. After completing the desorption, the liquid is a lean liquid, which flows out from the bottom of the desorption tower, passes through the lean and rich liquid heat exchanger, and returns to the absorption tower for the cyclic absorption of carbon dioxide [22]. The process flow is shown in Fig. 1.

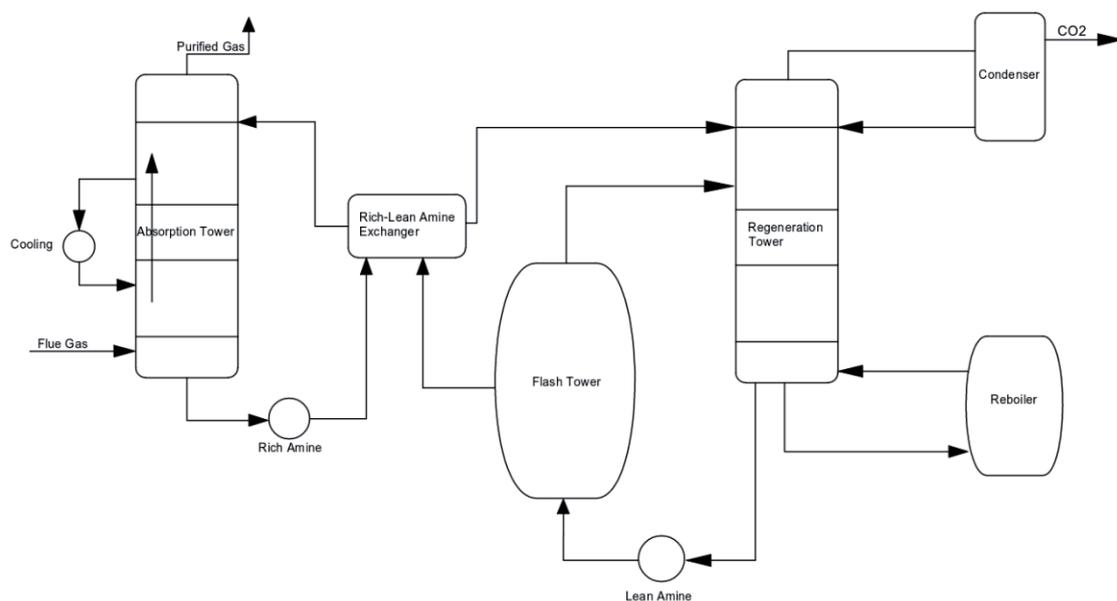At present, the commonly used absorbents in the actual industry are amine solutions (such as

Fig. 1. Industrial process diagram of using MEA as an absorbent to capture CO_2.

methanolamine or ethanolamine), which have the advantages of good adsorption capacity and high adsorption selectivity. This allows amine adsorbents to use industrial waste heat or a small amount of thermal energy to power the system at low-regeneration temperatures, and can increase reaction efficiency, thereby reducing the cost of the system. In addition, the recycling energy consumption of amine adsorbents is relatively low. However, the raw material cost of amine adsorbents is relatively high, and additional processing steps may be required due to the lower solubility of the generated salts.

In contrast, alkaline solutions have come to people's attention due to their unique reaction advantages. Alkaline solutions generally refer to aqueous solutions containing alkaline substances, including sodium hydroxide (NaOH), potassium hydroxide (KOH), and potassium carbonate (K_2CO_3) solutions. NaOH and KOH have strong alkalinity and can react chemically with carbon dioxide to form carbonates or other compounds. The advantage of using alkaline solutions such as NaOH or KOH is their strong absorption capacity and high absorption rate. These alkaline substances can maintain high absorption efficiency at lower partial pressures of carbon dioxide, making them effective in treating low-concentration carbon dioxide flue gas. In addition, the raw material cost of these alkaline solutions is relatively low and easy to obtain in industry. Moreover, alkaline solutions are usually able to specifically absorb carbon dioxide and can also simultaneously absorb other acidic gases such as H_2S, SO_2, etc.

Next, a comparative analysis will be conducted on the reaction mechanism, workflow, and impact effects of ethanolamine, represented by MEA, and alkaline solution, represented by NaOH, in capturing CO_2.

Comparison of CO_2 Absorption Reaction Mechanisms between MEA and NaOH

### Mechanism of the CO_2 Absorption Reaction in MEA

When the MEA solution comes into contact with a gas containing carbon dioxide, the carbon dioxide is captured by the MEA through both physical and chemical absorption. Physical absorption occurs through the physical dissolution process in a solution, while chemical absorption involves the chemical reaction between MEA and carbon dioxide.

In chemical reactions, MEA, as a primary amine, mainly reacts with carbon dioxide through acid-base reactions, where amine bases form salts with carbon dioxide.

Firstly, CO_2 reacts with MEA to produce intermediate products – zwitterions.

$$CO_2 + RNH = RN^+HCOO^- \tag{1}$$

Secondly, zwitterions undergo deprotonation reactions with substances in the solution.

$$RN^+HCOO^- + H_2O = RNCOO^- + H_3O^+ \tag{2}$$
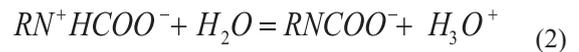
The above two reaction mechanisms already include the part where H_2O molecules in the solution react with CO_2 alone, and it is generally assumed that reaction two occurs instantaneously. Therefore, the reaction between MEA and CO_2 can be regarded as a one-step process.

The chemical reaction between MEA solution and CO_2 is shown in Table 2.

### Mechanism of CO_2 Absorption Reaction in NaOH

The reaction of NaOH absorbing CO_2 is an acid-base neutralization reaction that occurs in an aqueous

Table 2. Chemical equations and types of MEA solution and CO_2.

