



# Performance of a new water lean absorbent composed of EHA and DEGDEE in CO<sub>2</sub> capture and regeneration

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## ABSTRACT

Previous work has shown that non-aqueous absorbent composed of dimethyl sulfoxide (DMSO) and 2-ethylhexylamine (EHA) is superior to commercial monoethanolamine (MEA) in both absorption of CO<sub>2</sub> and desorption. However, the price of DMSO is too high, which leads to the high cost of reagents. It is worthwhile to choose a cheap solvent instead of DMSO, which can also achieve satisfactory absorption and desorption performance. Around this goal, we selected diethylene glycol diethyl ether (DEGDEE) to form a non-aqueous absorbent with EHA and investigated the absorption and desorption performance. The desorption efficiency of 70 wt% EHA +30 wt% DEGDEE was 99 % at 373 K. The desorption efficiency was 89.4 %, and the desorption energy consumption was only 45.1 % of MEA when the water content was 10 wt%. DEGDEE can achieve similar or even better performance than DMSO, while the cost of DEGDEE (12000–31000 RMB/ton, technical grade purity 99 %) is lower than DMSO (40000–48000 RMB/ton, technical grade purity 99 %). In addition, it also has a good recycling capacity. These advantages will certainly endow this newly developed absorbent with great application prospects in the field of CO<sub>2</sub> capture.

## 1. Introduction

One of the main causes of the phenomenon of global warming is the increasing concentration of CO<sub>2</sub> in the air [1]. Although renewable energy sources such as wind power and solar energy technology have become increasingly mature, global energy demand will still need to be met by fossil fuels [2]. It can be expected that in the foreseeable future, CO<sub>2</sub> emissions will continue to show a significant increase because of the massive use of fossil fuels. For this reason, the development of CO<sub>2</sub> capture technology has attracted strong attention. Among the many CO<sub>2</sub> capture technologies, post-combustion capture is an ideal choice because it is relatively mature, does not affect the normal operation of the existing equipment, and does not need to make obvious changes [3–7]. From the point of view of industrial practicality, chemical absorption has a higher CO<sub>2</sub> absorption rate and larger absorption amount, it is one of the most important CO<sub>2</sub> capture technologies for commercial application. Among the chemical absorption processes, Monoethanolamine (MEA) aqueous solution is the most typical representative, which has been put into commercial application in the process of natural gas

desulfurization and decarbonization and flue gas decarbonization in coal-fired power plants [8–10], but it has the disadvantages of easy evaporation and high regenerative energy consumption, restricting its further promotion and application. Especially in the field of coal-fired power plants of CO<sub>2</sub> capture, the current voice is to reduce energy consumption to less than 2.2 GJ/ton CO<sub>2</sub> as soon as possible. Obviously, the traditional MEA absorption does not have this potential.

To reduce energy consumption, various process improvements have been made, such as absorbent intercooling, flash stripper [11,12]. A large number of researchers have also developed new absorbents with lower energy consumption, such as mixed amine aqueous solutions [13–24], ionic liquid-based absorbents [25,26], water lean absorbents [27–31], non-aqueous absorbents [32–54], thus making CO<sub>2</sub> capture more technically and economically feasible. The energy consumption of non-aqueous absorption is particularly low, but because in the flue gas, the moisture can be dissolved in the absorbent if it can be used in industry, it is actually water lean absorption [55]. Even for water lean absorption, the regeneration energy consumption is much lower than that of commercial MEA absorption, so it has a very good prospect. The

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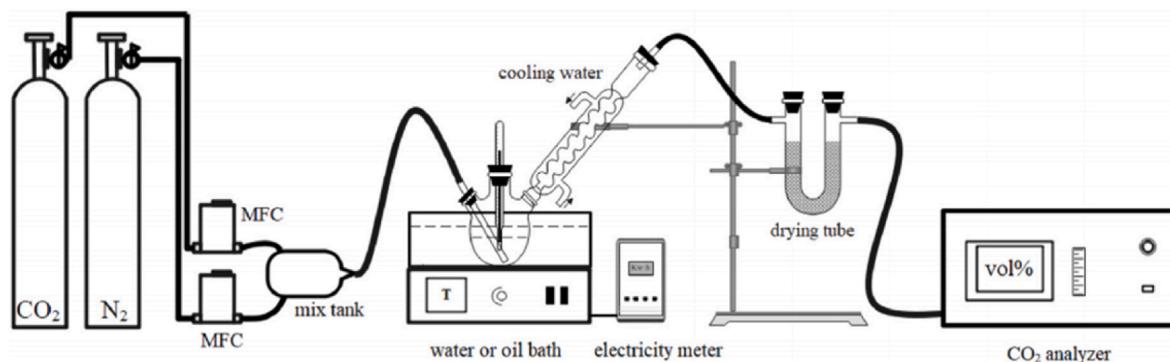
**Table 1**  
Description of relevant chemicals.

Chemicals	CAS No.	Purity <sup>a</sup>	Structure of chemicals	Source
Ethanolamine	141-43-5	≥99 %	<chem>NCCCO</chem>	Aladdin Reagent
2-ethylhexan-1-amine	104-75-6	≥99 %	<chem>NCC(C)CCCCC</chem>	Macklin Reagent
Diethylene glycol diethyl ether	112-36-7	> 98 %	<chem>CCOC(=O)COCCOC(=O)OC</chem>	Macklin Reagent
Water	7732-18-5	–	–	Laboratory

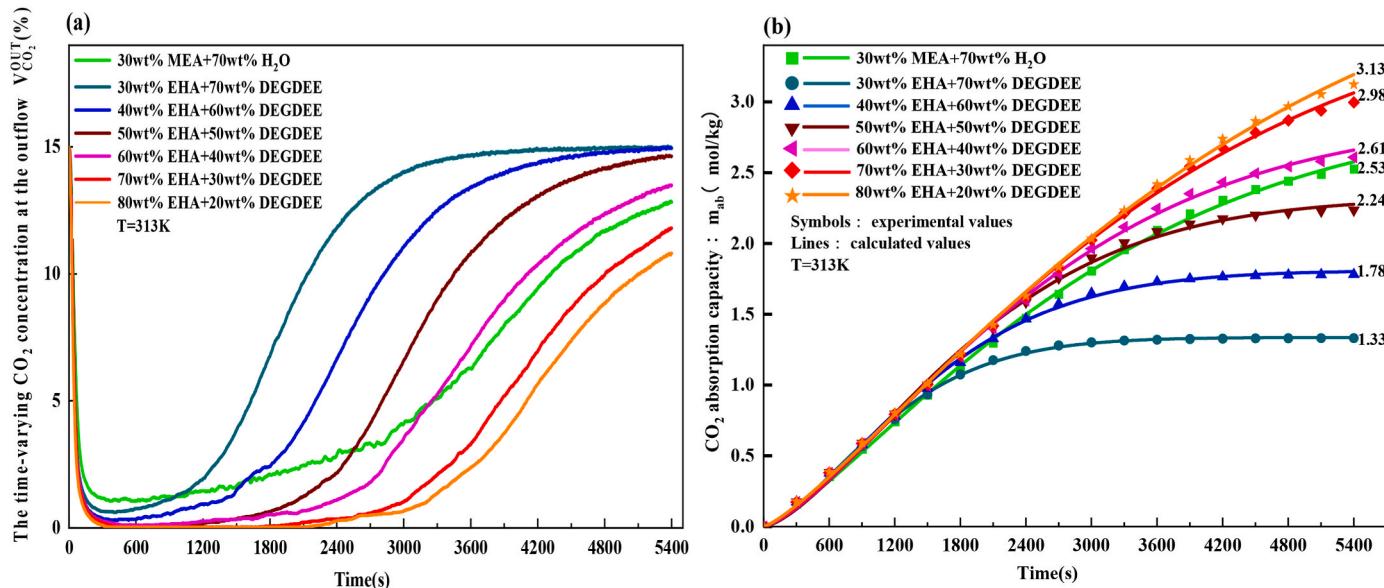
<sup>a</sup> The purity is sourced from the supplier.

