

Article

Development of MEA-Based and AEP-Based CO₂ Phase Change Absorbent

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Abstract: In energy conservation and low-carbon environmental protection, separating and capturing CO₂ from blast furnace gas is a crucial strategy for the steel industry to achieve its dual carbon goals. This study conducts an experimental study on the phase change absorption of carbon dioxide for the low-energy capture of carbon dioxide in blast furnace gas in iron and steel enterprises. The experiment used 30%wt monoethanolamine (MEA) and 30%wt 1-(2-aminoethyl)piperazine (AEP) as a reference to blend different absorbents, and the CO₂ absorption effect of the absorbents was tested. The results indicated that the MEA system phase change absorbents have the best absorption effect when the mass ratio of additives to water is 5:5, and the AEP system has the best absorption effect at 7:3. The absorption effect of different phase separators is as follows: n-propanol > sulfolane > isopropanol. AEP/n-propanol/H₂O (7:3) has a maximum absorption load of 2.03 molCO₂·mol⁻¹ amine, a relatively low rich phase ratio of 0.46, and low regeneration energy consumption. The load capacity of different absorbents was calculated based on the load experiment results, and it was found that the loading capacity of the MEA system was greater than that of the AEP system, with the maximum load capacity of MEA/n-propanol/H₂O (5:5) being 4.02 mol/L. Different types of absorbents exhibited an increase in rich phase density with the increase in additive quality. The regeneration performance of the absorbent indicated that at a temperature of 393.15 K, the desorption load of n-propanol aqueous solution rich phase in the absorbent was high, and the desorption speed was the fastest.

Keywords: phase change absorbent; CO₂ capture; MEA; AEP

Academic Editor: Vijaya Raghavan

Received: 14 November 2024

Revised: 22 December 2024

Accepted: 30 December 2024

Published: 2 January 2025

Citation: Wang, Y.; Cheng, F.; Li, J.;

Liu, Y.; Wang, H.; Li, Z.; Yang, X.

Development of MEA-Based and

AEP-Based CO₂ Phase ChangeAbsorbent. *Processes* **2025**, *13*, 92.[https://doi.org/10.3390/](https://doi.org/10.3390/pr13010092)[pr13010092](https://doi.org/10.3390/pr13010092)**Copyright:** © 2025 by the authors.

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1. Introduction

Countries worldwide are pursuing the goal of low-carbon emissions [1,2]. Vigorously promoting CCUS (carbon capture, utilization, and storage) technology is an important means of achieving the dual carbon goals of the steel industry. The steel production process in China is mainly based on the blast furnace converter method [3]. About 89% of energy input comes from coal, which has high carbon emissions. Steel enterprises' energy-saving and consumption reduction starts with the "three gases" (blast furnace gas, converter gas, and coke oven gas). Among them, blast furnace gas emissions are the highest. Therefore, the effective utilization of blast furnace gas is the key to energy conservation and consumption reduction in the steel industry [4].

Considering factors such as one-time investment, operating costs and energy consumption, and waste treatment, the chemical absorption method can fully leverage the advantages of comprehensive waste heat utilization in steel enterprises, effectively utilizing low-temperature heat. It is an ideal method for capturing carbon dioxide in blast furnace gas. Chemical absorbents are the key to the chemical absorption method. The traditional chemical absorbents mainly include ammonia absorbent [5], amino acid salt absorbent [6], potassium carbonate absorbent [7,8], and organic amine absorbent [9]. Among them, organic amine absorbent is the most representative chemical absorbent. Amine absorbent has the advantages of a fast reaction rate, high gas purification, good absorption effect, and low cost [10]. Monoethanolamine (MEA) [11], diethanolamine (DEA), and N-methyldiethanolamine (MDEA) [12] are commonly used. However, most traditional absorbents have their limitations, such as the volatilization of ammonia, slow absorption rate, low absorption capacity, and high energy consumption [8,13,14]. Han et al. [15] found that the energy consumption of absorbent regeneration can be reduced to 2.5 GJ/t, and the volume fraction of nitrogen in the tail gas leaving the absorption tower is as high as 0.02%. Mao et al. [16] reported that the average energy consumption of using monoethanolamine to capture CO₂ was 5.4 GJ/t. 30% MEA is one of the commonly used reference absorbents, but its high regeneration energy consumption (about 3.7–4.0 GJ/tCO₂) hinders its large-scale application [17]. The energy consumption of absorbent regeneration comprises thermal desorption reaction heat, sensible heat of absorbent rising temperature, and latent heat of water evaporation. P.H.M. Feron et al. [18] studied the thermal desorption energy consumption of 30% MEA absorbent. The results showed that the total energy consumption of 30% MEA absorbent was about 135–205 KJ·mol^{−1} CO₂, and the heat of thermal desorption reaction accounted for 40–60% of the total energy consumption, the latent heat of water evaporation accounts for 30–40% of the total energy consumption. Although water is the most suitable co-solvent from the cost and environmental impact perspective, the high water content (>50%) in the absorbent and the strong interaction between MEA and CO₂ are the reasons for the high desorption energy consumption. Therefore, researchers have developed new mixed amine absorbents [19,20], such as MEA+MDEA [21], MDEA+piperazine(PZ) [22], and Butyl ethanolamine (BAE)+2-Dimethylaminoethanol (DMAE) [23]. Although mixed amine absorbents can improve the drawbacks of single absorbers, they cannot simultaneously have high absorption and desorption performance [24].

Phase change absorption is considered as a CO₂ capture technology with great potential because it can greatly reduce the amount of recycled liquid and thus reduce energy consumption [25]. Phase change absorbent absorbs CO₂ and divides it into rich and lean phases [26]. Only the rich phase is regenerated, while the lean phase is directly returned to the absorption tower for reuse, greatly reducing the sensible heat and latent heat of vaporization required for adsorption. At first, researchers mixed different types of amines to develop phase separation absorbents. Wange et al. [27] adopted the mixed solution of diethylenetriamine(DETA) and 2-(diethylamine)-ethanol (DEEA) as a new phase change adsorbent to absorb CO₂, and the rich phase accounted for 70% when the rich phase load reached 2.23 mol/L. Liu et al. [28] mixed 50 wt% DEEA and 2-((2-aminoethyl) amino) ethanol (AEEA, 25 wt%). When the rich phase load reached 2.95 mol/kg, the rich phase accounted for 80%. The total amine concentration of mixed amine absorbents is relatively high, usually exceeding 60%. High concentrations can cause amine volatilization and degradation [29]. Excessive wealth ratio can also increase desorption energy consumption.

To address the drawbacks of mixed amine phase change absorbents. In recent years, the research direction is to use organic solvents to replace water in phase change absorbents. The most widely used organic solvents in phase separation are sulfoxide [30–33] and alcohol [34–37]. They promote the phase separation of the absorbent and the absorption

of CO₂ [38]. Wang et al. [33] used DETA and sulfolane to make phase change absorbent to simulate the absorption of CO₂. During the CO₂ absorption process, sulfolane, as an inert solvent, was separated from the absorption product instead of water, reducing the total heat load by 19%. Zhang et al. [36] prepared a CO₂ phase change adsorbent (CPCA) composed of MEA/alcohol/H₂O, and studied the species distribution, physical properties, circulation capacity, absorption, and regeneration capacity of CPCAs. Compared with 30 wt% MEA/H₂O, the CO₂ cycling capacity of CPCA increased by 62%. In the MEA–propanol system, propanol can significantly promote CO₂ mass transfer [39]. Adding organic solvents to the alcohol amine phase change absorbent can reduce the enrichment to 50%, and the desorption energy consumption is about 2.2–2.8 GJ/tCO₂ [29], which is an ideal phase change absorbent. It is also reported that there are primary amine/secondary amine + tertiary amine + organic physical solvent. In the mixed solution, primary amine/secondary amine is used as the absorption enhancer, while tertiary amine serves as the principal absorbents, and physical solvent act as phase separation agent. For example, Wang et al. [30] proposed a two-phase absorbent that can adjust the phase separation behavior of Triethylenetetramine (TETA)-DEEA through sulfolane without sacrificing high CO₂ absorption capacity, while reducing the volume ratio of the rich phase and increasing the CO₂ load. Wang et al. [40] proposed a tertiary amine-based biphasic solvent: N,N-dimethylethanolamine (DMEA)-PZ-1-Butanol for efficient CO₂ capture. The addition of 1-Butanol not only produced phase separation and reduced the activation energy of the catalyst, but also synergistically with PZ to increase the inherent slow absorption rate of DMEA to a level comparable to that of 5M MEA. Although the regenerative energy consumption can be greatly reduced in the circulation system, the phase change absorbent still has problems such as high viscosity, large volatility, and unsatisfactory phase separation ratio. Therefore, developing solutions with higher CO₂ load, smaller abundance ratio, and lower viscosity is the future direction of phase change absorbent.

This study aims to develop a new phase change absorbent with good absorption performance, low enrichment ratio, and suitable viscosity for carbon dioxide capture by the chemical absorption method. MEA and AEP were used as the main absorption components of the phase change absorbent, and n-propanol, isopropanol, and sulfolane were used as phase separation agents. The absorbent's absorption, desorption, and phase separation effects were observed.

2. Materials and Methods

2.1. Materials

MEA and AEP were selected as the main absorption components of the phase separation absorbent; n-propanol, isopropanol, and sulfolane were selected as the phase separation additives. Based on 30%wt MEA and 30%wt AEP, different kinds of absorbents were prepared by changing the ratios of water and additives, and the mixed-phase system of absorber components/additives/H₂O could be obtained.

MEA (AR) was obtained from InnoKai Technology Co., Ltd., Shenzhen, China; AEP (AR) was acquired from Bohr Chemical Reagent Co., Ltd., Shanghai, China. N-propanol (AR), Isopropanol (AR), and Sulfolane were purchased from Mindray Biochemical Technology Co., Ltd., Shenzhen, China. HCl (AR) was purchased from China National Pharmaceutical Group Chemical Reagent Beijing Co., Ltd., Beijing, China. CO₂ (≥99.99%, volume fraction) was purchased from Beijing Huanyu Jinghui Jingcheng Gas Technology Co., Ltd., Beijing, China. Throughout the experiments, deionized water was used and all the materials for this study were used without further purification.