Item No.	Chemical equation	Reaction type
1	$MEA^+ + CO_2 \Leftrightarrow MEA + H_3O^+$	Equilibrium reaction
2	$2H_2O \Leftrightarrow OH^- + H_3O^+$	Equilibrium reaction
3	$HCO_3^- + H_2O \Leftrightarrow H_3O^+ + CO_3^{2-}$	Equilibrium reaction
4	$CO_2 + OH^- \Leftrightarrow HCO_3^-$	Kinetic reaction
5	$HCO_3^- \Leftrightarrow CO_2 + OH^-$	Kinetic reaction
6	$MEA + CO_2 + H_2O \Leftrightarrow H_3O^+ + MEACOO^-$	Kinetic reaction
7	$H_3O^+ + MEACOO^- \Leftrightarrow MEA + CO_2 + H_2O$	Kinetic reaction

solution. NaOH is a strong base, while CO_2 is an acidic oxide that can be considered as an inorganic acid. When the two react, hydroxide ions (OH^-) in NaOH react with CO_2. The reaction mechanism is roughly as follows:

Firstly, CO_2 dissolves in water to form carbonic acid (H_2CO_3). CO_2 (or H_2CO_3) dissolved in water reacts with NaOH to produce sodium carbonate (Na_2CO_3) and water (H_2O). The chemical equation is:

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \tag{3}$$
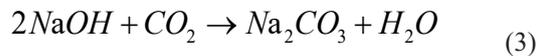
When there is an excess of carbon dioxide, that is, when carbon dioxide continues to be introduced, Na_2CO_3 in the above reaction will continue to react:

$$Na_2CO_3 + H_2O + CO_2 \rightarrow 2NaHCO_3 \tag{4}$$
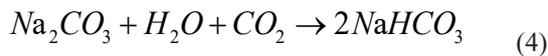
Secondly, at or near room temperature, when carbon dioxide (CO_2) gas is introduced into an aqueous solution of sodium hydroxide (NaOH), a neutralization reaction occurs, producing sodium bicarbonate ($NaHCO_3$) and water (H_2O):

$$NaOH + CO_2 \rightarrow NaHCO_3 \tag{5}$$
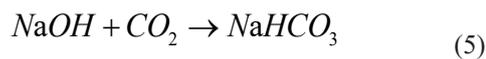
Finally, if sodium bicarbonate ($NaHCO_3$) is heated to a high temperature, approximately between 50ºC and 100ºC, it will decompose into sodium carbonate (Na_2CO_3), water (H_2O), and carbon dioxide (CO_2):

$$2NaHCO_3 \rightarrow Na_2CO_3 + H_2O + CO_2 \tag{6}$$
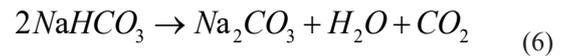
The chemical reaction between NaOH solution and CO_2 is shown in Table 3.

Results and Discussion

Comparison of CO₂ Absorption Processes between MEA and NaOH

CO₂ Absorption Process of MEA

The simulation flowchart of using MEA as an absorbent to capture carbon dioxide in Aspen Plus is shown in Fig. 2. The system mainly consists of two parts: absorption and regeneration. Firstly, the initial absorbent (MEA) and initial gas (IN) enter the absorption tower (T1). The flue gas entering the absorption tower is sprayed or gas-liquid contacted from bottom to top to bring carbon dioxide into reverse contact with the MEA and react to form the reaction-product absorption liquid. During this process, MEA, as a strong alkaline compound, has high selectivity and can undergo chemical absorption reactions with carbon dioxide. The gases that did not participate in the reaction and some unabsorbed carbon dioxide are discharged in gas form (OUT), while the MEA rich solution (RICH1) after the reaction is pressurized by a pump and enters the heater for heating, and then enters the desorption tower (T2) for carbon dioxide regeneration and capture.

Table 3. Chemical equations and types of NaOH solution and CO_2.

| Item No.	Chemical equation	Reaction type
1	$CO_2 + 2H_2O \Leftrightarrow HCO_3^- + H_3O^+$	Equilibrium reaction
2	$2H_2O \Leftrightarrow H_3O^+ + OH^-$	Equilibrium reaction
3	$HCO_3^- + H_2O \Leftrightarrow CO_3^{2-} + H_3O^+$	Equilibrium reaction
4	$HCl + H_2O \Leftrightarrow H_3O^+ + Cl^-$	Equilibrium reaction
5	$HCO_3^- \rightarrow CO_2 + OH^-$	Kinetic reaction
7	$CO_2 + OH^- \rightarrow HCO_3^-$	Kinetic reaction
8	$NaOH \rightarrow Na^+ + OH^-$	Dissociation reaction
9	$Na_2CO_3 \rightarrow 2Na^+ + CO_3^{2-}$	Dissociation reaction
10	$NaCl \rightarrow Na^+ + Cl^-$	Dissociation reaction
11	$NaHCO_3 \rightarrow Na^+ + HCO_3^-$	Dissociation reaction
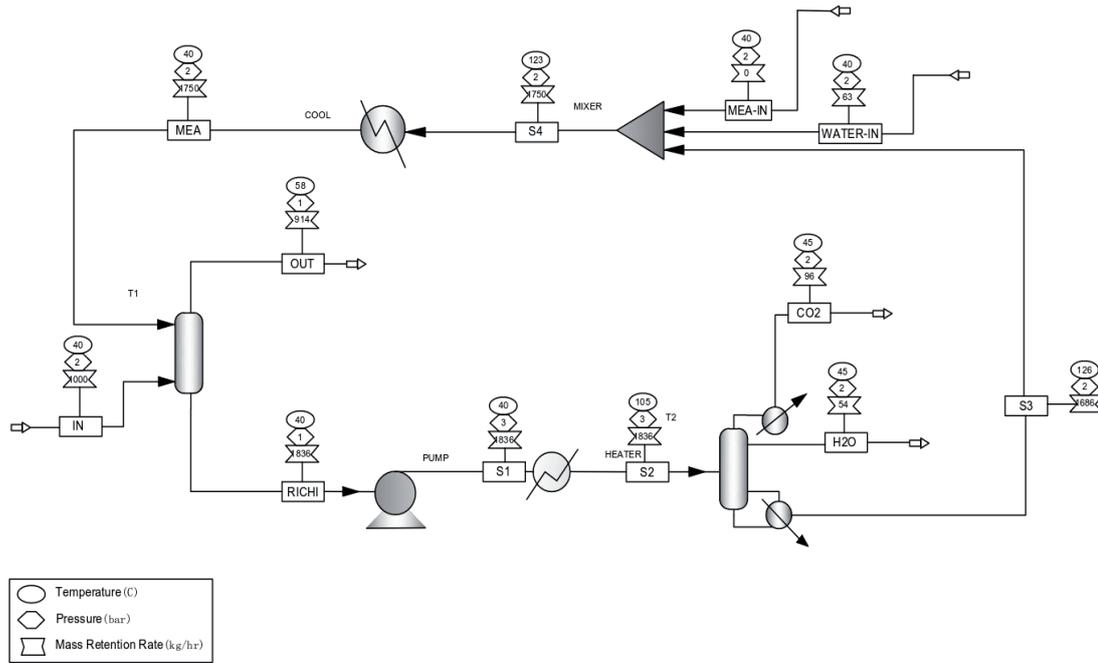
Fig. 2. CO$_2$ capture process diagram of MEA.