main idea of non-aqueous or water lean absorption is to use organic solvents to replace or partially replace water, because organic solvents have a smaller heat capacity than water, and the boiling point is higher than water, the energy consumption of the regeneration process can be significantly reduced. In particular, we reported the work of CO<sub>2</sub> capture with water lean absorbents in our previous work [44,54], in which the amine is EHA. As for organic solvents, we tried diglyme and dimethyl sulfoxide (DMSO), respectively. Although the absorption/desorption efficiency and energy consumption are satisfactory, we still feel that further reducing the cost of absorbent is an important issue to be solved

urgently when facing industrial applications. To this end, we compared a series of organic solvents, including key physical and chemical properties and the cost per ton of solvent. By comparison, we find that diethylene glycol diethyl ether (DEGDEE) is cheap and there are many manufacturers. It has the characteristics of a relatively high boiling point (101.3 kPa, 462.15K [56]) and a relatively low heat capacity (298K, 2.14J/(g, K) [57]). A high boiling point means that, at the same temperature, a small latent heat of vaporization during regeneration, and a small heat capacity means a small sensible heat of temperature rise during regeneration, both of which are very helpful in reducing energy consumption. In addition to the above advantages, it has a lower viscosity (1.238 mPa s at 298.15K) [58]. In the absorption process, low viscosity is good for CO<sub>2</sub> from the gas phase diffusion to the liquid phase. Moreover, the application of DEGDEE is very wide, for compression ignition engines, it may be considered a very promising fuel additive [59], it is a kind of solvent electrolyte used in lithium-air battery electrolytes [60], and it is also suitable for emissive applications such as in coatings, inks, adhesives, and cleaning compounds [61], therefore, its access is relatively stable and guaranteed. It is for this reason that DEGDEE appears frequently in recent research work on CO<sub>2</sub> capture [27, 32,62–68]. Machida et al. [27] developed a novel phase-change absorbent composed of 2-(butylamino)ethanol (BAE), DEGDEE, and water. The absorbent was homogeneous before CO<sub>2</sub> absorption and transformed into two liquid phases, a CO<sub>2</sub>-rich phase and a CO<sub>2</sub>-lean phase, after CO<sub>2</sub> absorption. Combined with a heat pump process, this system



**Fig. 1.** The schematic diagram of the device for CO<sub>2</sub> absorption and desorption [44].



**Fig. 2.** (a) The time-varying CO<sub>2</sub> concentration at the outflow; (b) The CO<sub>2</sub> absorption amount.

**Table 2**A series of parameters after fitting the Avrami model.<sup>a,b</sup>.

absorbents	parameters				
	$m_{s,exp}$	$m_{s,cal}$	$k \times 10^3$	n	$R^2$
30 wt% MEA +70 wt% H <sub>2</sub> O	2.53	2.97	0.32	1.31	0.999
30 wt% EHA +70 wt% DEGDEE	1.33	1.34	0.76	1.51	0.999
40 wt% EHA +60 wt% DEGDEE	1.78	1.81	0.58	1.48	0.999
50 wt% EHA +50 wt% DEGDEE	2.24	2.33	0.46	1.47	0.998
60 wt% EHA +40 wt% DEGDEE	2.61	2.89	0.36	1.38	0.999
70 wt% EHA +30 wt% DEGDEE	2.98	3.79	0.29	1.30	0.999
80 wt% EHA +20 wt% DEGDEE	3.13	4.31	0.24	1.26	0.999

<sup>a</sup>  $m_{s,exp}$  (mol/kg) is the CO<sub>2</sub> absorption amount from absorption at 5400s,  $m_{s,cal}$  (CO<sub>2</sub>/kg) is the calculated amount of saturated CO<sub>2</sub> absorption, k(s<sup>-1</sup>) is absorption rate constants of the Avrami kinetic model, n is the exponent of Avrami model.

<sup>b</sup> Temperature is 313K; Pressure is 101 kPa.

**Table 3**The viscosity of the solution after 5400s absorption<sup>a</sup>.

Sorbents	$\eta$ (mPa·s)
30 wt% EHA+70 wt% DEGDEE	3.1
40 wt% EHA+60 wt% DEGDEE	4.5
50 wt% EHA+50w t% DEGDEE	6.7
60 wt% EHA+40w t% DEGDEE	11.7
70 wt% EHA+30w t% DEGDEE	24.7
80 wt% EHA+20w t% DEGDEE	47.1

<sup>a</sup> Temperature is 313K; Pressure is 101 kPa.

could reduce the capture energy consumption to 1.6 GJ/ton CO<sub>2</sub>, significantly lower than the 4 GJ/ton CO<sub>2</sub> of MEA. Barzaghi et al. [32] developed the 2-(ethylamino)ethanol (EAE)-DEGDEE phase-change CO<sub>2</sub> absorbent, which exhibited a high absorption efficiency of up to 97.6 % and advantages such as lower regeneration energy consumption compared to aqueous MEA solutions. Despite these advantages, phase-change absorption processes have some drawbacks, such as the need for additional process steps and equipment to separate the two-phase solution formed after CO<sub>2</sub> absorption [34,40,45,47,51]. Compared to phase-change absorption processes, homogeneous non aqueous absorption processes do not require additional separation equipment, preserving the relatively simple operational procedures of traditional organic amine processes.

Based on our previous work experience [44,54,69], we propose to select the primary amine 2-ethylhexylamine (EHA) and DEGDEE to form a novel homogeneous non aqueous absorbent. On the one hand, among the primary amine series, EHA has the advantage of a high CO<sub>2</sub> absorption rate, and the steric hindrance effect around the amino group in the EHA molecule is conducive to reducing the stability of the absorption products, thereby lowering the desorption temperature. On the other hand, compared with traditional alkanolamines, EHA does not contain hydroxyl groups, which is beneficial for maintaining a relatively low viscosity of the system after CO<sub>2</sub> absorption. Furthermore, DEGDEE possesses advantages such as a high boiling point, low viscosity, and small heat capacity. Therefore, the objective of this study is to develop a novel non aqueous absorbent for CO<sub>2</sub> capture from coal-fired power plant flue gas based on EHA and DEGDEE. The CO<sub>2</sub> absorption/desorption performance, water resistance, and cyclic stability of the absorbent will be systematically investigated. Simultaneously, the regeneration energy consumption will be evaluated, aiming to obtain a new CO<sub>2</sub> capture system with superior performance and lower cost.

## 2. Materials and methods

### 2.1. Materials

The chemicals are detailed in Table 1.

### 2.2. Absorption and desorption experiments

The schematic diagram of the device for absorption and desorption of CO<sub>2</sub> is shown in Fig. 1. The absorption and desorption experiments were executed in a three-necked flask, and detailed experimental procedures were shown in the literature [44]. In the absorption experiment, the gas was composed of 30 ml/min CO<sub>2</sub> + 170 ml/min N<sub>2</sub> and the temperature was 313 K. During the desorption process, the desorption temperatures were set to 363 K, 368 K, and 373 K, and the desorption time was 3600 s and 5400 s, respectively. Similar to the literature reports [20–23,28,34,70,71] and our previous work [44,54], in order to speed up the desorption process, 200 ml/min N<sub>2</sub> was used.

The absorption rate  $R_{ab}$ (mol/kg·s) can be calculated from equation (1):

$$R_{ab} = \frac{[Q_{CO_2}^{in} - Q_{N_2}^{in}x_{CO_2}^{out}] / (1 - x_{CO_2}^{out})}{M \times 22.4 \times 1000} \left( \frac{T_s P_e}{T_e P_s} \right) \quad (1)$$

in which  $Q_{CO_2}^{int}$  and  $Q_{N_2}^{int}$  are the volume flow of CO<sub>2</sub> and N<sub>2</sub> at the entrance (ml/s),  $x_{CO_2}^{out}$  is the concentration of CO<sub>2</sub> detected by the analyzer,  $T_s$  is the standard temperature(K),  $T_e$  is the experimental temperature (K),  $P_s$  is the standard pressure(kPa),  $P_e$  is the experimental pressure (kPa).