2.2. Experimental Methods

2.2.1. Absorption Experiment

The schematic diagram of the absorption experimental device is shown in Figure 1, which is composed of a rotameter, a gas washing bottle, a constant temperature water bath device, and a soap film flowmeter. CO₂ enters the gas washing bottle through the flow rate controlled by the rotameter and reacts with the absorbent. After being absorbed and saturated, it flows out from the outlet of the washing bottle. The soap film flowmeter connected to the outlet records the CO₂ flow rate. The absorption device is in a constant temperature water bath, ensuring an absorption temperature of 40 °C. Adjust the rotameter to set the intake flow rate to 200 mL/min and introduce CO₂ into the prepared absorbent. After the absorbent is introduced into the gas, CO₂ is gradually measured from the outlet, and the gas flow rate is measured every 2 min using a soap film flowmeter. After the outlet flow rate is equal to the inlet flow rate, it is considered close to absorption saturation. Continue ventilation for 10 min and complete a set of experiments.

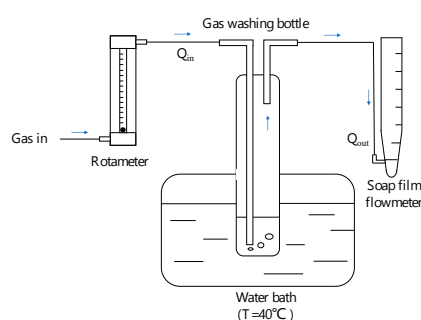


Figure 1. Schematic of absorption apparatus.

Evaluate the absorption performance of the absorbent through absorption rate and absorption load. According to Xiao et al. [41], the CO₂ absorption rate was defined as follows:

$$r_{co2,ab} = \frac{Q_{in} - Q_{out}}{n_{MEA} \times V_0} \left(\frac{P_{act} T_0}{P_0 T_{act}} \right) \quad (1)$$

where $r_{co2,ab}$ (molCO₂·mol^{−1}amine·min^{−1}) is the absorption rate, Q_{in} (L·min^{−1}) is the intake flow rate, n_{MEA} (mol) is the molar amount in the washing gas cylinder, V_0 (22.4 L·mol^{−1}) is the molar volume of gas at 1×10^5 Pa and 273.15 K, P_{act} (Pa) is the experimental gas pressure, and T_{act} (K) is the experimental gas temperature, P_0 (1×10^5 Pa), T_0 (273.15 K).

The absorption load can be calculated based on the absorption rate, and its formula is as follows:

$$\alpha = \int_0^t r_{co2,ab} dt \quad (2)$$

where α (molCO₂·mol^{−1}amine) is the absorption load, and t (min) is the reaction time.

After the absorption experiment, if the phase is separated, a measuring cylinder will be used to measure the volume of the lean phase and the rich phase to obtain the proportion of the rich phase volume. The proportion of rich phase volume was defined as follows:

$$\beta_1 = V_{rich} / (V_{rich} + V_{lean}) \quad (3)$$

where β_1 is the proportion of rich phase volume, V_{rich} (mL) is the volume of rich phase, and V_{lean} (mL) is the volume of the lean phase.

2.2.2. Desorption Experiment

The schematic diagram of the desorption experimental device is shown in Figure 2 and is composed of a condenser, a flask, a magnetic stirrer, and a soap film flowmeter. The phase change absorbent after CO₂ absorption is divided into two phases, and the rich phase is taken for desorption research. The high-temperature CO₂ produced after heating the rich phase is cooled by the condenser tube and then enters the soap film flowmeter connected to the air outlet to measure the flow rate at this time. Set up a heating magnetic stirrer to heat to a desorption temperature of 120 °C, take 10 mL of saturated absorbent, and put it into a constant temperature kerosene while ensuring the rotor is evenly stirred in the solution. After cooling and drying in the condenser pipe, the released gas is passed into the soap film flowmeter, and the outlet gas flow rate is measured every 2 min until it cannot be measured from the outlet to the gas overflow.

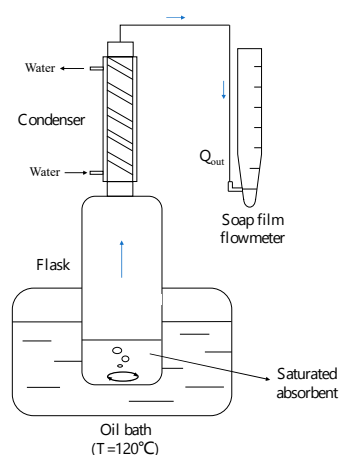


Figure 2. Schematic of desorption apparatus.

The desorption rate can be calculated by the gas outlet rate of the device, and is defined as follows:

$$r_{co2,des} = \frac{Q_{out}}{n_{MEA} \times V_0} \left(\frac{P_{act} T_0}{P_0 T_{act}} \right) \quad (4)$$

where $r_{co2,des}$ (molCO₂·mol^{−1}amine·min^{−1}) is the desorption rate.

The desorption load can be obtained by integrating the desorption rate with time, and is defined as follows:

$$\alpha' = \int_0^t r_{co2,des} dt \quad (5)$$

where α' (molCO₂·mol^{−1} amine) is the desorption load.

2.2.3. CO₂ Load Measurement Experiment

The CO₂ load measurement device is shown in Figure 3 and consists of a U-shaped tube, burette, agitator, and conical bottle. After the absorption of CO₂ by the absorbent is completed, let it stand for a while and observe stable phase separation. Separate the upper and lower liquid phases. Excessive hydrochloric acid is dripped into the liquid to be measured by a burette, and the CO₂ produced by the reaction enters the connected U-shaped tube for quantitative measurement. Record the initial reading V_1 when the U-tube is connected to the atmosphere, and record the amount of hydrochloric acid as V_2 . Hydrochloric acid reacts with absorbent to release CO₂, creating a pressure difference in the U-shaped tube and a liquid level difference. After the reaction, adjust the position of the U-tube, and record the reading V_3 in the U-tube at this time.

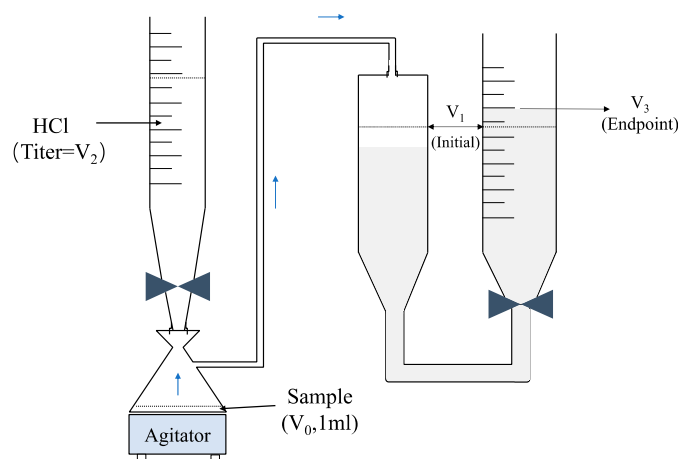


Figure 3. Schematic of CO₂ loading titration apparatus.

The load of CO₂ is defined as follows:

$$\text{loading}(\text{mol/L}) = \frac{V_3 - V_2 - V_1}{24.4 \times V_0} \quad (6)$$

where V_0 (mL) is the volume of the solution to be tested, and 24.4 refers to the volume of 1 mol gas at room temperature (298.15 K). V_1 (mL) is usually taken as the initial reading before the reaction in the U-shaped tube; V_2 is the titration amount of dilute hydrochloric acid, mL; V_3 (mL) is the reading of the end point after the completion of the reaction in the U-shaped tube.

3. Results

3.1. Phase Separation of Absorbent

A total weight of 100 g of absorbent was prepared by selecting n-propanol, isopropanol, and sulfolane as phase separators when the concentration of MEA was 30 wt% and the adsorption temperature was 313.15 K. That is, each absorbent includes 30 g of MEA. All ratios mentioned below are the mass ratio of phase separation additives to water under the premise of a total weight of 70 g. Table 1 shows the phase separation results at different mass ratios. It can be seen that the MEA/propanol/H₂O absorbents absorb CO₂ in the various phases until the mass ratio of 4:6, which is due to the large proportion of water in the system, which can completely dissolve the additive and absorb the reaction products.

Table 1. Phase separation results of MEA/phase separation agent/H₂O absorbent with different mass ratios.

Additive–Water	n-Propanol	Isopropanol	Sulfolane
1:9	x	x	x
2:8	x	x	x
3:7	x	x	✓
4:6	✓	✓	✓
5:5	✓	✓	✓
6:4	✓	✓	✓
7:3	✓	✓	✓
8:2	✓	✓	✓
9:1	✓	✓	✓

According to the results of the phase separation of the phase-change absorber in the MEA system, when the weight ratio of phase separator–water reaches the extreme

value, various absorption properties of phase-separated absorber are weak and the phase separation effect is not obvious. Therefore, three ratios of 3:7, 5:5, and 7:3 were selected for the absorption experiments with AEP as the main component of the phase change absorber, and the absorbent was uniformly separated after the absorption was completed.

Observe the phase change absorbent with phase separation, as shown in Tables 2 and 3. As the additive content increases, the volume of the rich phase gradually decreases, and the rich phase ratio decreases. At the same mass ratio, sulfolane brings the greatest rich phase ratio, and n-propanol and isopropanol are relatively small. The lower the proportion of the rich phase of the adsorbent after phase separation, the less the solution flows into the desorption tower for regeneration in the process, which is more conducive to reducing the energy consumption of regeneration. The 7:3 group of the AEP system absorbent added with n-propanol has an excellent absorption capacity and a relatively low phase-rich volume ratio of 0.46, which is beneficial for reducing regeneration energy consumption.