In fact, the desorption tower is a distillation tower. Its main function is to separate carbon dioxide through a reboiler. At the same time, a large amount of water vapor and a small amount of active component vapor enter the cooler for cooling. After the separation of steam and water by the separator, the condensed water will reflux back to the desorption tower. After the decomposed carbon dioxide and some water are discharged, the remaining lean solution enters the Mixer, where MEA solution and water are replenished based on the reaction amount and initial amount in the entire process. After completion, they flow together into the condenser for cooling treatment, and then return to the absorption tower for the CO$_2$ absorption process, thus breaking through the cycle of the entire experimental process. Through this absorption-desorption cycle, the repeated use of MEA absorbent is achieved.

The CO$_2$ Absorption Process of NaOH

As shown in Fig. 3, similar to the MEA capture system, the NaOH capture system mainly consists of two parts: absorption and regeneration. Firstly, the initial absorbent (NaOH) and initial gas (IN) enter the absorption tower (T1), and the flue gas from the absorption tower enters from the bottom layer and flows from bottom to top. The absorption liquid from the top layer of the tower plate will come into reverse contact with carbon dioxide in the flue gas through downward spraying or being brought into gas–liquid contact, and undergo a chemical reaction to form reaction-product absorption liquid. During this process, NaOH, as a strong alkaline compound, undergoes a chemical absorption reaction with the acidic oxide carbon dioxide. The gases that did not participate in the reaction (N$_2$, O$_2$, H$_2$O) and some unabsorbed carbon
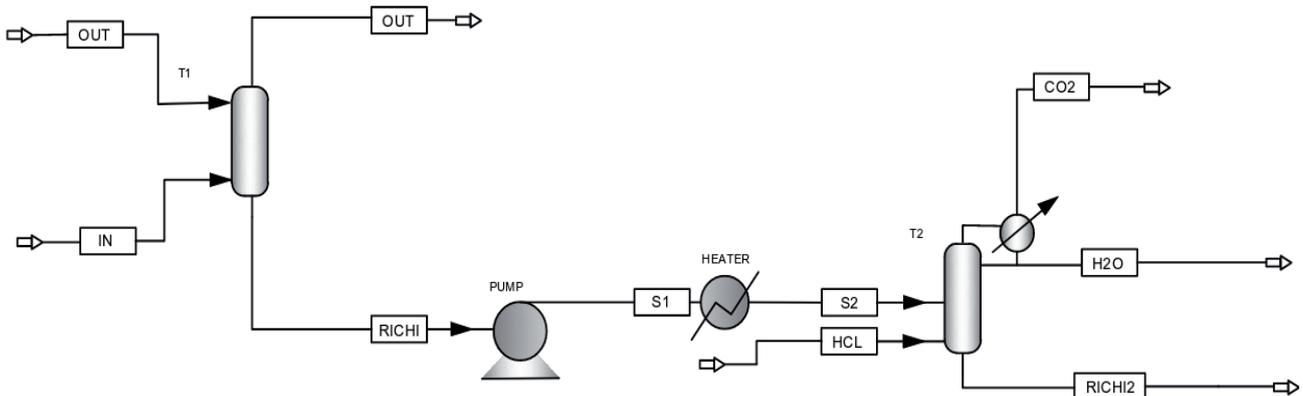

Fig. 3. CO$_2$ capture process diagram of NaOH.

dioxide are discharged in gas form from the upper outlet of the absorption tower (OUT), while the Na_2CO_3 and $NaHCO_3$-rich solution (RICH1) after the reaction is completed is discharged from the lower outlet of the absorption tower. After being pressurized by a pump (PUMP), it enters the heater for heating, and then enters the desorption tower (T2) for carbon dioxide regeneration and capture. In fact, the desorption tower is a distillation tower. Due to the high heating cost of decomposing Na_2CO_3 and $NaHCO_3$ solutions into carbon dioxide at high temperatures between 800ºC and 1000ºC after absorption, hydrochloric acid (HCl) was chosen for an acid-base neutralization reaction in this experiment to generate reaction products such as carbon dioxide, water, and sodium chloride. Among them, water vapor and a small amount of active component vapor leave the desorption tower from above and enter the cooler for cooling. After the separation of steam and water by the separator, the condensed water will reflux back to the desorption tower. After the decomposed carbon dioxide and some water are discharged, the remaining sodium chloride in the tower will be discharged from below and collected separately for subsequent reactions. Due to the influence of factors such as their respective contents, reaction rates, and uniformity of material mixing, different reactions may occur between sodium hydroxide and carbon dioxide, resulting in the production of the intermediate product sodium bicarbonate. However, theoretically, as long as a sufficient amount of hydrochloric acid is involved in the decomposition reaction, all carbonate and bicarbonate ions will eventually be completely converted into sodium chloride, carbon dioxide, and water.