The CO<sub>2</sub> absorption capacity ( $m_{m,ab}$ , mol/kg) can be calculated from equation (2):

$$m_{m,ab} = \sum_0^t R_{ab} \quad (2)$$

The desorption rate  $R_{de}$  (mol/kg·s) is defined by equation (3):

$$R_{de} = \frac{[Q_{N_2}^{in}x_{CO_2}^{out}] / (1 - x_{CO_2}^{out})}{M \times 22.4 \times 1000} \left( \frac{T_s P_e}{T_e P_s} \right) \quad (3)$$

The CO<sub>2</sub> desorption amount ( $m_{m,de}$ , mol/kg) can be calculated from equation (4):

$$m_{m,de} = \sum_0^t R_{de} \quad (4)$$

The desorption efficiency ( $\eta$ , %) is defined by equation (5):

$$\eta = \frac{m_{m,de}}{m_{m,ab}} \times 100\% \quad (5)$$

### 2.3. Fit the amount of absorption/desorption over time

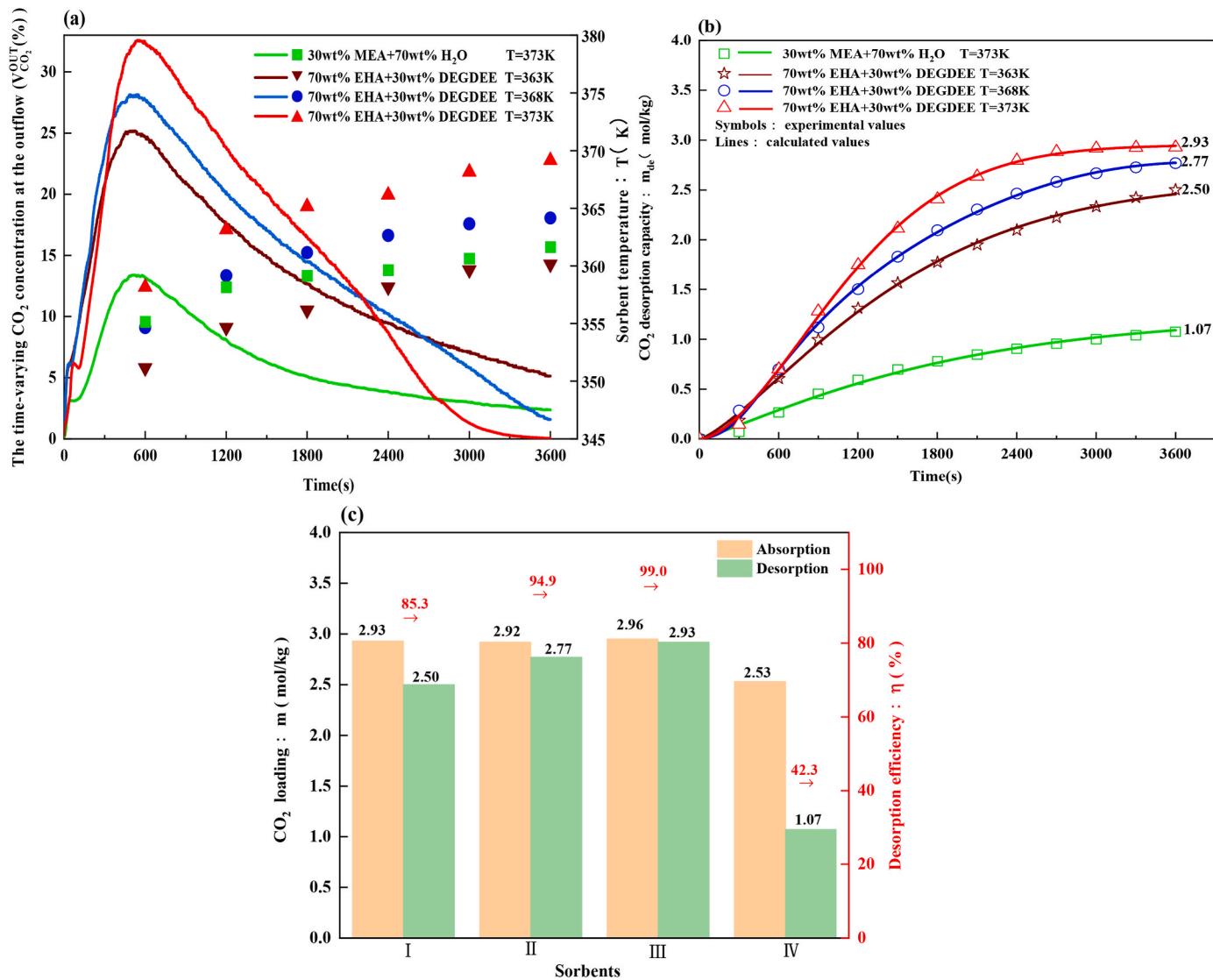
The modified Avrami model [72] can predict the absorbent rate and saturation absorbent amount, which can be calculated from equation (6):

$$m_{t,exp} = m_{m,cal}[1 - \exp(-kt)^n] \quad (6)$$

in which  $m_{t,exp}$  is the experimental absorption amount at a specific time,  $m_{m,cal}$  is calculated as the amount of CO<sub>2</sub> saturation absorbed, k is the rate constant of the Avrami model (s<sup>-1</sup>), n is the index of the Avrami model.

### 2.4. Viscosity

A digital rotary viscometer (NDJ-5s, Changji, China) was used to measure the viscosities ( $\eta$ , mPa·s) of both CO<sub>2</sub>-unloaded and CO<sub>2</sub>-loaded absorbents at 313K.



**Fig. 3.** (a) The time-varying  $\text{CO}_2$  concentration at the outflow; (b) The  $\text{CO}_2$  desorption capacity; (c) The desorption performance of sorbents (absorption at 313K for 5400s; desorption time is 3600s, I: 70 wt% EHA + 30 wt% DEGDEE at 363 K, II: 70 wt% EHA + 30 wt% DEGDEE at 368 K, III: 70 wt% EHA + 30 wt% DEGDEE, at 373 K, IV: 30 wt% MEA+70 wt%  $\text{H}_2\text{O}$ , at 373 K).

**Table 4**

The desorption parameters fitted to the Avrami kinetic model.<sup>a</sup>

Sorbents	$T$ (K)	$m_{\text{exp}}$	$\eta(\%)$	$k \times 10^3$	$n$	Ref
70 wt% EHA + 30 wt% DEGDEE <sup>b</sup>	363	2.50	85.3	0.62	1.33	This work
	368	2.77	94.9	0.68	1.41	This work
	373	2.93	99.0	0.77	1.70	This work
70 wt% EHA + 30 wt% diglyme <sup>b</sup>	373	2.88	99.0	0.77	1.69	[44]
60 wt% EHA + 40 wt% DMSO <sup>c</sup>	373	2.99	97.1	0.72	1.43	[54]
30 wt% MEA + 70 wt% $\text{H}_2\text{O}$ <sup>b</sup>	373	1.07	42.3	0.67	1.35	This work

<sup>a</sup>  $k(\text{s}^{-1})$  is the desorption rate constant, and  $n$  is the exponent.

<sup>b</sup> the desorption time is 3600 s.

<sup>c</sup> the desorption time is 5400 s.

## 2.5. Isobaric heat capacity

A differential scanning calorimeter (DSC, 200F3, NETZSCH, accuracy  $\pm 0.05\%$ ) was used to determine the isobaric heat capacity ( $C_p$ , J/(g, K)) of the adsorbent (absorbing 5400 s) during the temperature rise (first 3600 s) of the  $\text{CO}_2$  desorption process.