Table 2. Rich phase volume ratio of MEA/additive/H₂O absorbent.

Reagent Components	n-Propanol	Isopropanol	Sulfolane
3:7	Unseparated phase	Unseparated phase	0.88
5:5	0.67	0.66	0.68
7:3	0.47	0.65	0.67

Table 3. Rich phase volume ratio of AEP/additive/H₂O absorbent.

Reagent Components	n-Propanol	Isopropanol	Sulfolane
3:7	0.81	0.85	0.94
5:5	0.63	0.60	0.74
7:3	0.46	0.44	0.69

3.2. Phase Separation Mechanism

MEA and AMP can undergo phase separation because the solubility of MEA-CO₂ and AMP-CO₂ in water is higher than in alcohol after the reaction. CO₂ is introduced into the MEA/additive/water system, and the reaction is shown in Equation (7) [42]. The phase separation situation of MEA/n-propanol/H₂O absorbent is shown in Figure 4. This reaction is a salinization reaction, generating carbamate and protonated MEA, which were formed and could be regarded as MEA salt. Water will first solvate these components. With the addition of salt, phase separation would happen for a water-miscible organic liquid from its aqueous solution. MEA salts cause water clusters to evolve around them, forming alcohol clusters gradually. When the size of water and alcohol groups reaches the macroscopic scale, two phases are formed. After phase separation, the upper liquid phase mainly contains additives and related components and is a lean liquid phase. The lower liquid phase mainly contains CO₂ absorption products and MEA, making it a rich liquid phase.



When the concentration of propanol in the absorbent increases, the CO₂ load in the lower phase increases, and the concentration of propanol slightly decreases. The CO₂ load in the upper phase remains unchanged. While the concentration of propanol increases, water content decreases [43]. The concentration of salt can affect the solubility of organic solvents, thereby affecting the phase separation of absorbents [44,45]. The increase in the concentration of propanol also represents a decrease in the concentration of water. After the absorption reaction is completed, the concentration of salt increases, but the amount

of water that can interact with propanol decreases. As a result, more propanol rises to the lean phase, leading to a change in concentration.

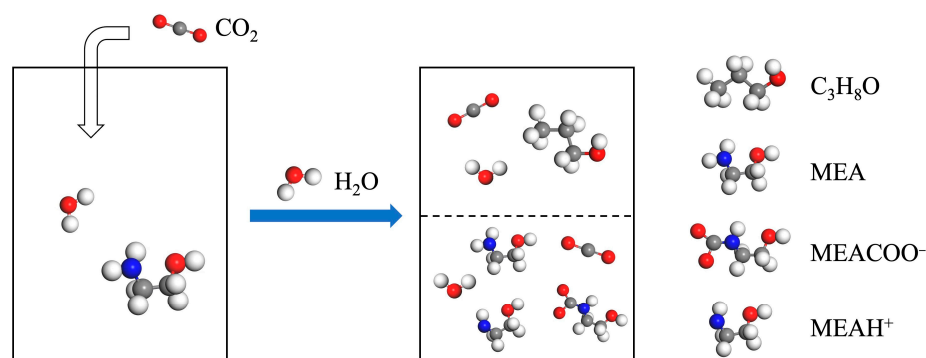


Figure 4. Phase separation diagram of MEA/n-propanol/H₂O absorbent.

The phase change behavior of absorbents is also related to the hydrophobicity of additives, and the higher the hydrophobicity, the more obvious the phase separation phenomenon. Sulfolane is a highly hydrophobic solvent, while the alcohol amines and reaction-related products used in the experiment are hydrophilic solutes. Therefore, as CO₂ is introduced, the concentration of the products gradually increases. Sulfolane is gradually discharged from the aqueous phase, and the solution is divided into two phases from a homogeneous phase. After the absorbent of the AEP/additive/water system absorbs CO₂, a reaction occurs, as shown in Equation (8). The product (AEPH⁺ and AEP⁻ as shown in Figure 5) and additive are immiscible and migrate to the upper liquid phase to form a rich phase with amines, while the remaining additives and related components remain in the lower liquid phase as a lean solution.

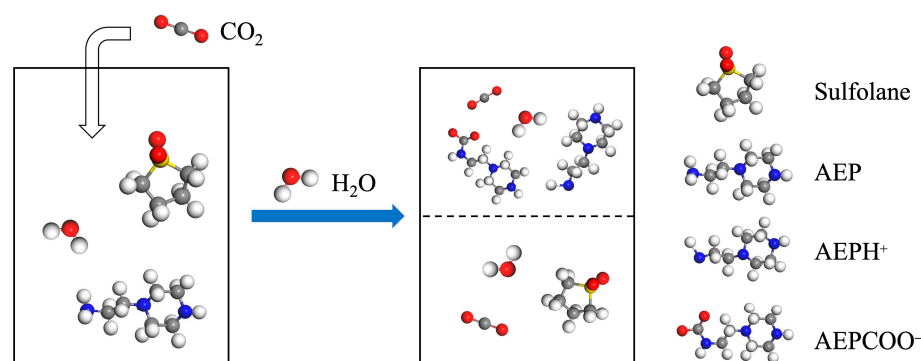


Figure 5. Diagram of the relationship between the phase separation phenomenon and the dipole moment of AEP/sulfolane/H₂O absorbent (Debye is the dipole moment).

The phase separation behavior of phase change absorbents may also be related to the polarity of the components. Typically, the larger the dipole moment of a molecule, the stronger its polarity [46]. The dipole moments of AEP and sulfolane are small, while the reaction products with CO₂ have high polarity. It can be inferred from this that after absorbing CO₂, the rich liquid phase contains highly polar products, which cannot be miscible with sulfolane, resulting in a phase transition, as shown in Figure 5.

In summary, the essence of the phase change absorbent adding organic solvent as a phase separation agent is to replace the water in the phase change absorbent with organic solvent to achieve the phase separation effect while reducing the volume proportion of the

rich phase. The reaction of MEA and AEP in contact with CO₂ is similar, and the difference in phase separation ratio is mainly due to the characteristics of the added organic solvent.

3.3. Research on CO₂ Absorption by Phase Change Absorbent

3.3.1. Phase Change Absorbent with MEA as the Main Component

The mixed solvent absorption loads of MEA and different additives are shown in Figure 6. The absorption load curves all showed that the rate of absorption load increased rapidly in the early stage of adsorption, and the increased rate of absorption load slowed down with the extension of time. Overall, the phase change absorbents with MEA as the main absorption component have the highest absorption load when the mass ratio of the phase separation agent to water is 5:5. Among them, MEA/n-propanol (0.65 molCO₂·mol⁻¹amine) > MEA/sulfolane (0.61 molCO₂·mol⁻¹amine) > MEA/isopropanol (0.45 molCO₂·mol⁻¹amine). Liu et al. [28] mixed DEEA and MEA aqueous solution as phase change absorbents, and the CO₂ absorption load at 40 °C was 0.49 molCO₂·mol⁻¹amine. Zhang et al. [47] studied the optimal ratio and performance of MEA/n-propanol/H₂O and adjusted the mass ratio of n-propanol to water to maintain the MEA with a mass fraction of 30%. The results showed that the optimal ratio of m (MEA):m (n-propanol):m (H₂O) = 3:3:4 system has a circulating CO₂ load of 1.70 mol/kg (absorbent), which is 1.3 times that of 30% MEA. In this paper, the maximum absorption load at m (MEA):m (n-propanol):m (H₂O) = 3:3.5:3.5 was obtained, which is close to the known results.

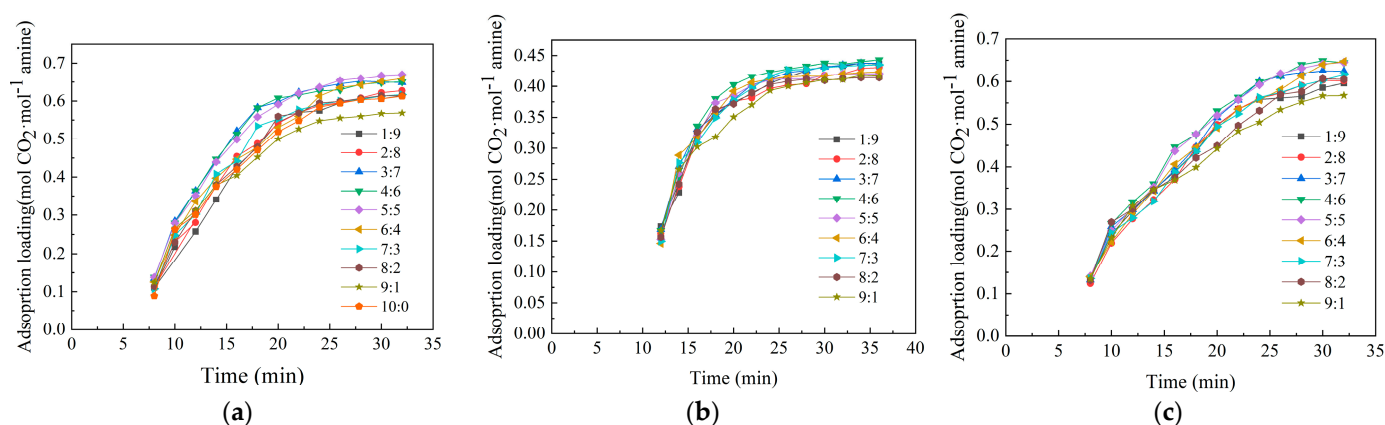


Figure 6. Absorption loads of MEA-based absorbents with different additives at different concentrations: (a) MEA/n-propanol; (b) MEA/isopropanol; (c) MEA/sulfolane.