Table 5. Settings of the other components.

Project	MEA	NaOH
Pump	Pump model	Pump model
Pressure (bar)	3	3
Heater	HEATER model	HEATER model
Temperature (ºC)	105	45

Selection and Setting of Various Components

Tables 4 and 5 show the selection and setting of various components.

Comparison of CO₂ Capture Efficiency between MEA and NaOH

Comparison of the Impact of Absorbent Concentration on CO₂ Capture Efficiency

To investigate the effect of MEA concentration on CO_2 capture rate, a reaction temperature of 40ºC, a pressure of 1 bar, and a CO_2 volume fraction of 10% were set. CO_2 gas was introduced into the absorption tower at a rate of 1000 kg/h, and MEA solution was introduced into the tower at a rate of 1700 kg/h. The concentrations were set to 30%, 31%, 32%, 33%, and 34%, respectively. Fig. 4 shows the changes in CO_2 capture rate at different initial MEA concentrations.

As shown in Fig. 4, under a certain initial temperature and pressure, keeping the concentration of CO_2 and the flow rate constant, increasing the initial concentration of MEA from 30% to 34% continuously

Table 4. Settings of the absorption tower and the desorption tower.

| Project	MEA		NaOH	
	Absorption tower	Desorption tower	Absorption tower	Desorption tower
Type	RadFrac/Rate-based		RadFrac/Rate-based	
Tower height (m)	20	20	20	20
Tower diameter (m)	0.4	0.29	0.4	0.29
Plate number	20	20	5	5
Temperature (ºC)	40	45	40	40
Pressure (bar)	1	2	1.5	1.5
Condenser	None	Partial-Vapor-Liquid	None	Partial-Vapor-Liquid
Reboiler	None	Kettle	None	Kettle
Liquid capacity (l)	10	10	500	700
Filler	IMTP	FLEXIPAC	IMTP	FLEXIPAC
Flow model	Vplug-Pavg	MIXED	Vplug-Pavg	MIXED
Membrane resistance	Discretize film (liquid phase); Consider film (gas-phase)		Discretize film (liquid phase); Consider film (gas-phase)	
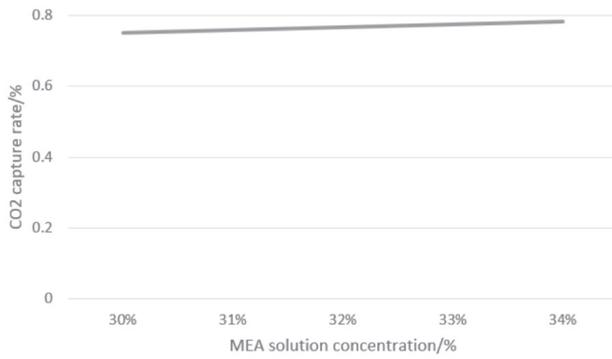
Fig. 4. CO_2 capture rates at different concentrations of MEA.

Table 6. Impact of absorbent concentration on CO_2 capture efficiency.

MEA		NaOH	
MEA solution concentration (%)	CO_2 capture rate (%)	NaOH solution concentration (%)	CO_2 capture rate (%)
30	75.2	10	71.0
31	76.0	12	73.2
32	76.8	14	74.8
33	77.6	16	75.3
34	78.3	18	74.5

improves the CO_2 capture efficiency. However, as the concentration continues to increase, the degree of improvement in CO_2 capture efficiency also decreases. At an MEA concentration of 30%, the CO_2 capture rate can reach 75.2%. As the concentration of MEA increases to 34%, the CO_2 capture rate is 78.3%, and the increase is very limited.

Generally speaking, an increase in MEA concentration will enhance the absorption rate of CO_2, thereby increasing the reaction capture rate. Because increasing the concentration of MEA increases the likelihood of reacting with CO_2 molecules, thereby accelerating the transfer of CO_2 from the gas phase to the liquid phase. When the concentration of MEA is too high, concentration limitations may be encountered, and further increasing the concentration of MEA may not significantly improve the reaction capture rate. This is because at high concentrations, the reaction rate may be limited by mass transfer.

In general, the concentration of sodium hydroxide (NaOH) used in industry can be between 10% and 30%. In this article, the concentrations of the absorbent NaOH are selected as 10%, 12%, 14%, 16%, and 18%, respectively; The solution flow rate is 1000 kg/h; The volume fraction of carbon dioxide is 10%, its flow rate

is 1000 kg/h, the initial temperature is set at 40ºC, and the absorption tower pressure is 1.5 bar. Fig. 5 shows the changes in carbon dioxide capture efficiency under different solution concentrations of NaOH.

From Fig. 5, it can be seen that the concentration of NaOH solution has a significant impact on the absorption of carbon dioxide. When the concentration of NaOH is below 16% but above 10%, the absorption efficiency of carbon dioxide increases with the increase of concentration. However, when the concentration of NaOH is above 16%, the absorption rate of carbon dioxide is inversely proportional to it and shows a downward trend. At a concentration of 16% NaOH, the absorption efficiency of carbon dioxide reaches its highest point at 75.3%.

Comparison of two absorbents is shown in Table 6.