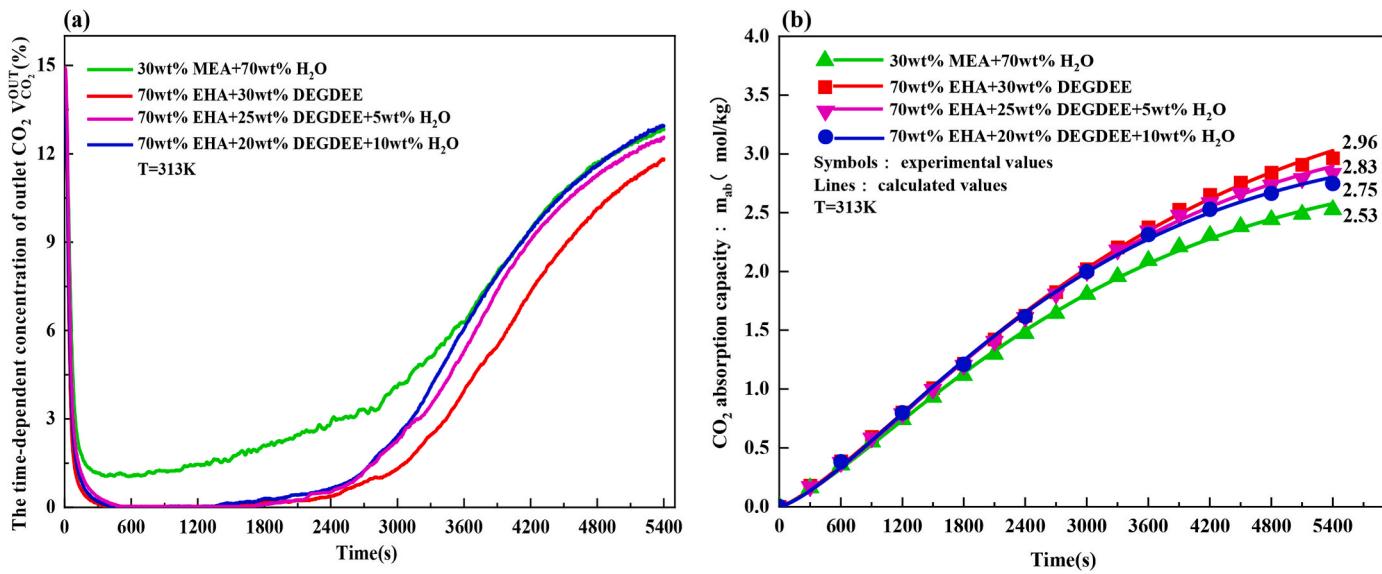
## 2.6. Energy consumption required for desorption of $\text{CO}_2$ (EC)

### 2.6.1. EC based on electricity consumption

Desorption of  $\text{CO}_2$  required EC (GJ/ton  $\text{CO}_2$ ) is defined by equation (7) [34]:

$$EC = E_c \times 3600 / M_{\text{de}} \quad (7)$$

wherein  $E_c(\text{kW}\cdot\text{h}) = E_{\text{total}} - E_{\text{blank}}$ ,  $E_{\text{total}}$  (kW·h) is the total electric energy consumption during  $\text{CO}_2$  desorption (kW·h) measured by the meter when the desorption experiment is carried out,  $E_{\text{blank}}$  (kW·h) is the electricity consumption required to maintain the oil bath temperature at 373 K was taken as the blank value, and  $M_{\text{de}}$  is the quality of  $\text{CO}_2$  desorption (g).



**Fig. 4.** (a) The time-varying  $\text{CO}_2$  concentration at the outflow; (b) The  $\text{CO}_2$  absorption capacity.

**Table 5**  
Viscosity values before and after absorption of  $\text{CO}_2$  by the absorbents.<sup>a</sup>

Absorbents	$\eta(\text{mPa}\cdot\text{s})$	
	$\text{CO}_2$ -free	$\text{CO}_2$ -rich
30 wt% MEA+70 wt% $\text{H}_2\text{O}$	1.7	2.5
70 wt% EHA+30 wt% DEGDEE	0.9	24.3
70 wt% EHA+25 wt% DEGDEE+5 wt% $\text{H}_2\text{O}$	1.3	28.9
70 wt% EHA+20 wt% DEGDEE+10 wt% $\text{H}_2\text{O}$	1.9	30.5

<sup>a</sup> Temperature is 313K; Pressure is 101 kPa.

### 2.6.2. EC based on $C_p$

The EC (GJ/ton  $\text{CO}_2$ ) based on  $C_p$  can be calculated from equation (8) [43]:

$$\text{EC} = C_{p-\text{av}} \times M \times \Delta T \times 1000 / M_{\text{de}} \quad (8)$$

wherein  $C_{p-\text{av}}$  (J/(g,K)) denotes the average isobaric heat capacity of the sorbent in different temperature-rise periods of the  $\text{CO}_2$  desorption process,  $M$  (30.00 g) is the mass of  $\text{CO}_2$ -free sorbent,  $\Delta T$  (K) denotes the temperature difference of the sorbent in different temperature-rise periods.

The relative energy consumption ( $EC_{\text{re}}$ , %) is defined by equation (9) [34]:

$$EC_{\text{re}} = \frac{EC_{\text{EHA}}}{EC_{\text{MEA}}} \times 100\% \quad (9)$$

Wherein the  $EC_{\text{EHA}}$  is the EHA + DEGDEE absorbents of the desorption  $\text{CO}_2$  energy consumption (GJ/ton  $\text{CO}_2$ );  $EC_{\text{MEA}}$  is the desorption energy consumption during  $\text{CO}_2$  desorption (GJ/ton  $\text{CO}_2$ ) of 30 wt% MEA aqueous solution.

### 2.7. Water content

The water content was measured using the Karl Fischer moisture meter (V30S, Mettler Toledo, Switzerland).

## 3. Results and discussion

### 3.1. Absorbent composition

The composition of the absorbents can affect the absorption rate,

absorption amount, and viscosity, referring to the previous work [44, 54]. In this regard, in this section, absorbents with a range of mass fractions were prepared and the absorption performance and viscosity were experimentally determined. On this basis, we try to determine a more appropriate mass fraction of EHA and DEGDEE.

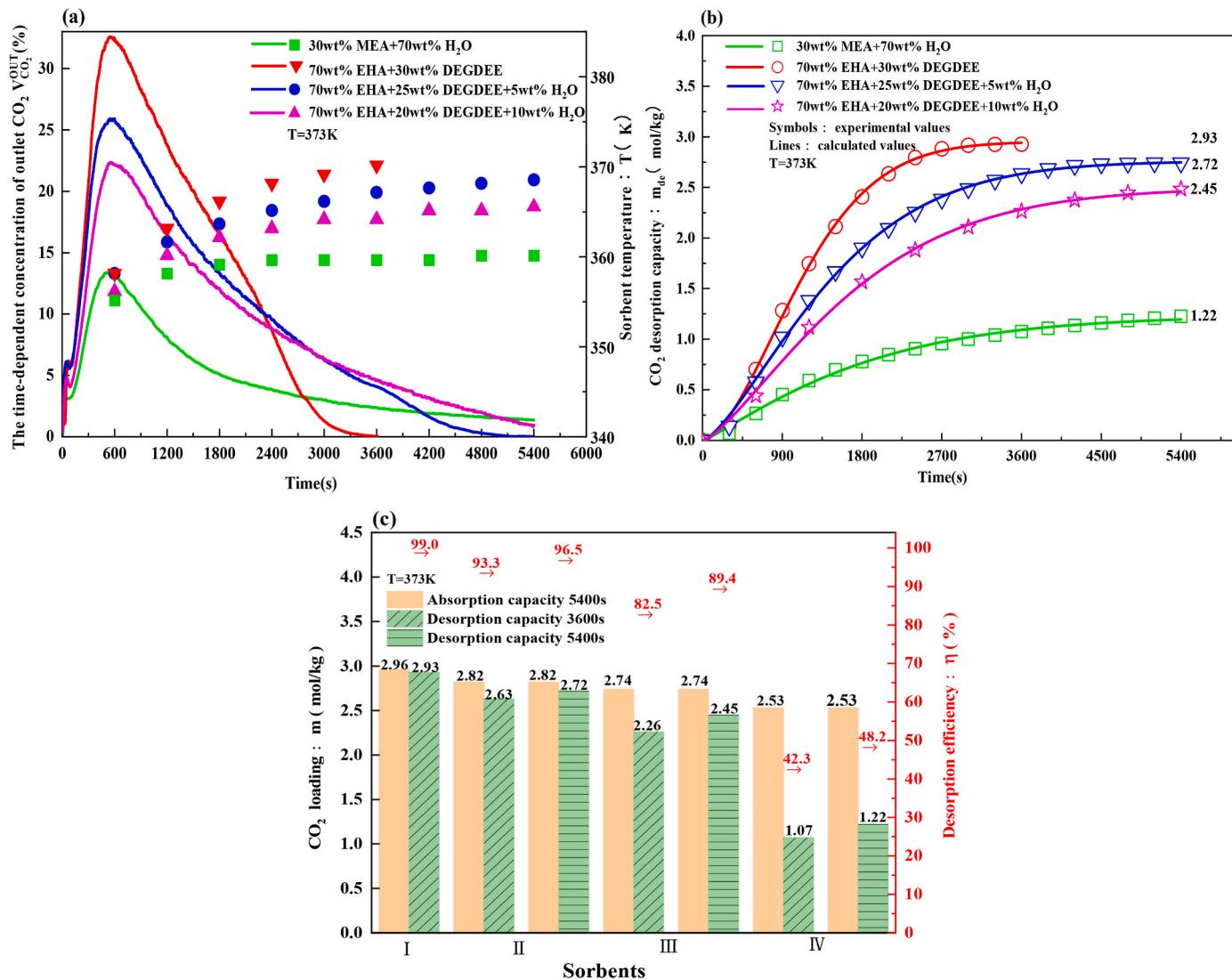
#### 3.1.1. Absorption performance

The effect of absorbent composition on  $\text{CO}_2$  absorption performance under 313K can be seen from Fig. 2.