The absorption rates of mixed solvents of MEA and different additives are shown in Figure 7. As shown in the figure, the absorption rate of each group shows a similar trend. In the initial stage of gas introduction, the absorption rate rapidly decreases. As the ventilation time increases, the downward trend of the absorption rate slows down until it approaches 0. Overall, there is not much difference in the absorption rate of each group of absorbents under different weight ratios. At the same 5:5 ratio, initial absorption rate was sulfolane (0.020 molCO₂·mol⁻¹amine·min⁻¹) > N-propanol (0.016 molCO₂·mol⁻¹amine·min⁻¹) > Isopropanol (0.014 molCO₂·mol⁻¹amine·min⁻¹). The 5:5 group, which performed excellently in absorbing load, was found to have a moderate absorption rate among different mass ratio groups. Zhang et al. [47] found that in the MEA/n-propanol/H₂O system, the initial absorption rate of the system with the optimal ratio of m (MEA):m (n-propanol):m (H₂O) = 3:3:4 was 5 times that of the mass fraction of 30% MEA. The presence of propanol will increase the diffusion coefficient of CO₂ and thus increase the absorption rate of the absorbent, but the high concentration of propanol will inhibit the MEA and CO₂ reaction.

The addition of sulfolane has a more significant effect on increasing the CO₂ absorption rate, because sulfolane has a strong affinity with acidic gases.

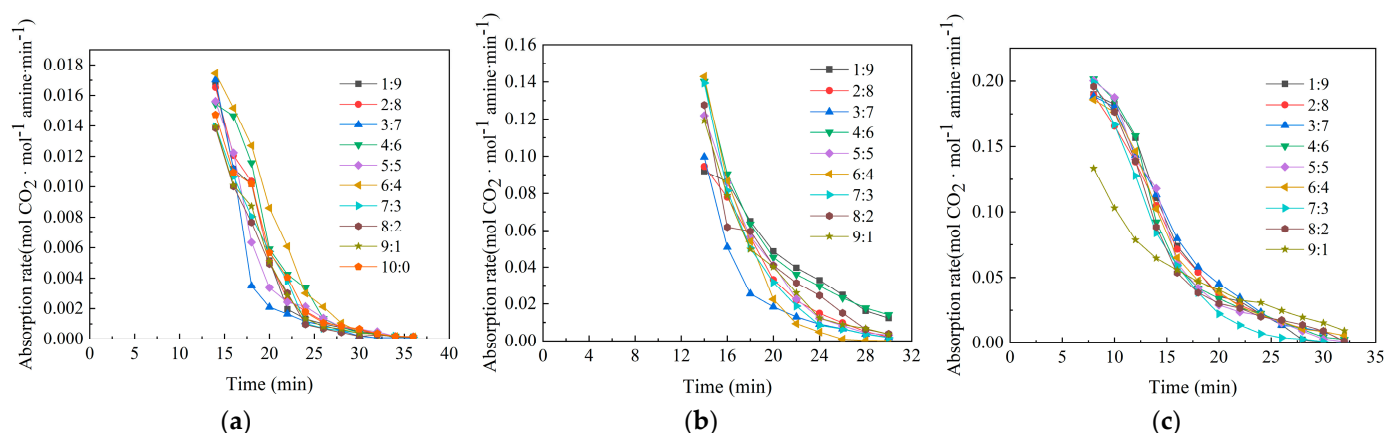


Figure 7. Absorption rate of MEA-based absorbents with different additives at different concentrations: (a) MEA/n-propanol; (b) MEA/isopropanol; (c) MEA/sulfolane.

3.3.2. Phase Change Absorbent with AEP as the Main Component

The mixed solvent absorption loads of AEP and different additives are shown in Figure 8. The absorption load of the 7:3 group in each absorbent was significantly higher than the other two groups, with AEP/n-propanol ($2.03 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{amine}$) > AEP/sulfolane ($1.60 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{amine}$) > AEP/isopropanol ($1.56 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{amine}$). The absorption rates of mixed solvents of AEP and different additives are shown in Figure 9. The rate trend is the same as that of the MEA system absorbent. The 7:3 group performed best in absorbing load but the slowest absorption rate. Li et al. [37] optimized the ratio of AEP and 1-propanol, and the results showed that under the optimal ratio of m (AEP):m (1-propanol):m (H₂O) = 2:4:4, the CO₂ loading capacity was 2.3 times that of 30% MEA.

The absorption rates of AEP and different additives in mixed solvents are shown in Figure 9. At the same 7:3 ratio, the initial absorption rates of different phase separation agents were as follows: isopropanol ($0.016 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{amine} \cdot \text{min}^{-1}$) > sulfolane ($0.015 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{amine} \cdot \text{min}^{-1}$) > n-propanol ($0.014 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{amine} \cdot \text{min}^{-1}$). The absorption saturation time of AEP-based absorbent is longer than that of MEA-based absorbent, and it is generally completed 45 min after ventilation, but the absorption load is greater.

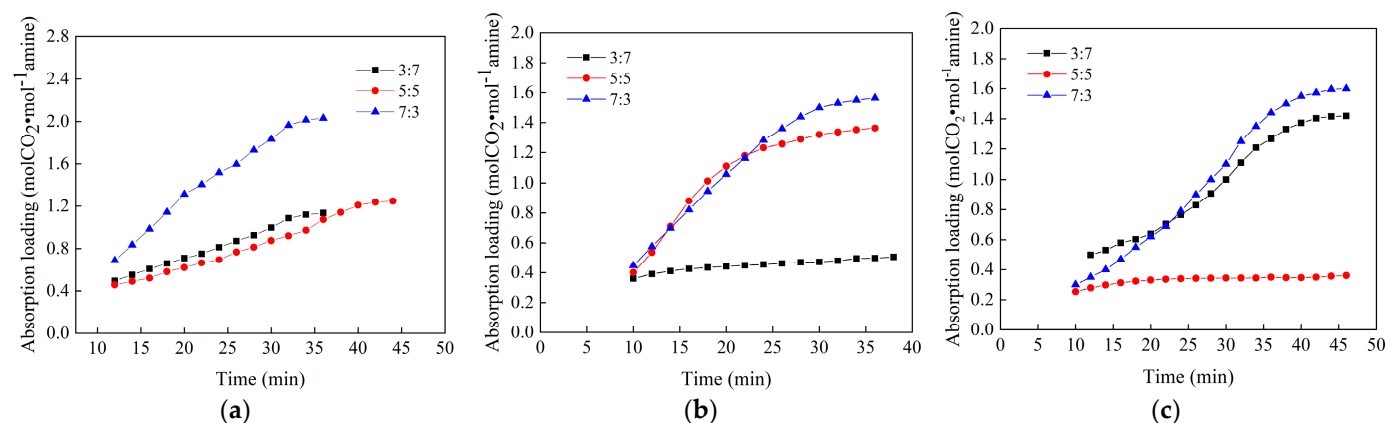


Figure 8. Absorption load of AEP-based absorbents with different additives at different concentrations: (a) AEP/n-propanol; (b) AEP/isopropanol; (c) AEP/sulfolane.

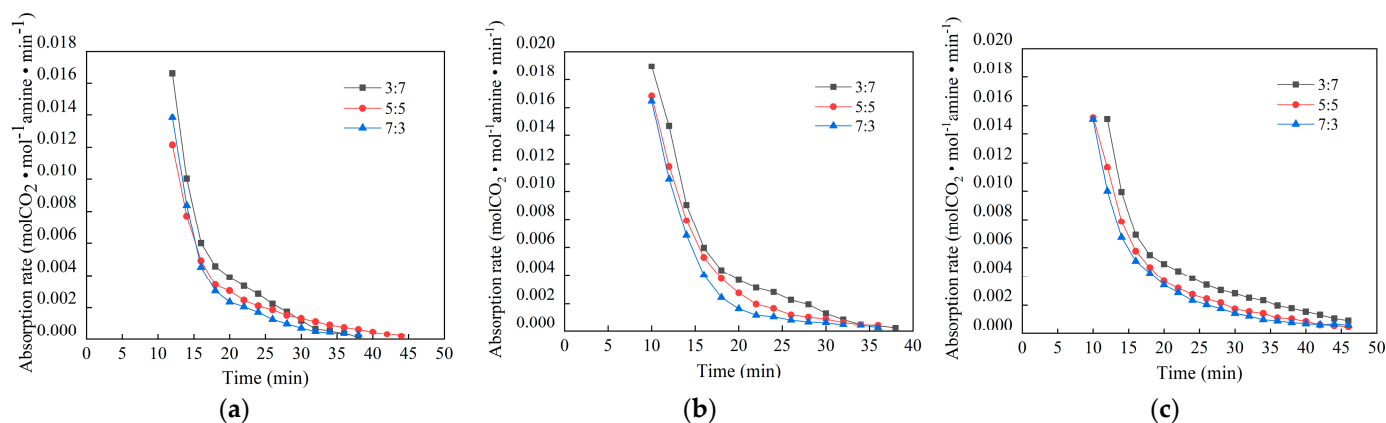


Figure 9. Absorption rate of AEP-based absorbents with different additives at different concentrations: (a) AEP/n-propanol; (b) AEP/isopropanol; (c) AEP/sulfolane.

Table 4 shows the key performance parameters for MEA and AEP to obtain the optimal absorption load. The phase change absorbent of the MEA system has the best absorption effect when the mass ratio of the phase separation agent to water is 5:5. The phase change absorbents of the AEP system have the best absorption effect when the mass ratio of the phase separation agent to water is 7:3. The absorption load is higher than that of the MEA system. Compared to MEA, the primary (secondary) amino group of AEP can add a strong absorb effect. Its steric hindrance effect is also beneficial for the regeneration cycle, and propanol plays a major role in phase separation in the system. The absorption rate of the absorbents of the two systems decreased significantly within 15 min, and the absorption rate curves were similar, which may be because the sample mass was small and the difference was not obvious.

Table 4. Comparison of optimal absorption effect points for MEA-based and AEP-based absorbents.