Comparison of the Impact of Initial CO_2 Concentration and Inlet Flow Rate on CO_2 Capture Efficiency

During the experiment, an MEA solution with a specified mass fraction of 30% was introduced into the absorption tower at a flow rate of 1700 kg/h. CO_2
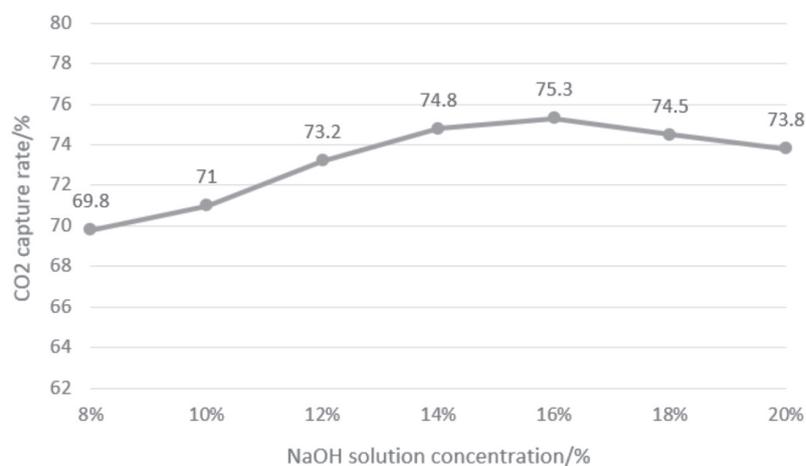

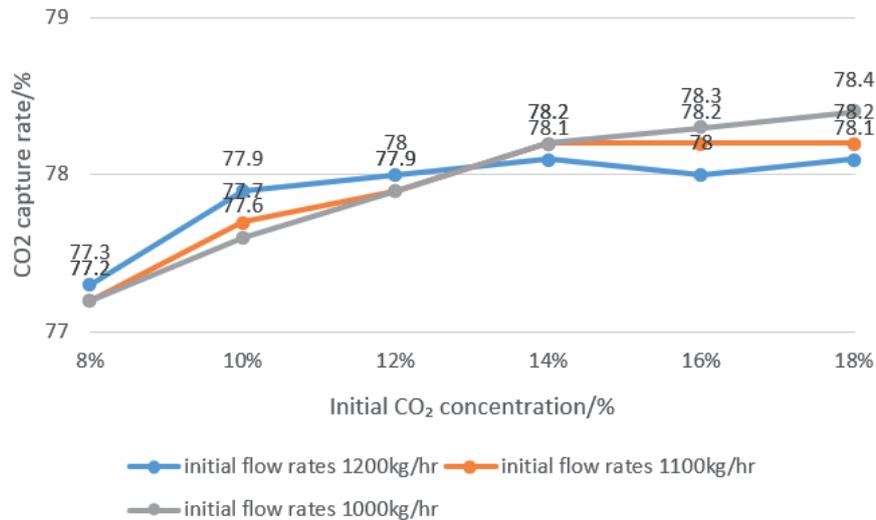Fig. 5. CO_2 capture rate at different concentrations of NaOH.

Fig. 6. CO_2 capture rate under different initial concentrations and flow rates of CO_2.

was introduced at flow rates of 1000 kg/h, 1100 kg/h, and 1200 kg/h, and the volume fractions were set to 8%, 10%, 12%, 14%, 16%, and 18%, respectively. The initial temperature of the inlet and MEA were set to 40ºC, and the pressure of the absorption tower was set to 1.5 bar. All parameters in the capture tower were not changed. Fig. 6 shows the changes in absorption rate at different initial concentrations and flow rates of CO_2.

From Fig. 6, it can be concluded that under the same initial intake flow rate, the initial concentration of carbon dioxide has a certain impact on its final capture rate. Increasing the initial concentration can improve the capture rate of carbon dioxide to a certain extent, but as the concentration continues to increase, the magnitude of the increase in capture rate also decreases. On the other hand, the initial flow rate has little effect on the capture rate. At lower concentrations, higher initial flow rates have better absorption performance. However, as the concentration also increases, higher initial flow rates have a negative impact on the capture rate.

This phenomenon may occur because a higher initial CO_2 flow rate means that a larger amount of CO_2 needs to be processed per unit time. Most capture technologies require a certain amount of time to effectively absorb CO_2. When the flow rate increases, it may not be possible to capture sufficiently, resulting in a decrease in capture efficiency.

To investigate the effects of CO_2 concentration and flow rate on absorption rate, the initial volume fractions of CO_2 were set to 8%, 10%, 12%, 14%, 16%, 18%, and 20%, respectively. The initial flow rates were set to 800 kg/h, 1000 kg/h, 1200 kg/h, 1400 kg/h, and 1600 kg/h, with a temperature of 40ºC, an absorption tower pressure of 1.5 bar, a NaOH concentration of 20%, and a flow rate of 2000 kg/h. The results are shown in Fig. 7.

From Fig. 7, it can be seen that under unchanged NaOH concentration, flow rate, and various absorption

environmental conditions, the effect of CO_2 flow rate on the capture efficiency of carbon dioxide is not very significant. When the CO_2 flow rate is around 1000 kg/h, the capture rate of carbon dioxide can reach its maximum, and both too low and too high flow rates will affect its final capture efficiency. In addition, only when the initial flow rate is too high will the absorption rate of carbon dioxide show a significant decrease.

At the same time, the initial concentration of carbon dioxide has a more significant impact on absorption efficiency. As the volume fraction of carbon dioxide increases from 8% to 20%, its absorption efficiency also shows an upward trend. However, as the concentration gradually increases, the increase in its capture rate actually decreases.

Comparative experimental analysis was conducted with the reaction of MEA, as shown in Fig. 8. At the same initial concentration of CO_2, the absorption efficiency of a 30% MEA solution is higher than that of a 20% NaOH solution under the same conditions. However, as the initial concentration of CO_2 increases, the difference decreases continuously. The capture rate of MEA has little effect on the concentration of CO_2, but it has a significant impact on the final absorption of NaOH and shows a positive trend.

Comparison of the Impact of Absorption Tower Pressure and Inlet Temperature on CO_2 Capture Efficiency

To compare the effects of absorption tower pressure and CO_2 inlet temperature on the CO_2 capture efficiency of MEA and NaOH, the following two experiments were conducted.