In Fig. 2 (a), when the mass fraction of EHA ( $w_{\text{EHA}}$ ) is bigger than 0.5, there is a very noteworthy problem, the time-varying  $\text{CO}_2$  concentration at the outflow can be maintained at 0 for a long time, indicating that at this time interval, the  $\text{CO}_2$  can be 100 % captured in the flue gas. The reason for this phenomenon can be attributed to the high  $\text{CO}_2$  absorption capacity and fast absorption rate of the EHA-DEGDEE system when the mass fraction of EHA ( $w_{\text{EHA}}$ ) is greater than 0.6. Under these conditions, the absorbent can rapidly and effectively absorb the  $\text{CO}_2$  in the flue gas, resulting in nearly complete removal of  $\text{CO}_2$  from the gas stream for an extended period. This high absorption efficiency is crucial for industrial applications, as it minimizes the  $\text{CO}_2$  emissions and ensures a stable outlet gas composition. Similar observations have been reported in previous studies on non-aqueous or water lean amine-based absorbents [44,54]. 100 % capture does reflect that the absorbent has a particularly strong ability to absorb  $\text{CO}_2$ . In contrast, the capability of the MEA is somewhat worse, for example, its corresponding minimum  $\text{CO}_2$  concentration at the outlet is not less than 1 %. In Fig. 2 (b), with the increasing mass fraction of EHA, the absorption capacity gradually increased, at three specific EHA mass fractions (0.6, 0.7 and 0.8), the absorption capacity was greater than that of MEA.

#### 3.1.2. The absorption rate and absorption rate of prediction

From the Avrami model, one can obtain the absorption rate constant  $k$  by fitting the experimental data, which can be seen in Table 2. In a sense,  $k$  can also represent how quickly the absorbent absorbs  $\text{CO}_2$ . With the increase of the EHA fraction,  $k$  showed a decreasing trend. It may be that with more  $\text{CO}_2$  absorbed, the absorbent became more sticky, and from the gas to the liquid phase, the transfer of  $\text{CO}_2$  became more difficult. From this point of view,  $w_{\text{EHA}}$  of 0.6 and 0.7 is appropriate. On the one hand, when  $w_{\text{EHA}}$  is small, for example,  $w_{\text{EHA}} = 0.3$ , the absorption capacity is too small, and when  $w_{\text{EHA}}$  is between 0.6 and 0.7, the absorption capacity is stronger than the MEA absorbent. Besides, the  $\text{CO}_2$  capture process requires an appropriate rate, and when the  $w_{\text{EHA}}$  is



**Fig. 5.** Comparison of related properties between non-aqueous absorbers and water lean absorbers: (a) The time-varying  $\text{CO}_2$  concentration at the outflow; (b) The  $\text{CO}_2$  desorption amount; (c) The desorption efficiency: Sorbent I: 70 wt% EHA + 30 wt% DEGDEE; II: 70 wt% EHA + 25 wt% DEGDEE + 5 wt%  $\text{H}_2\text{O}$ ; III: 70 wt% EHA + 20 wt% DEGDEE + 10 wt%  $\text{H}_2\text{O}$ ; IV: 30 wt% MEA + 70 wt%  $\text{H}_2\text{O}$ .

between 0.6 and 0.7, the  $k$  value is close to that of the MEA absorbent.

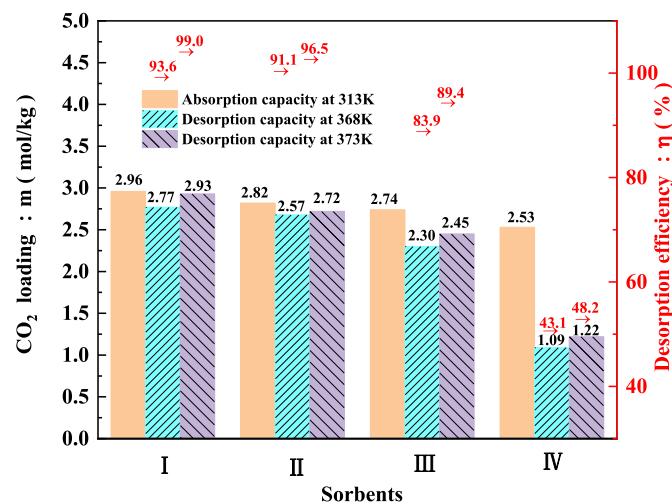
### 3.1.3. Determination of absorbent composition

As shown in Fig. 2 and Table 2, as  $w_{\text{EHA}}$  increases, the absorption capacity increases but the absorption rate decreases. Therefore, the determination of an appropriate EHA mass fraction requires a trade-off of a number of characteristics. Here, we determine the  $w_{\text{EHA}}$  based on the viscosity. High viscosity can adversely affect mass transfer efficiency and thermal efficiency, thus, the interaction between the absorbent and  $\text{CO}_2$  is weakened. Therefore, to study the viscosity of  $\text{CO}_2$  absorbed by different proportions of absorbents is important. The relationship between the viscosity of the  $\text{CO}_2$ -loaded absorbent and  $w_{\text{EHA}}$  is in Table 3. When  $w_{\text{EHA}}$  changes from 0.7 to 0.8, the viscosity increases sharply and almost doubles. This sharp rise in viscosity must seriously affect the mass transfer and thus the absorption rate, as shown in Table 2. Therefore, we believe that 70 wt% EHA is an appropriate value, which can ensure a larger absorption capacity, and also ensure a proper viscosity and absorption rate. In the subsequent experiments,  $w_{\text{EHA}}$  was taken as 0.7 unless otherwise specified.

### 3.2. Desorption performance

Temperature is very important for both desorption efficiency and regeneration energy consumption. If at a relatively low temperature, a satisfactory desorption efficiency can be obtained, it will certainly help to reduce energy consumption. For this purpose, we set 363 K, 368 K, and 373 K three desorption temperatures. The desorption rate, desorption efficiency, and desorption capacity were determined experimentally.

The concentration of  $\text{CO}_2$  desorbed by different absorbents has a similar trend over time, as shown in Fig. 3 (a). In addition, the temperature change trend of the liquid to be desorbed is roughly the same, and will eventually stabilize around the set desorption temperature. It can be divided into three stages in detail: 1) At the beginning of desorption, the temperature of the liquid awaiting desorption rises slowly, and the desorption rate increases; 2) With the rise of temperature, the loaded  $\text{CO}_2$  is fully desorbed, so the  $\text{CO}_2$  desorption rate reached a maximum; 3) The remaining firmly bound  $\text{CO}_2$  began to desorb slowly, the  $\text{CO}_2$  desorption rate decreased slowly until the desorption ended. In Fig. 3 (a), at 373K, the  $\text{CO}_2$ -loaded EHA/DEGDEE was fully desorbed at 3600 s. But at the same temperature and the same time, the outlet concentration of  $\text{CO}_2$  from MEA aqueous solution was



**Fig. 6.** Comparison of desorption efficiencies at desorption temperatures of 368 K and 373 K: Sorbent I: 70 wt% EHA + 30 wt% DEGDEE, desorption time is 3600s; II: 70 wt% EHA + 25 wt% DEGDEE + 5 wt% H<sub>2</sub>O, desorption time is 5400s; III: 70 wt% EHA + 20 wt% DEGDEE + 10 wt% H<sub>2</sub>O, desorption time is 5400s; IV: 30 wt% MEA + 70 wt% H<sub>2</sub>O, desorption time is 5400s.