	MEA	AEP
Phase separator	n-propanol	n-propanol
Mass ratio	5:5	7:3
Highest absorption load	0.65 molCO ₂ · mol ^{−1} amine	2.03 molCO ₂ · mol ^{−1} amine

In terms of CO₂ absorption performance, the experiments in this paper show that the absorber with n-propanol added possesses the maximum absorption load. On the one hand, the volatilization rate of n-propanol is smaller than that of isopropanol, and the high volatility of the absorbent components is not favorable to the overall reaction balance of the absorption process, and also leads to the loss of absorbent, which in turn affects the absorption effect. On the other hand, MEA reacts with CO₂ to produce salts with different solubility in different solvents, and the polarity of organic solvents has a great influence on the solubility of substances. Overall, the solubility and absorption rate of CO₂ when propanol is used as a solvent is better than that of water [48]. Compared with alcohols, sulfolane has a stronger affinity for CO₂, so it can effectively improve the CO₂ absorption performance, but the melting point of sulfolane is extremely low, and the density of the phase change absorber of the sulfolane system is much larger, and the amine is required to have a certain degree of hydrophilicity [49]; otherwise, it is possible to have solid–liquid partitioning, which to a certain extent increases the uncontrollable factors and influences the actual absorption effect.

3.4. Research on CO₂ Desorption of Phase Change Absorbents

3.4.1. Phase Change Absorbent with MEA as the Main Component

The phase change absorber splits into two phases after absorbing carbon dioxide, which has the advantage of reducing the consumption of renewable energy by simply heating the rich phase for desorption. The rich phase of MEA/additive aqueous solution with a mass ratio of 5:5 was investigated under the most suitable desorption conditions (desorption temperature of 120 °C) and the desorption curves were tested, as shown in Figure 10. It can be seen that with the increase in desorption time, the desorption rates of the three adsorbents showed the change rule of increasing and then decreasing. At the beginning of desorption, the temperature of the solution increased rapidly due to the effect of 120 °C oil bath, and the desorption rate also increased, and reached the maximum value at the measurement point of 2 min; thereafter, due to the gradual decrease in the concentration of carbon dioxide in the product, the desorption rate began to decrease rapidly, but the three kinds of solutions slowed down after 10 min, 14 min, and 12 min, and the gas could not be detected from the outlet at 28 min, until it was almost 0. The desorption curve of the three adsorbents showed a change rule of increasing and then decreasing. The desorption load generally reached a high level at 10 min. At this point, the desorption of MEA/n-propanol was 77% of the final desorption (0.44 mol CO₂·mol^{−1} amine), MEA/isopropanol was 84% of the final desorption (0.30 mol CO₂·mol^{−1} amine), and MEA/sulfolane was 93% of the final desorption (0.40 mol CO₂·mol^{−1} amine).

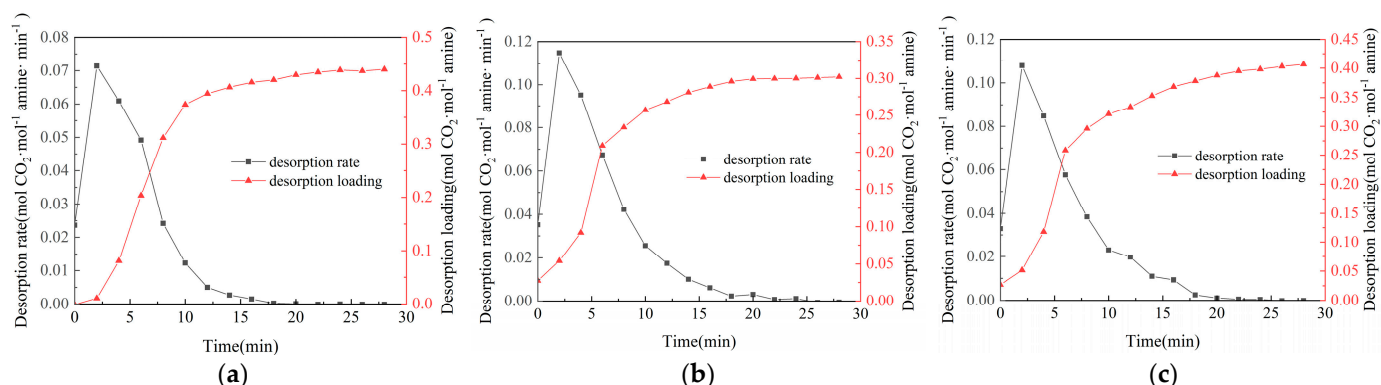


Figure 10. Desorption rate and desorption load of MEA-based absorbent with different additives (mass ratio is 5:5): (a) MEA/n-propanol; (b) MEA/isopropanol; (c) MEA/sulfolane.

The overall desorption efficiency of the MEA/sulfolane adsorbent was higher compared to the MEA/n-propanol adsorbent, with a greater magnitude of desorption over a short period of time, and a higher percentage of final desorption loading. The overall desorption efficiency of the aqueous MEA/iso-propanol solution was intermediate between that of the MEA/sulfolane and the MEA/n-propanol. The desorption rate of the aqueous MEA/iso-propanol solution was faster than that of the MEA/sulfolane and the MEA/isopropanol adsorbent over the period of 2–10 min. MEA/n-propanol adsorbents, but the final desorption was not as high as these two adsorbents because the absorption load was smaller than them.

3.4.2. Phase Change Absorbent with AEP as the Main Component

AEP/additive aqueous solutions with a mass ratio of 7:3 were investigated under optimum desorption conditions (desorption temperature of 120 °C), and its desorption profile was tested as shown in Figure 11. The trends in desorption rate and desorption load profiles were similar to those of the MEA/additive aqueous solution adsorbent, but the desorption time was shorter. As the desorption time increased, the des-

orption load increased and the rate of increase slowed down with time until saturation. The desorption load generally reached basic saturation at 6 min and the final desorption load was reached at 12 min when the rate of resolution was almost zero. AEP/n-propanol ($1.00 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{ amine}$) > AEP/iso-propanol ($0.73 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{ amine}$) > AEP/sulfolane ($0.66 \text{ molCO}_2 \cdot \text{mol}^{-1} \text{ amine}$). The 30 wt% AEP/n-propanol aqueous solutions of the three adsorbents with AEP as the main component had higher rich phase desorption loadings and faster desorption rates at a desorption temperature of 393.15 K. The results showed that the three adsorbents had higher rich phase desorption loadings than those of the three adsorbents.

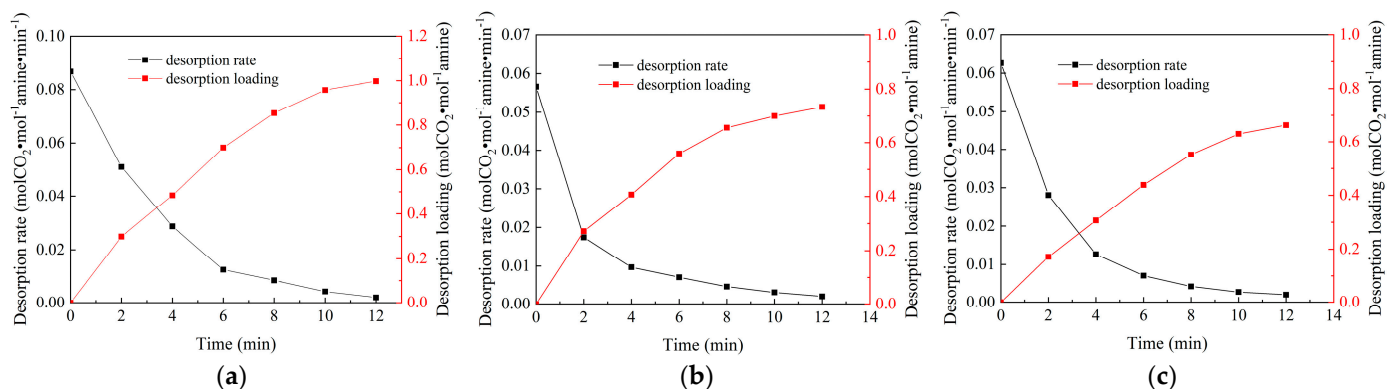


Figure 11. Desorption rate and desorption load of AEP-based absorbent with different additives (mass ratio is 7:3): (a) AEP/n-propanol; (b) AEP/isopropanol; (c) AEP/sulfolane.

Table 5 shows a comparison of the desorption loadings obtained for MEA-based and AEP-based absorbent at mass ratios of 5:5 and 7:3, respectively. The aqueous solution of n-propanol as the additive in both MEA-based and AEP-based absorbents had the highest desorption load and the fastest desorption rate among the three additive solutions. Because of the higher absorber load in the AEP-based absorbent, the desorption load is also higher than in the MEA-based absorbent. However, the absorber desorption rate is slower in the AEP-based absorbent. After absorption, the absorbent-rich phase is separated by static separation. The rich absorber phase of the AEP-based absorbent has a higher viscosity than the MEA-based absorbent. After placing the solution in the desorption unit, the rotor takes some time to stir smoothly, which affects the initial desorption rate.

Table 5. Comparison of desorption loads of MEA and AEP systems with different additives.

		n-Propanol	Isopropanol	Sulfolane
MEA	Mass ratio	5:5	5:5	5:5
	desorption loads ($\text{molCO}_2 \cdot \text{mol}^{-1} \text{ amine}$)	1.00	0.73	0.66
AEP	Mass ratio	7:3	7:3	7:3
	desorption loads ($\text{molCO}_2 \cdot \text{mol}^{-1} \text{ amine}$)	1.00	0.73	0.66

3.5. CO₂ Loading Experiment of Phase Change Absorbent

Absorption load is the total amount absorbed as the absorber reaches saturation with increasing absorption time. All measurements in this section are rich phase loads, indicating the amount of CO₂ absorption per liter of the rich phase of the absorbent, which is an indicator to test the absorption performance. The homogeneous absorbent is left to stand after absorbing CO₂ and is divided into liquid–liquid phases, i.e., the lean phase and the rich phase.