In order to study the CO_2 capture rate of MEA absorption solution under different CO_2 inlet temperatures and absorption tower pressures, CO_2 capture rate experiments were designed at inlet temperatures of 20ºC, 30ºC, 40ºC, 50ºC, 60ºC, and
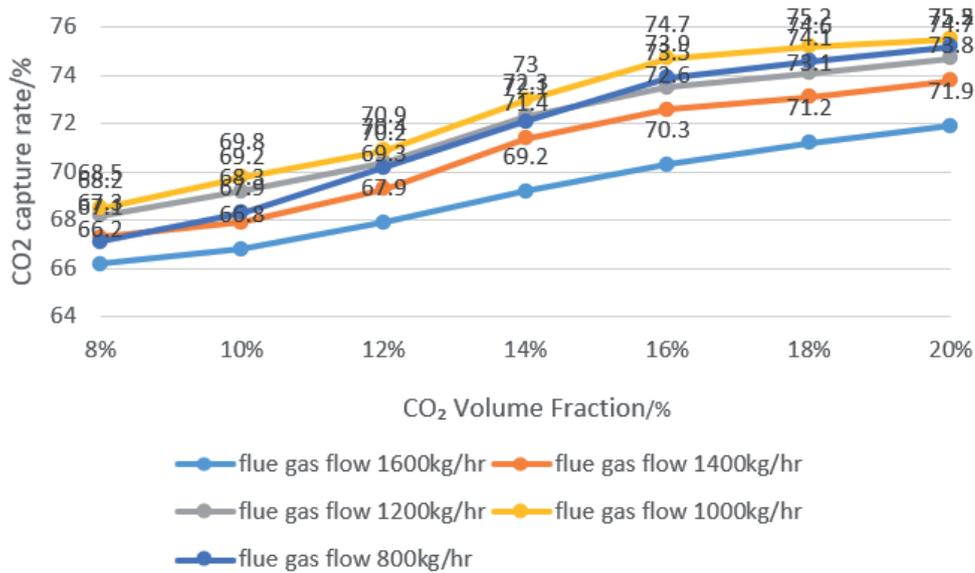
Fig. 7. CO_2 capture rate under different initial concentrations and flow rates of CO_2.

absorption tower pressures of 1 bar, 1.3 bar, 1.5 bar, and 1.7 bar, respectively. The volume fraction of CO_2 was 10%, the flow rate was 1000 kg/h, the MEA concentration was 30%, the flow rate was 1700 kg/h, and the reflux ratio was set to 2. The data of the CO_2 capture rate were measured as a function of absorption tower pressure and CO_2 inlet temperature.

In order to study the CO_2 capture rate of NaOH absorption solution under different CO_2 inlet temperatures and absorption tower pressures, CO_2 capture rate experiments were designed at inlet temperatures of 10ºC, 15ºC, 20ºC, 25ºC, 30ºC, 40ºC, and 45ºC and absorption tower pressures of 0.7 bar, 0.9 bar, 1.1 bar, 1.3 bar, 1.5 bar, 1.7 bar, and 1.9 bar.

Among them, the CO_2 intake flow rate was 1000 kg/h, the volume fraction was 16%, the NaOH concentration was 20%, and the flow rate was 1000 kg/h. The data of the CO_2 capture rate were measured as a function of absorption tower pressure and CO_2 inlet temperature.

Fig. 9 shows the impact of absorption tower pressure on the CO_2 capture efficiency of MEA and NaOH.

From Fig. 9, it can be seen that the absorption tower pressure has a significant impact on the capture rate. When only the absorption pressure is changed, the capture efficiency of carbon dioxide will increase with the increase of the absorption tower pressure. According to Henry's Law, at a constant temperature, the solubility of a gas is proportional to its partial pressure. Therefore,
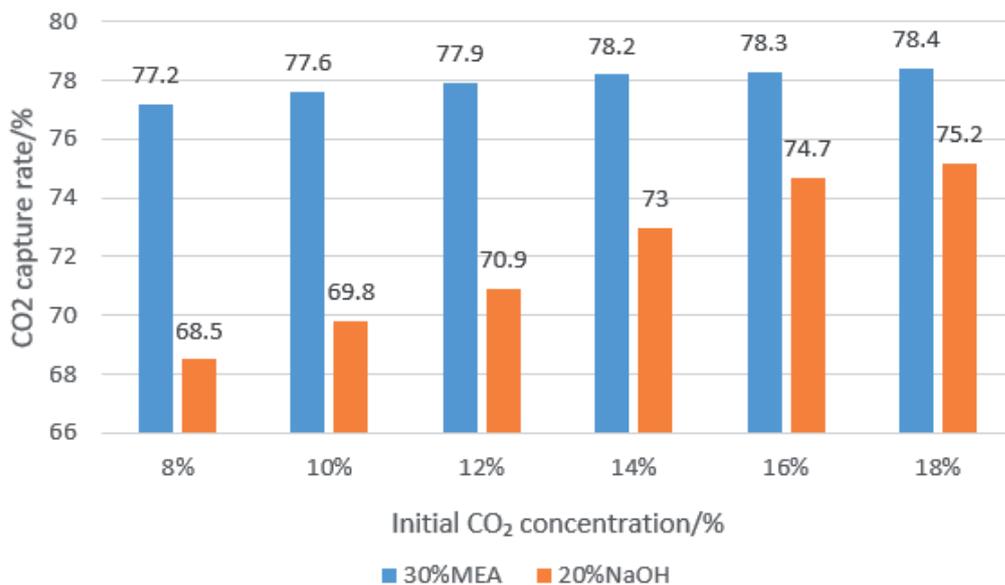