**Table 6**

The electricity consumption during the desorption of CO<sub>2</sub> and the desorption quality of CO<sub>2</sub> (M<sub>de</sub>). Sorbents: I: 30 wt% MEA + 70 wt% H<sub>2</sub>O; II: 70 wt% EHA + 30 wt% DEGDEE; III: 70 wt% EHA + 25 wt% DEGDEE + 5 wt% H<sub>2</sub>O; IV: 70 wt% EHA + 20 wt% DEGDEE + 10 wt% H<sub>2</sub>O.

Sorbents	Time(s)					
	600	1200	1800	2400	3000	3600
I	E <sub>blank</sub> (kW·h)	0.011	0.022	0.033	0.045	0.056
	E <sub>total</sub> (kW·h)	0.017	0.032	0.045	0.060	0.074
	E <sub>c</sub> (kW·h)	0.006	0.010	0.012	0.015	0.018
	M <sub>de</sub> (g)	0.35	0.78	1.03	1.19	1.32
II	E <sub>total</sub> (kW·h)	0.017	0.030	0.043	0.058	0.071
	E <sub>c</sub> (kW·h)	0.006	0.008	0.010	0.013	0.015
	M <sub>de</sub> (g)	0.92	2.30	3.18	3.69	3.85
	E <sub>total</sub> (kW·h)	0.018	0.030	0.043	0.058	0.072
III	E <sub>c</sub> (kW·h)	0.007	0.008	0.010	0.013	0.016
	M <sub>de</sub> (g)	0.76	1.82	2.51	2.97	3.28
	E <sub>total</sub> (kW·h)	0.018	0.031	0.044	0.058	0.073
	E <sub>c</sub> (kW·h)	0.007	0.009	0.011	0.013	0.017
IV	M <sub>de</sub> (g)	0.58	1.47	2.07	2.48	2.78
	E <sub>total</sub> (kW·h)	0.018	0.031	0.044	0.058	0.086
	E <sub>c</sub> (kW·h)	0.007	0.009	0.011	0.013	0.017
	E <sub>blank</sub> (kW·h)	0.58	1.47	2.07	2.48	2.99

still around 2 %, which indicated that the desorption had not been completed. It may be because the actual desorption temperature of the absorbent is different under the same heating conditions. When the Oil bath temperature was 373K, the actual temperature in the MEA aqueous solution was lower than that in the non-aqueous solution of EHA/DEGDEE.

In Fig. 3 (b), with the increase in desorption temperature, the desorption amount of CO<sub>2</sub> showed an increasing trend. At the same time, the desorption temperature was ignored, the desorption capacity of EHA/DEGDEE was always higher than the MEA solution. When the desorption temperature was 363 K, 368 K and 373 K, the desorption efficiency of EHA/DEGDEE respectively was 85.3 %, 94.9 % and 99.0 %. The MEA aqueous solution desorption efficiency of 373 K (42.3 %) was smaller than the EHA/DEGDEE at 363 K (85.3 %). It should be noted that the efficiency of each desorption is very important for the absorption performance of the next cycle. The viscosity is closely related to the CO<sub>2</sub> loading of the absorbent, the greater the CO<sub>2</sub> loading, the greater the viscosity. If the CO<sub>2</sub> desorption efficiency of the absorbent is low, it will lead to a high CO<sub>2</sub> loading of the depleted liquid, which results in a higher viscosity, this in turn affects the next absorption performance.

Therefore, although the viscosity of EHA/DEGDEE is higher than that of MEA aqueous solution, the relatively high desorption efficiency can ensure that the absorption performance is relatively stable after multiple cycles. Especially when the desorption temperature is 373 K, the desorption efficiency is 99 %, which will endow EHA/DEGDEE with strong practical application potential. A comparison was made between the desorption performance of EHA/DEGDEE with that of EHA/diglyme and EHA/DMSO reported in our previous work [44,54]. The contents of the comparison include desorption amount (mol/kg), desorption efficiency (%) and desorption rate constant ( $\times 10^4$ ), as shown in Table 4. The desorption performance of the three non-aqueous absorbents was similar. When the desorption temperature is 373 K, the desorption efficiency of EHA/DEGDEE is slightly better than that of EHA/DMSO. The selection of organic solvents for non-aqueous absorbents is a work worthy of continuous improvement and enhancement. In this work, we used DEGDEE instead of DMSO, although the desorption efficiency increased by only 2 %, we still believe that this improvement is satisfactory.

### 3.3. Water resistance

We found that both EHA and DEGDEE are soluble in water, and during our experiments, it was found that when 10 wt% of water was dissolved, the solution was uniformly transparent. At this time, the solution is no longer non-aqueous, but a water lean solution. Since the flue gas contains moisture, the change in the absorbent due to the dissolution of water must be considered. Our research work has shown that there are important differences in the absorption performance of CO<sub>2</sub> between non-aqueous and water lean absorbents, and the desorption performance is similar. Although it is difficult to determine exactly how much water is present in a real application, we estimate that it will not exceed 5 wt%. Here, we consider more extreme conditions and set the water content values to 5 wt% and 10 wt%. The 70 wt% EHA+25 wt% DEGDEE+5 wt% H<sub>2</sub>O and 70 wt% EHA+20 wt% DEGDEE+10 wt%H<sub>2</sub>O of absorption performance and desorption performance are shown in Figs. 4 and 5.

#### 3.3.1. The influence of water content on the absorption performance

The maximum CO<sub>2</sub> absorption rates with water contents of 0 wt%, 5 wt% and 10 wt% of the absorbents all occurred in the time range of 300s–2000s, and the values were very similar, which were significantly higher than the MEA aqueous solution, as shown in Fig. 4 (a). This is important to illustrate that, even with 10 wt% water dissolved, the maximum CO<sub>2</sub> absorption rate of EHA/DEGDEE is higher than that of MEA aqueous solution. A significant difference was observed after 2700 s, when the water content increased, the absorption rate became lower, but the CO<sub>2</sub> absorption rate of EHA/DEGDEE with a water content of 10 wt% was still higher than that of MEA. Therefore, from the parameter of absorption rate, EHA/DEGDEE is suitable in the flue gas for CO<sub>2</sub> capture. In addition, the viscosity values of the three absorbents were measured before and after absorbing CO<sub>2</sub>. As presented in Table 5, the viscosities of the four CO<sub>2</sub>-unloaded absorbents are all below 2.0 mPa s. However, after 5400 s of absorption, the viscosities of the CO<sub>2</sub>-loaded absorbents containing 0 wt%, 5 wt%, and 10 wt% water increase significantly to 24.3 mPa s, 28.9 mPa s, and 30.5 mPa s, respectively. These values are approximately 9–13 times higher than that of the CO<sub>2</sub>-loaded 30 wt% MEA aqueous solution (2.5 mPa s). This substantial increase in viscosity may be attributed to the formation of absorption products with longer chain lengths in the EHA + DEGDEE system. Despite the higher viscosities, Fig. 4 clearly demonstrates that the apparent CO<sub>2</sub> absorption rates of the three EHA + DEGDEE solutions are considerably higher than that of the 30 wt% MEA aqueous solution.

#### 3.3.2. The influence of water content on the desorption performance

In Fig. 5, on the desorption and adsorption, the effects of water content effects were similar. In Fig. 5 (a), the maximum desorption rate

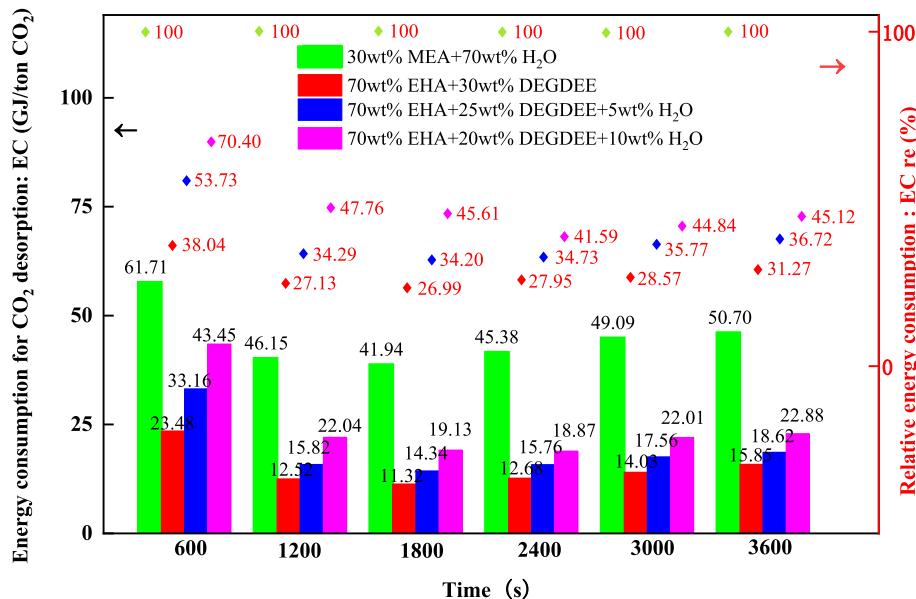


Fig. 7. Based on the power consumption of CO<sub>2</sub> desorption energy consumption values (EC), and the relative values comparison of energy consumption(EC re).