3.5.1. Phase Change Absorbent with MEA as the Main Component

The results of the loading size of rich phase CO₂ for MEA/additives and the relationship between rich phase density and mass ratio are shown in Figure 12. The rich phase density of different absorbents increased with additive quality.

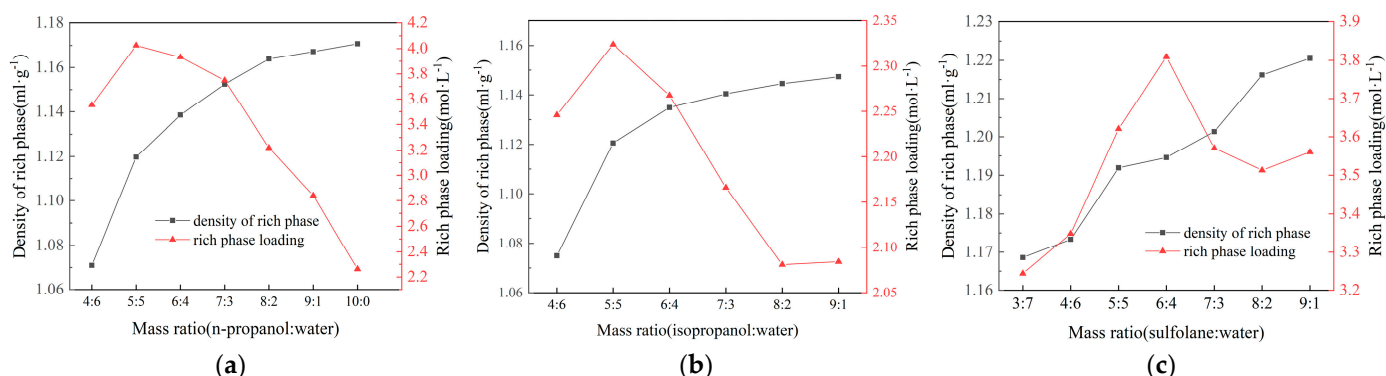


Figure 12. Density and load of MEA-based absorbent rich phase (mass ratio is 5:5): (a) MEA/n-propanol; (b) MEA/isopropanol; (c) MEA/sulfolane.

From the experimental results shown in Figure 12, it can be seen that different solvent systems have a great influence on the CO₂ loading capacity. After the passage of sufficient CO₂, the rich phase loading of MEA/iso-propanol ranges from 2.0 to 2.4 mol/L, while the rich phase loading of MEA/sulfolane and MEA/n-propanol is above 2 mol/L. The rich phase loading of MEA/sulfolane and MEA/n-propanol is above 2 mol/L. The rich phase loading did not increase as the proportion of n-propanol increased, with the highest value occurring around 5:5 at 4.02 mol/L. Although the adsorption loadings of the solutions did not change much, the rich phase loading decreased due to the increase of CO₂ in the lean phase. The MEA/iso-propanol system was similar to the MEA/n-propanol system; the rich phase load decreases after the peak value (2.32 mol/L) when the mass ratio is 5:5, but the reduction amplitude is smaller than that of MEA/n-propanol system. The rich phase CO₂ loading reached a maximum value of 3.81 mol/L at a mass ratio of 6:4 and then decreased. The mass ratio of sulfolane to water did not affect the loading capacity of the rich phase, which may be because some of the CO₂ products went into the lean phase.

In the MEA/n-propanol system, although the fastest absorption rate was observed at a mass ratio of 7:3, the highest rich phase loading was observed at 5:5, which had the highest rich phase loading of the three solutions. The MEA/n-propanol solution with a mass ratio of 7:3 had a relatively large phase-rich ratio, although the phase-rich loading was also larger. In addition, the solidification temperature range of sulfolane between 21.8 °C and 27.3 °C may affect the adsorption effect. Therefore, combining the above factors, the MEA/n-propanol system with 5:5 had the best adsorption effect with a suitable rich phase ratio and ideal loading capacity.

3.5.2. Phase Change Absorbent with AEP as the Main Component

The results of the magnitude of the phase-rich CO₂ loading of AEP/additives and the phase-rich density versus mass ratio are shown in Figure 13. The rich phase densities of the different absorbents all increased with the increase in additive mass. It was found that the maximum rich phase CO₂ loading was achieved at a mass ratio of 5:5, and the minimum loading of AEP/n-propanol was 0.71 mol/L. In contrast, the minimum loadings of AEP/iso-propanol and AEP/sulfolane were 0.49 mol/L and 1.12 mol/L, respectively. The maximum loading of AEP/sulfolane system at 7:3 was 1.56 mol/L, which was higher than that of AEP/n-propanol at 0.99 mol/L. However, the rich phase ratio was too large,

the viscosity was high, and the sulfolane, which was a solid at room temperature, had to be melted before use, which consumed more energy and was unsuitable for recycling in the actual process.

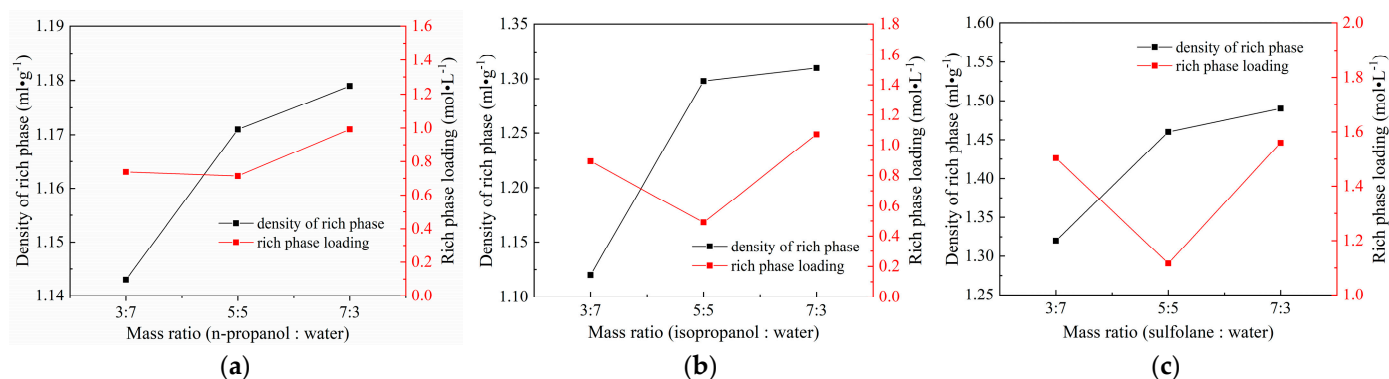


Figure 13. Density and load of AEP-based absorbent rich phase (mass ratio is 7:3): (a) AEP/n-propanol; (b) AEP/isopropanol; (c) AEP/sulfolane.

Table 6 shows a comparison of the maximum points of the rich phase loading capacity of the MEA and AEP systems with different additives. In general, the phase rich load of the MEA system is larger than that of the AEP system. After phase separation, the rich phase viscosity of the AEP system absorbent is obviously greater than that of the MEA system, and the high viscosity is not conducive to material transfer in solution and also affects the chemical reaction in the loading experiment. In practical application, when the rich phase viscosity of the absorbent increases, the heat transfer area of the rich and lean liquid needs to be changed, and the heat load of the reboiler increases, thus increasing the generation energy consumption.

Table 6. Comparison of rich phase loads of MEA and AEP systems with different additives.

		n-Propanol	Isopropanol	Sulfolane
MEA	Mass ratio	5:5	5:5	6:4
	Rich phase load (mol/L)	4.02	2.32	3.81
AEP	Mass ratio	7:3	7:3	7:3
	Rich phase load (mol/L)	0.99	1.07	1.56

4. Discussion

The CO₂ adsorption performance of the MEA-based system had a maximum value of 0.65 molCO₂·mol⁻¹amine with n-propanol as an additive and a phase separator to water ratio of 5:5, while the CO₂ absorption performance of the AEP-based system had a maximum value of 2.03 molCO₂·mol⁻¹amine with n-propanol as an additive and a phase separator to water ratio of 7:3. Among the similar results reported so far, Zhang et al. [47] reported that the cyclic capacity of the CPCA with 30% MEA + 30% 1-propanol + 40% H₂O was 1.70 mol/kg, and Li et al. [37] proposed a novel biphasic solvent of AEP/1-propanol/H₂O solution (under the optimal ratio of m (AEP):m (1-propanol):m (H₂O) = 2:4:4), and the absorption capacity was 1.26 molCO₂·mol⁻¹amine. The experiments in this paper contain less water components in the dosage of the absorbent, which theoretically has a lower energy consumption while maintaining the existing excellent CO₂ absorption performance because the latent heat of vaporization of water is reduced.

The lower the rich phase of the absorber after phase separation, the lower the flow rate of the solution into the desorber for regeneration in the process, and the more favorable to reduce the regeneration energy consumption. In addition, the AEP/n-propanol solution

has a relatively low rich phase ratio of 0.46 at a ratio of 7:3, which is a relatively excellent performance in reducing energy consumption.

Phase change absorbers have higher viscosities compared to typical chemical absorbers. Xu et al. [50] measured the viscosity of a formulated 4M DEEA/2M BDA absorber at an absorption temperature of 40 °C, which was increased by a factor of 6 compared to the commonly used 30% WMEA single-phase absorber. The viscosity of the phase-rich phase of the AEP system absorber was significantly higher than that of the MEA system absorber after phase separation. After phase separation, the viscosity of the rich phase of the AEP system absorber is significantly higher than that of the MEA system absorber, which may be inconvenient for the transfer of substances in solution and affect the chemical reactions in the loading experiments. In practice, when the viscosity of the absorbent rich phase increases, the rich-rich heat exchange area needs to be changed because the heat exchange of the heat exchanger will be affected [51], and the above series of reactions increase the heat load of the reboiler, which in turn increases the regeneration energy consumption. However, high viscosity is beneficial for better phase stabilization of the absorber after CO₂ absorption, so that a separation state can be maintained between the CO₂ absorbed rich liquid and the unreacted absorber-lean liquid, which is helpful for the subsequent separation operation. Moreover, a larger viscosity allows the absorbent to flow more slowly during the reaction process, thereby prolonging the contact time between the CO₂ and the absorbent and potentially improving the efficiency of CO₂ absorption.