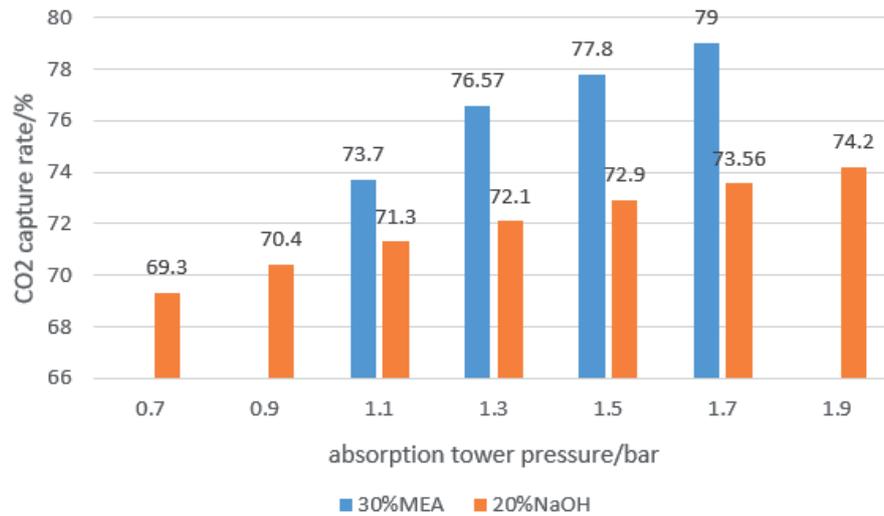Fig. 8. The effect of different initial CO_2 concentrations of MEA and NaOH on capture efficiency.

Fig. 9. CO_2 capture efficiency under different absorption tower pressures.

increasing pressure will increase the solubility of CO_2 in solution, which helps to improve the absorption efficiency of NaOH for CO_2. Moreover, increasing pressure can promote the reaction as it increases the collision frequency between molecules. This will cause CO_2 to dissolve faster into NaOH solution.

Compared with MEA, the pressure change amplitude of NaOH is relatively small, and the corresponding increase amplitude is also limited, while the influencing factors of MEA are larger, especially when the absorption pressure is not high, the CO_2 capture efficiency increases significantly with the increase of absorption tower pressure.

Fig. 10 shows the impact of CO_2 inlet temperature on the CO_2 capture efficiency of MEA and NaOH.

As shown in Fig. 10, under the conditions of constant concentration and flow rate of NaOH and CO_2 in the absorption solution, by changing the inlet temperature of CO_2, it can be seen that the capture rate of CO_2 decreases significantly with the increase of inlet temperature, and the decrease in capture rate becomes greater with the increase of initial temperature. The highest capture rate in Fig. 10 occurs when the inlet temperature of CO_2 is 10ºC, which is 78.1%.

Generally speaking, an increase in temperature will reduce the solubility of CO_2 in water, which means that at higher temperatures, the concentration of CO_2 in the liquid phase may be lower, and the required CO_2 molecules for the reaction are less likely to exist in the liquid phase, thereby inhibiting the reaction between CO_2 and NaOH. This affects the reaction rate between CO_2 and NaOH. Therefore, in practical applications, lower temperatures are usually chosen to improve the absorption efficiency of CO_2.
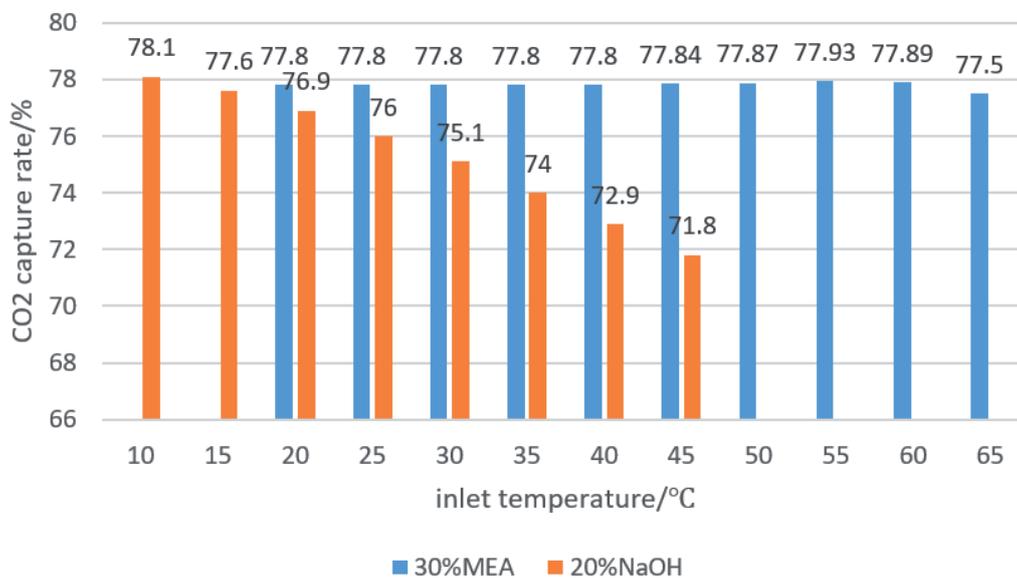

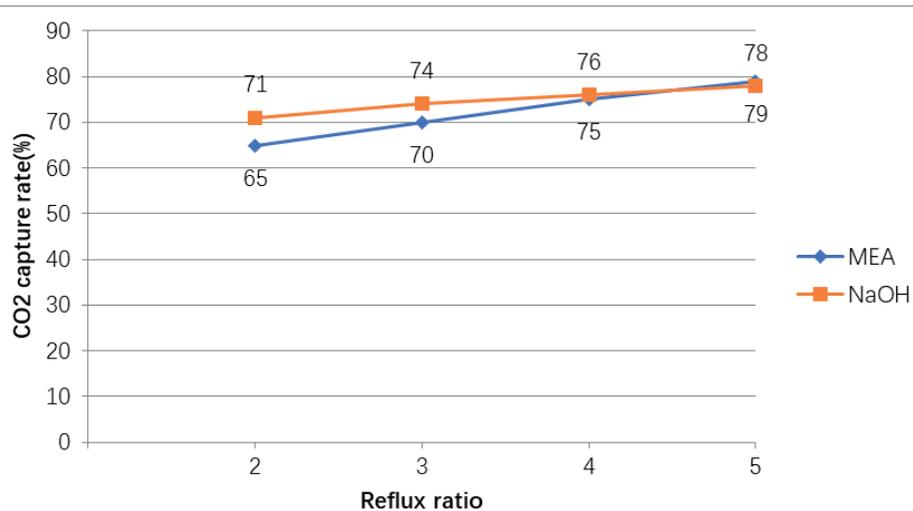Fig. 10. CO_2 capture efficiency under different CO_2 inlet temperatures.