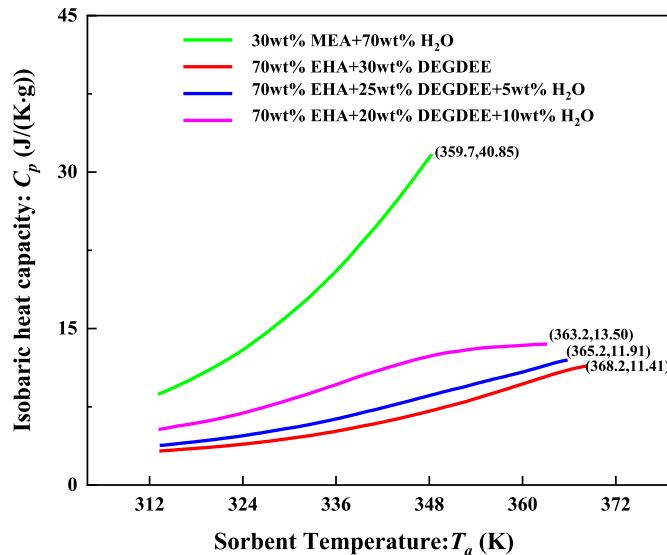


Fig. 8. The isobaric heat capacity (C<sub>p</sub>) of the four sorbents (5400 s of absorption) in the temperature-rise period (first 2400 s) of the desorption process.

occurs at about 600 s and then decreases rapidly. The greater the water content, the smaller the maximum desorption rate, but even if the water content is 10 wt%, it is still higher than the maximum desorption rate of the CO<sub>2</sub>-loaded MEA aqueous solution. After 600 s, the amount of desorbed CO<sub>2</sub> decreased rapidly, indicating that the residual CO<sub>2</sub> became less and less. Unlike the non-aqueous case, desorbed CO<sub>2</sub> could still be detected at 5400 s when the water content reached 10 wt%, indicating that this time was not enough for the CO<sub>2</sub>-loaded absorbent to be fully regenerated, but the desorbed CO<sub>2</sub> content was less than that of the CO<sub>2</sub>-loaded MEA aqueous solution. This may be related to the true temperature at which CO<sub>2</sub> is desorbed, which we have explained in the previous section in detail. Fig. 5 (b) shows the amount of desorption versus time. In the absence of water, the time-dependent desorption ends at 3600 s because, as shown in Fig. 5 (a), no desorbed CO<sub>2</sub> can be detected after 3600 s. In contrast, when the content of water is 5 wt% and 10 wt%, the capacity of CO<sub>2</sub> desorbed is far from the capacity of CO<sub>2</sub> absorbed, indicating that 5400 s is not enough to completely desorb the CO<sub>2</sub>.

loaded absorption solution (of course, it is also possible that at this temperature, no matter how much time, it cannot be completely desorbed). It can be seen from this that the growth of the water content is indeed very harmful to desorption.

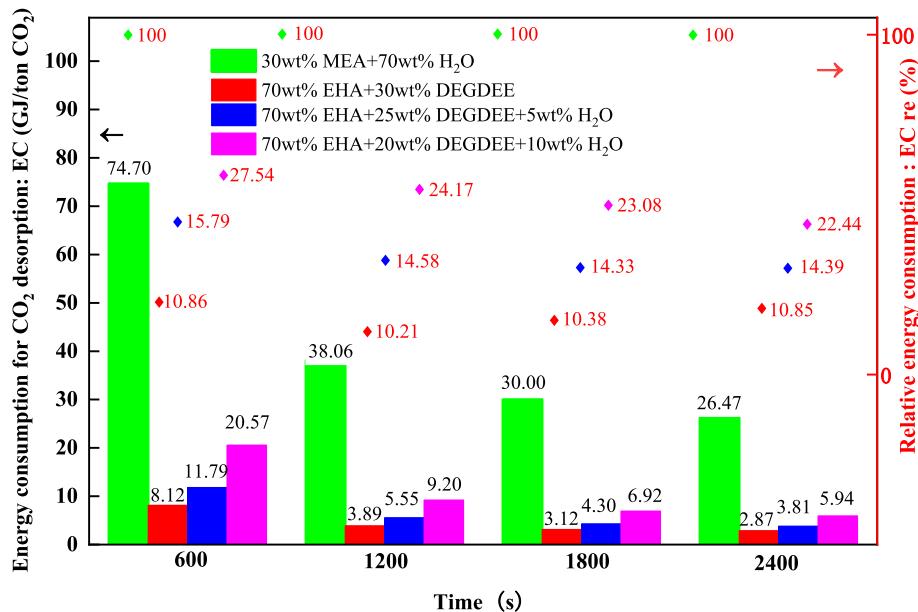
In Fig. 5 (c), the four different absorbents of the desorption capacity and desorption efficiency were compared. At 3600 s, the desorption efficiency of the EHA/DEGDEE with 0 wt%, 5 wt% and 10 wt% water is 99.0 %, 93.3 %, and 82.5 %, respectively. When extending the desorption time to 5400 s, the desorption efficiencies of CO<sub>2</sub> absorbent containing 5 % and 10 % water are 96.5 % and 89.4 %, respectively. In contrast, the desorption efficiencies of CO<sub>2</sub>-loaded MEA aqueous solution are only 42.3 % and 48.2 % at 3600 s and 5400 s, which is a significant difference. Therefore, considering the important parameter of desorption efficiency, EHA/DEGDEE is suitable in flue gas containing a large amount of moisture for capturing CO<sub>2</sub>. As for why non-aqueous absorbents and water lean absorbents have significantly higher desorption efficiency, it is inferred that organic solvents can desorb more CO<sub>2</sub> in a shorter time, from a molecular point of view, because the hydrogen bonds of water molecules are less likely to break or move due to temperature increase than the loose and weak dipole-dipole bonds of organic solvents [73].

### 3.3.3. The influence of water content on the desorption performance at different temperatures

To investigate the effect of lowering the desorption temperature on the absorbent performance, the desorption temperature was decreased from 373 K to 368 K, and a comparative study was conducted on the EHA-DEGDEE system with different water contents and the MEA aqueous solution. As shown in Fig. 6, the results showed that the desorption efficiency drop of the EHA system ranged from 5.3 % to 5.5 % for different water contents. Even at 368 K and 10 % water content, the desorption efficiency of the EHA system still reached 83.9 %, which was much higher than that of the aqueous 30 wt% MEA system (43.1 %). This indicates that the EHA-DEGDEE system can maintain highly efficient desorption at lower temperatures and has good potential for reducing energy consumption.

### 3.4. Desorption energy consumption

Before this section, the good absorption rate, absorption amount, desorption rate, desorption efficiency, and water resistance of EHA/



**Fig. 9.** Based on the power consumption of CO<sub>2</sub> desorption energy consumption values (EC), and the relative values comparison of energy consumption (EC<sub>re</sub>).

**Table 7**

The average isobaric heat capacities ( $C_{p\text{-av}}$ ) and temperature difference ( $\Delta T$ ) during the desorption of CO<sub>2</sub> and the desorption quality of CO<sub>2</sub> ( $M_{de}$ ). Sorbents: I: 30 wt% MEA+70 wt% H<sub>2</sub>O; II: 70 wt% EHA +30 wt% DEGDEE; III: 70 wt% EHA +25 wt% DEGDEE +5 wt% H<sub>2</sub>O; IV: 70 wt% EHA +20 wt% DEGDEE +10 wt% H<sub>2</sub>O.