Considering the one-time investment, operation cost, energy consumption, waste disposal, and other factors, the chemical absorption method can effectively bring out the advantages of comprehensive utilization of waste heat in iron and steel enterprises. It can make good use of low-temperature thermal mass, minimize investment, and improve profitability. Compared with the traditional absorption method, the phase change absorption method can reduce the regeneration energy consumption of the system, which is considered a CO₂ capture technology with great development potential. However, problems such as high enrichment ratio, high solution viscosity, and high volatility still exist. Currently, research in this field focuses on screening better absorbers by changing the composition, but systematic studies on the kinetics of phase separation time after absorption and how to reduce volatility and viscosity are still lacking and need to be carried out in depth to ensure the maximization of benefits and further industrialization and promotion.

5. Conclusions

In this work, based on 30%wt MEA and 30%wt AEP, different absorbents were prepared to test the absorption effect of CO₂, and the regeneration performance of absorbents was tested using the thermal desorption method. The load test results calculated the load capacity of different absorbents. In this paper, the phase separation mechanism of different absorbent systems is also analyzed, and the changes in rich phase density and rich ratio of each phase transition absorbent after phase separation are studied. Finally, the phase change absorbent suitable for CO₂ absorption was selected based on the results. The main conclusions are as follows:

1. Different absorbents were mixed based on 30%wt MEA and 30%wt AEP. The phase separation mechanisms of the different absorbent systems were analyzed, and the changes in physical properties, such as rich phase density and rich phase ratio of each phase change absorbent after phase separation were investigated. It was found that, with the increase in additive content, different types of absorbents showed the law that the volume of the rich phase gradually decreased, the ratio of the rich phase gradually decreased, and the density of the rich phase gradually increased.

2. The CO₂ phase change absorption effect was experimentally tested. The results showed that the MEA phase change absorbent had the best absorption effect when the mass ratio of additive to water was 5:5. In contrast, the AEP system had the best absorption effect at 7:3. The absorption effects of different phase separators were as follows: n-propanol > sulfolane > iso-propanol, and AEP/n-propanol/H₂O (7:3) had a maximum absorption load of 2.03 molCO₂·mol^{−1}amine. The AEP/n-propanol absorbent at 7:3 had excellent absorption load and a relatively low rich phase volume ratio of 0.46.
3. The loading capacities of different absorbents were calculated based on the results of the loading tests. It was concluded that the rich phase loading capacity of the MEA system is greater than that of the AEP system, and the maximum loading capacity of the MEA/n-propanol/H₂O (5:5) system was 4.02 mol/L.
4. The regeneration performance of the absorbent was tested by the thermal desorption method, and the results showed that the desorption load of the n-propanol aqueous-rich phase in the absorbent was higher, and the desorption rate was fastest at the temperature of 393.15 K. Compared with the MEA system absorbent, the AEP system absorbent had a higher desorption load but a slower desorption rate.

Author Contributions: Conceptualization, Y.W. and F.C.; methodology, Y.L., X.Y. and Z.L.; software, F.C.; validation, Y.W.; formal analysis, J.L. and H.W.; investigation, J.L.; resources, Z.L. and X.Y.; data curation, J.L. and H.W.; writing—original draft preparation, F.C.; writing—review and editing, Y.W.; visualization, Y.W. and F.C.; supervision, Z.L. and X.Y.; project administration, Y.L., Z.L. and X.Y.; funding acquisition, X.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key R&D Program of China, grant number 2022YFC3005803, and Xizang Autonomous Region Science and Technology Plan, grant number XZ202401YD0004.

Data Availability Statement: The original contributions presented in this study are included in the article; further inquiries can be directed to the corresponding authors.

Conflicts of Interest: Author Fanghui Cheng was employed by the Shaanxi Blower (Group) Co., Ltd. Author Jingsong Li was employed by the Research Institute of Technology of Shougang Group. Author Haihong Wang was employed by the company R&D Center Department, Beijing District Heating Group. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Mon, M.T.; Tansuchat, R.; Yamaka, W. CCUS Technology and Carbon Emissions: Evidence from the United States. *Energies* **2024**, *17*, 1748. [\[CrossRef\]](#)
2. Gupta, N.; Tanwar, R.; Dipesh; Kaushik, A.; Singh, R.; Patra, A.; Sar, P.; Khakharia, P. Perspectives on CCUS deployment on large scale in India: Insights for low carbon pathways. *Carbon Capture Sci. Technol.* **2024**, *12*, 100195. [\[CrossRef\]](#)
3. Zhang, Y.J.; Gao, F.; Wang, Z.H. Updated resource depletion characterization factors for life cycle assessment-case studies on iron and steel production in China. *Mater. Sci. Forum* **2016**, *847*, 358–365. [\[CrossRef\]](#)
4. Jin, P.; Jiang, Z.; Bao, C.; Lu, Y.; Zhang, J.; Zhang, X. Mathematical Modeling of the Energy Consumption and Carbon Emission for the Oxygen Blast Furnace with Top Gas Recycling. *Steel Res. Int.* **2016**, *87*, 320–329. [\[CrossRef\]](#)
5. Yang, N.; Yu, H.; Li, L.; Xu, D.; Han, W.; Feron, P. Aqueous ammonia (NH₃) based post combustion CO₂ capture: A review. *Oil Gas Sci. Technol.—Rev. IFP Energ. Nouv.* **2014**, *69*, 931–945. [\[CrossRef\]](#)
6. Aronu, U.E.; Hessen, E.T.; Haug-Warberg, T.; Hoff, K.A.; Svendsen, H.F. Vapor–liquid equilibrium in amino acid salt system: Experiments and modeling. *Chem. Eng. Sci.* **2011**, *66*, 2191–2198. [\[CrossRef\]](#)
7. Ayithey, F.K.; Saptorio, A.; Kumar, P.; Wong, M.K. Parametric study and optimisation of hot K₂CO₃-based post-combustion CO₂ capture from a coal-fired power plant. *Greenh. Gases Sci. Technol.* **2022**, *10*, 631–642. [\[CrossRef\]](#)
8. Luo, H.; Chioyama, H.; Thürmer, S.; Ohba, T.; Kanoh, H. Kinetics and structural changes in CO₂ capture of K₂CO₃ under a moist condition. *Energy Fuels* **2015**, *29*, 4472–4478. [\[CrossRef\]](#)