Fig. 11. CO$_2$ capture efficiency under different reflux ratios.

In contrast, the intake temperature of MEA has little impact, with a fluctuation range of no more than 1% in its capture rate from a temperature of 20°C to a temperature of 65°C, making it almost negligible in actual industrial production.

Comparison of the Impact of Reflux Ratio on CO$_2$ Capture Efficiency

Reflux ratio is the ratio of reflux liquid (condensate liquid) to the original feed liquid.

To investigate the effect of the reflux ratio of the desorption tower on CO$_2$ capture efficiency, the absorption pressure was maintained at 1.5 bar during the experiment, and the initial temperature, volume fraction, and flow rate of CO$_2$, MEA, and NaOH were kept constant. The reflux ratio of the desorption tower was increased from 2 to 5, and the change in CO$_2$

capture efficiency was observed. Fig. 11 was obtained.

As shown in Fig. 11 of MEA and NaOH, it can be seen that the reflux ratio of the desorption tower has a significant impact on the capture rate. When only the reflux ratio is changed, the capture efficiency of carbon dioxide will increase with the increase of reflux ratio. When the reflux ratio is small, the capture rate increases with a higher amplitude, and as the reflux ratio increases, the increase gradually decreases. An increase in reflux ratio indicates that more liquid will reflux from the bottom to the top of the tower, which will increase the concentration gradient of the liquid inside the tower, thereby enhancing the mass transfer driving force. NaOH and CO$_2$ will have more contact opportunities and reaction rates, thereby improving their resolution.
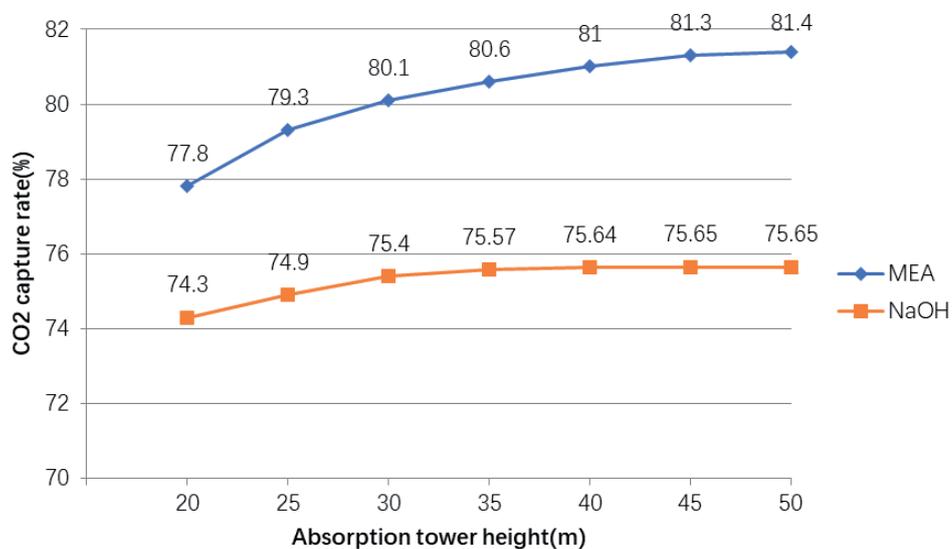

Fig. 12. CO$_2$ capture efficiency at different tower heights.

*Comparison of the Impact of Absorption
Tower Height on CO₂ Capture Efficiency*

From Fig. 12, it can be seen that the height of the MEA and NaOH absorption towers has a relatively small impact on the absorption of carbon dioxide. The overall trend is that the capture rate increases to a certain extent with the increase of tower height, but the increase is not significant. Due to the increase in tower height, the gas-liquid contact time will be prolonged, allowing the gas to stay in the packing layer for a longer period of time, which is beneficial for the contact and reaction between carbon dioxide and the absorbent, thereby improving the absorption efficiency. Moreover, increasing the tower height can improve the distribution and redistribution of liquid within the packing layer, making the absorbing liquid cover the packing surface more evenly and increasing the contact opportunity between carbon dioxide and absorbent. But when the tower height exceeds 40 m, its impact is already very small and can be almost ignored. Considering the economic cost required for the height of the tower, choosing a tower height of 30 m is the most suitable.

Conclusions

This article mainly focuses on MEA (ethanolamine) and NaOH solution as absorbents for absorbing and capturing CO_2, and compares and analyzes the absorption performance of MEA and NaOH. Specifically, simulation experiments were conducted using Aspen Plus software to establish a rate model. Considering the application of gas-liquid mass transfer theory in this experiment, the process steps widely used in industry were simulated to obtain various parameters inside the absorption tower. The final capture rate was analyzed based on changing the reaction gas, absorption liquid parameters, and the settings of the absorption tower and desorption tower.

During the experiment, an MEA solution with a flow rate of 1700 kg/h, a 30% mass fraction, and a temperature of 40ºC was selected as the absorbent. CO_2 gas with a flow rate of 1000 kg/h, a 10% volume fraction, and a temperature of 40ºC was chosen as the absorption object. At this time, the CO_2 capture rate of the system can reach about 77.8%.

NaOH was chosen with a flow rate of 2000 kg/h, a mass fraction of 10%, and a temperature of 40ºC as the absorbent, and CO_2 gas with a flow rate of 2000 kg/h, a volume fraction of 10%, and a temperature of 40ºC as the absorption target. At this point, the CO_2 capture rate of the system can reach around 74%.

Considering the differences in actual conditions and the errors of detection instruments, the CO_2 capture rates of the two are approximately equivalent. However, the price of MEA in the market is 1050 dollars/ton, and the price of NaOH is 340 dollars/ton. In comparison, using NaOH is more economical and beneficial for large-scale market promotion, even with the same CO_2 capture effect.

Conflicts of Interest

The authors declare no conflict of interest.

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