9. Luo, Q.; Cao, Y.; Liu, Z.; Feng, B.; Zhou, Q.; Li, N. A feasible process for removal and utilization of CO₂ in thermal power plants by MDEA+ DMSO scrubbing and Cu/TiO₂ photocatalytic reduction. *Appl. Therm. Eng.* **2019**, *153*, 369–378. [\[CrossRef\]](#)
10. Sun, Q.; Liu, Y.; Liu, A.; Guo, X.; Yang, L. Separation of CO₂ from Flue Gas via Absorption of Alcohol Amines. *Univers. J. Chem.* **2016**, *4*, 25–30. [\[CrossRef\]](#)
11. Lv, B.; Guo, B.; Zhou, Z.; Jing, G. Mechanisms of CO₂ capture into monoethanolamine solution with different CO₂ loading during the absorption/desorption processes. *Environ. Sci. Technol.* **2015**, *49*, 10728–10735. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Donaldson, T.L.; Nguyen, Y.N. Carbon dioxide reaction kinetics and transport in aqueous amine membranes. *Ind. Eng. Chem. Fundam.* **1980**, *19*, 260–266. [\[CrossRef\]](#)
13. Yu, H.; Qi, G.; Xiang, Q.; Wang, S.; Fang, M.; Yang, Q.; Wardhaugh, L.; Feron, P. Aqueous ammonia based post combustion capture: Results from pilot plant operation, challenges and further opportunities. *Energy Procedia* **2013**, *37*, 6256–6264. [\[CrossRef\]](#)
14. Zhang, Z.; Li, Y.; Zhang, W.; Wang, J.; Soltanian, M.R.; Olabi, A.G. Effectiveness of amino acid salt solutions in capturing CO₂: A review. *Renew. Sustain. Energy Rev.* **2018**, *98*, 179–188. [\[CrossRef\]](#)
15. Han, K.; Ahn, C.K.; Lee, M.S. Performance of an ammonia-based CO₂ capture pilot facility in iron and steel industry. *Int. J. Greenh. Gas Control* **2014**, *27*, 239–246. [\[CrossRef\]](#)
16. Mao, Y.L.; Qu, Y.L.; Li, B.; Jing, X.; Zhu, J.B. Development and application potential analysis of carbon dioxide capture technology from flue gas in steel works. *IronSteel* **2016**, *51*, 6–10. [\[CrossRef\]](#)
17. Gao, W.; Liang, S.; Wang, R.; Jiang, Q.; Zhang, Y.; Zheng, Q.; Xie, B.; Toe, C.Y.; Zhu, X.; Wang, J.; et al. Industrial carbon dioxide capture and utilization: State of the art and future challenges. *Chem. Soc. Rev.* **2020**, *49*, 8584–8686. [\[CrossRef\]](#)
18. Feron, P.H.M.; Jansen, A.E. Capture of carbon dioxide using membrane gas absorption and reuse in the horticultural industry. *Energy Convers. Manag.* **1995**, *36*, 411–414. [\[CrossRef\]](#)
19. Gautam, A.; Monday, M.K. Review of recent trends and various techniques for CO₂ capture: Special emphasis on biphasic amine solutions. *Fuel* **2023**, *334*, 126616. [\[CrossRef\]](#)
20. Liu, F.; Qi, Z.; Fang, M.; Ding, H. Pilot test of water lean solvent of 2- (ethylamine) ethanol, 1-methyl-2-pyrrolidinone, and water for post combustion CO₂ capture. *Chem. Eng. J.* **2023**, *459*, 141634. [\[CrossRef\]](#)
21. Idem, R.; Wilson, M.; Tontiwachwuthikul, P.; Chakma, A.; Veawab, A.; Aroonwilas, A.; Gelowitz, D. Pilot plant studies of the CO₂ capture performance of aqueous MEA and mixed MEA/MDEA solvents at the University of Regina CO₂ capture technology development plant and the boundary dam CO₂ capture demonstration plant. *Ind. Eng. Chem. Res.* **2006**, *45*, 2414–2420. [\[CrossRef\]](#)
22. Khan, A.A.; Halder, G.N.; Saha, A. Experimental investigation on efficient carbon dioxide capture using piperazine (PZ) activated aqueous methyldiethanolamine (MDEA) solution in a packed column. *Int. J. Greenh. Gas Control* **2017**, *64*, 163–173. [\[CrossRef\]](#)
23. Gautam, A.; Monoj, K.M. Novel aqueous amine blend of 2-(Butylamino) ethanol and 2-Dimethylaminoethanol for CO₂ capture: Equilibrium CO₂ loading, RSM optimization, desorption study, characterization and toxicity assessment. *Sep. Purif. Technol.* **2023**, *322*, 124279. [\[CrossRef\]](#)
24. Archane, A.; Gicquel, L.; Provost, E.; Fürst, W. Effect of methanol addition on water–CO₂–diethanolamine system: Influence on CO₂ solubility and on liquid phase speciation. *Chem. Eng. Res. Des.* **2008**, *86*, 592–599. [\[CrossRef\]](#)
25. Ye, Q.; Wang, X.; Lu, Y. Screening and evaluation of novel biphasic solvents for energy-efficient post-combustion CO₂ capture. *Int. J. Greenh. Gas Control* **2015**, *39*, 205–214. [\[CrossRef\]](#)
26. Hu, Y.; Wang, Q.; Hu, D.; Zhang, Y.; Furqan, M.; Lu, S. Experimental study on CO₂ capture by MEA/n-butanol/H₂O phase change adsorbent. *RSC Adv.* **2024**, *14*, 3146–3157. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Wang, L.; An, S.; Yu, S.; Zhang, S.; Zhang, Y.; Li, M.; Li, Q. Mass transfer characteristics of CO₂ absorption into a phase-change solvent in a wetted-wall column. *Int. J. Greenh. Gas Control* **2017**, *64*, 276–283. [\[CrossRef\]](#)
28. Liu, F.; Fang, M.; Dong, W.; Wang, T.; Xia, Z.; Wang, Q.; Luo, Z. Carbon dioxide absorption in aqueous alkanolamine blends for biphasic solvents screening and evaluation. *Appl. Energy* **2019**, *233*, 468–477. [\[CrossRef\]](#)
29. Li, Q.; Huang, X.; Li, N.; Qi, T.; Wang, R.; Wang, L.; An, S. Energy-efficient biphasic solvents for industrial CO₂ capture: Absorption mechanism and stability characteristics. *Energy* **2024**, *293*, 130710. [\[CrossRef\]](#)
30. Wang, L.; Liu, S.; Wang, R.; Li, Q.; Zhang, S. Regulating phase separation behavior of a DEEA–TETA biphasic solvent using sulfolane for energy-saving CO₂ capture. *Environ. Sci. Technol.* **2019**, *53*, 12873–12881. [\[CrossRef\]](#)
31. Luo, W.; Guo, D.; Zheng, J.; Gao, S.; Chen, J. CO₂ absorption using biphasic solvent: Blends of diethylenetriamine, sulfolane, and water. *Int. J. Greenh. Gas Control* **2016**, *53*, 141–148. [\[CrossRef\]](#)
32. Wang, R.; Jiang, L.; Li, Q.; Gao, G.; Zhang, S.; Wang, L. Energy-saving CO₂ capture using sulfolane-regulated biphasic solvent. *Energy* **2020**, *211*, 118667. [\[CrossRef\]](#)
33. Wang, L.; Yu, S.; Li, Q.; Zhang, Y.; An, S.; Zhang, S. Performance of sulfolane/DETA hybrids for CO₂ absorption: Phase splitting behavior, kinetics and thermodynamics. *Appl. Energy* **2018**, *228*, 568–576. [\[CrossRef\]](#)
34. Wang, R.; Yang, Y.; Wang, M.; Lin, J.; Zhang, S.; An, S.; Wang, L. Energy efficient diethylenetriamine–1-propanol biphasic solvent for CO₂ capture: Experimental and theoretical study. *Appl. Energy* **2021**, *290*, 116768. [\[CrossRef\]](#)

35. Wang, N.; Peng, Z.; Gao, H.; Sema, T.; Shi, J.; Liang, Z. New insight and evaluation of secondary Amine/N-butanol biphasic solutions for CO₂ Capture: Equilibrium Solubility, phase separation Behavior, absorption Rate, desorption Rate, energy consumption and ion species. *Chem. Eng. J.* **2022**, *431*, 133912. [[CrossRef](#)]
36. Zhang, W.; Jin, X.; Tu, W.; Ma, Q.; Mao, M.; Cui, C. Development of MEA-based CO₂ phase change absorbent. *Appl. Energy* **2017**, *195*, 316–323. [[CrossRef](#)]
37. Shen, L.; Liu, F.; Shen, Y.; Sun, C.; Zhang, Y.; Wang, Q.; Li, S.; Li, W. Novel biphasic solvent of AEP/1-propanol/H₂O for CO₂ capture with efficient regeneration performance and low energy consumption. *Sep. Purif. Technol.* **2021**, *270*, 118700. [[CrossRef](#)]
38. Wang, L.; Zhang, Y.; Wang, R.; Li, Q.; Zhang, S.; Li, M.; Liu, J.; Chen, B. Advanced monoethanolamine absorption using sulfolane as a phase splitter for CO₂ capture. *Environ. Sci. Technol.* **2018**, *52*, 14556–14563. [[CrossRef](#)]
39. Wang, R.; Liu, S.; Wang, L.; Li, Q.; Zhang, S.; Chen, B.; Jiang, L.; Zhang, Y. Superior energy-saving splitter in monoethanolamine-based biphasic solvents for CO₂ capture from coal-fired flue gas. *Appl. Energy* **2019**, *242*, 302–310. [[CrossRef](#)]
40. Wang, R.; Zhao, H.; Qi, C.; Yang, X.; Zhang, S.; Li, M.; Wang, L. Novel tertiary amine-based biphasic solvent for energy-efficient CO₂ capture with low corrosivity. *Energy* **2022**, *260*, 125045. [[CrossRef](#)]
41. Xiao, L.; Qiu, Z.; Feng, S.; Duan, X.; Zhao, Z.; Liu, Y.; Ma, L. Carbon dioxide absorption and desorption experiments based on MDEA. *Chem. Eng. Process.-Process Intensif.* **2024**, *204*, 109931. [[CrossRef](#)]
42. Danckwerts, P.V. The reaction of CO₂ with ethanolamines. *Chem. Eng. Sci.* **1979**, *34*, 443–446. [[CrossRef](#)]
43. Energy. New Findings from Beijing University of Chemical Technology Update Understanding of Energy (Development of MEA based CO₂ phase change adsorbent). *Energy Wkly. News* **2017**, 366.
44. Malinowski, J.J.; Daugulis, A.J. Salt effects in extraction of ethanol, 1-butanol and acetone from aqueous solutions. *AIChE J.* **1994**, *40*, 1459–1465. [[CrossRef](#)]
45. Marcilla, A.; Ruiz, F.; García, A.N. Liquid-liquid-solid equilibria of the quaternary system water-ethanol-acetone-sodium chloride at 25 °C. *Fluid Phase Equilibria* **1995**, *112*, 273–289. [[CrossRef](#)]
46. Liu, F.; Fang, M.; Yi, N.; Wang, T. Research on Alkanolamine-Based Physical–Chemical Solutions As Biphasic Solvents for CO₂ Capture. *Energy Fuels* **2019**, *33*, 11389–11398. [[CrossRef](#)]
47. Zhang, W.; Jin, X.; Tu, W.; Ma, Q.; Mao, M.; Cui, C. A novel CO₂ phase change absorbent: MEA/1-propanol/H₂O. *Energy Fuels* **2017**, *31*, 4273–4279. [[CrossRef](#)]
48. Wanderley, R.R.; Pinto, D.D.D.; Knuutila, H.K. Investigating opportunities for water-lean solvents in CO₂ capture: VLE and heat of absorption in water-lean solvents containing MEA. *Sep. Purif. Technol.* **2020**, *231*, 115883. [[CrossRef](#)]
49. Liu, S.; Ling, H.; Lv, J.; Gao, H.; Na, Y.; Liang, Z. New insights and assessment of primary alkanolamine/sulfolane biphasic solutions for post-combustion CO₂ capture: Absorption, desorption, phase separation, and technological process. *Ind. Eng. Chem. Res.* **2019**, *58*, 20461–20471. [[CrossRef](#)]
50. Xu, Z.; Wang, S.; Chen, C. Solubility of N₂O in and Density and Viscosity of Aqueous Solutions of 1, 4-Butanediamine, 2-(Diethylamino)-ethanol, and Their Mixtures from (298.15 to 333.15) K. *J. Chem. Eng. Data* **2013**, *58*, 1633–1640. [[CrossRef](#)]
51. Li, L.; Voice, A.K.; Li, H.; Namjoshi, O.; Nguyen, T.; Du, Y.; Rochelle, G.T. Amine blends using concentrated piperazine. *Energy Procedia* **2013**, *37*, 353–369. [[CrossRef](#)]

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