Sorbents		Time(s)			
		600	1200	1800	2400
I	$C_{p\text{-av}}$ (J/(g,K))	20.75	21.99	22.39	22.58
	$\Delta T$ (K)	42.0	45.0	46.0	46.5
	$M_{de}$ (g)	0.35	0.78	1.03	1.19
II	$C_{p\text{-av}}$ (J/(g,K))	5.53	5.96	6.23	6.42
	$\Delta T$ (K)	45.0	50.0	53.0	55.0
	$M_{de}$ (g)	0.92	2.30	3.18	3.69
III	$C_{p\text{-av}}$ (J/(g,K))	6.64	6.94	7.12	7.25
	$\Delta T$ (K)	45.0	48.5	50.5	52.0
	$M_{de}$ (g)	0.76	1.82	2.51	2.97
IV	$C_{p\text{-av}}$ (J/(g,K))	9.25	9.59	9.75	9.82
	$\Delta T$ (K)	43.0	47.0	49.0	50.0
	$M_{de}$ (g)	0.58	1.47	2.07	2.48

DEGDEE in absorbing CO<sub>2</sub> have been fully verified. However, in addition to the above five parameters, for the industrial application of absorbents, there is another fatal parameter, which is the regeneration energy consumption.

#### 3.4.1. Desorption energy consumption based on electricity consumption

To this end, we measured the electricity of EHA/DEGDEE with three water contents, calculated the energy consumption, and compared it with that of MEA, and the results are shown in Table 6 and Fig. 7. It is hoped that this comparison can be used to quantitatively illustrate the advantages of EHA/DEGDEE in terms of regeneration energy consumption. The determination method and calculation method of energy consumption, as well as the analysis of energy consumption of non-aqueous and water lean absorbents, have been introduced in detail in our previous work [44,54]. From Table 6, the growth of the water content will significantly increase the energy consumption, but in any case, the advantage of water lean absorbent in regeneration energy consumption compared with MEA is huge.

#### 3.4.2. Desorption energy consumption based on $C_p$

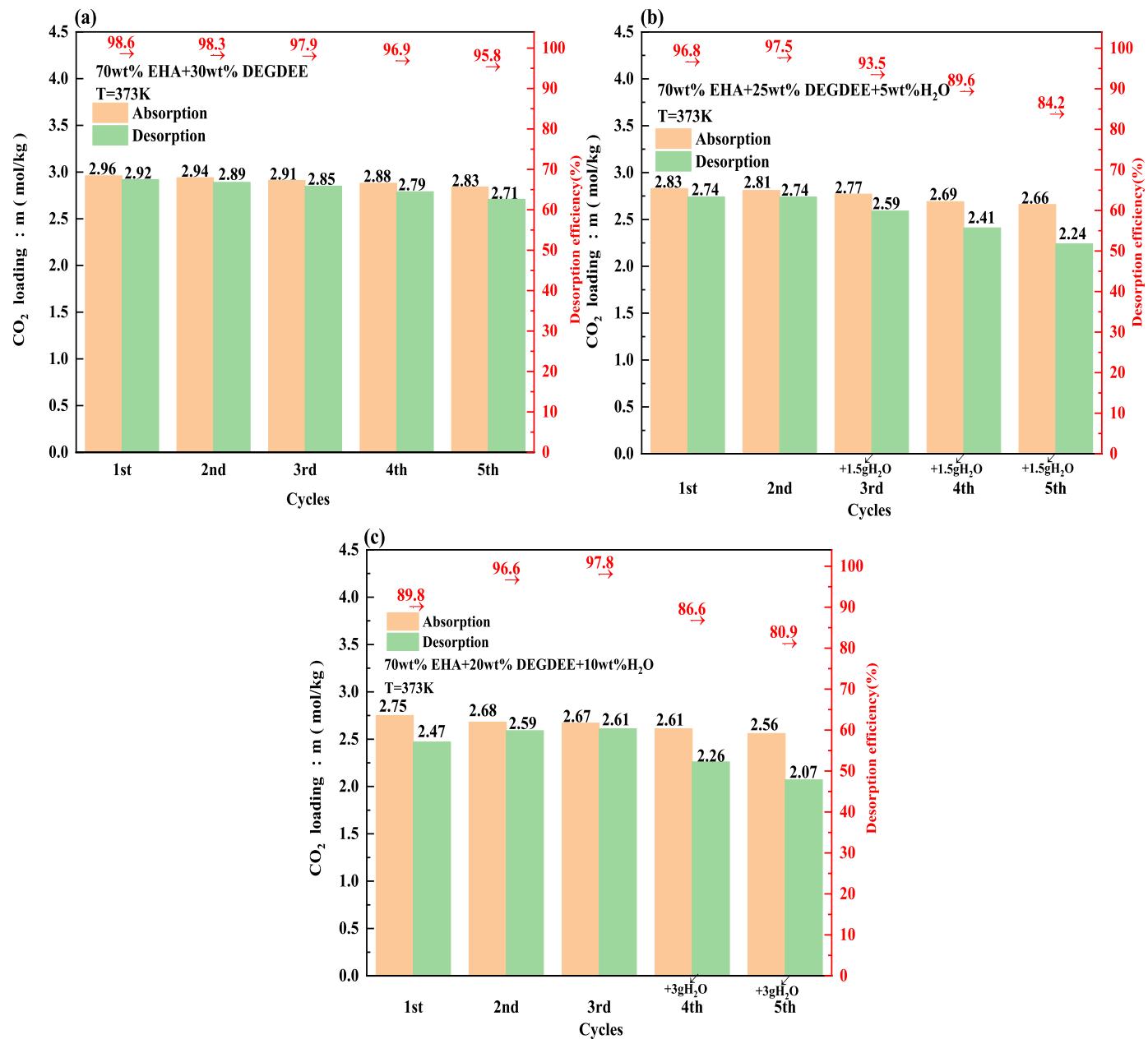
Fig. 8 shows the  $C_p$  of four CO<sub>2</sub>-rich absorbents (after 5400 s of absorption) during the temperature rise period (the first 2400 s) of the CO<sub>2</sub> desorption process. The three types of heat involved during the temperature rise period are the sensible heat of temperature rise, the latent heat of evaporation, and the reaction heat of CO<sub>2</sub> desorption. Therefore, according to equation (8) and the data in Table 7, the average isobaric heat capacity ( $C_{p\text{-av}}$ ) of the CO<sub>2</sub>-rich absorbents during this period can be regarded as the sum of the above three types of energy, representing the energy required to raise the temperature of 1 g of absorbent by 1 K, which can be used to calculate EC. As shown in Fig. 8, the EC of the four absorbents gradually decreases with increasing time, but the EC<sub>re</sub> of the absorbents containing 0 wt%, 5 wt%, and 10 wt% water remains basically stable at approximately 11.0 %, 14.0 %, and 22.0 %, respectively (see Fig. 9).

The results obtained by the two methods indicate that the EC of the absorbents containing 0 wt%, 5 wt%, and 10 wt% water is much lower than that of the 30 wt% MEA aqueous solution. Moreover, the EC based on  $C_p$  is generally smaller than the value based on  $E_c$ , which may be because the former can further reduce the influence of useless work such as heat loss in equipment.

#### 3.5. Cycle performance

The number of cycles is directly related to the operating cost, therefore, it is one of the vital indicators of the evaluation of industrial application potential. So it is necessary to study the cyclic stability of the absorbent. The results of 5 cycles of absorption/desorption are shown in Fig. 10.

As shown in Fig. 10 (a), after five times of absorption/desorption, the desorption efficiency of 70 wt% EHA+30 wt% DEGDEE was still higher than 95 %. This fully shows that the non-aqueous absorbent developed in this work has excellent recycling ability. We have repeatedly emphasized the existence of moisture in the flue gas, which may lead to the change of absorbent from non-aqueous to water lean, but since our absorbent has not been applied in the pilot test plan so far, we can't provide detailed values of the change of water content during the use of absorbent. In addition, to the dissolution of water vapor from the flue gas, there is another problem that exists objectively and needs to be seriously considered, that is, the evaporation of water in the absorbent. Therefore, we consider the limiting case and roughly set two values of 5



**Fig. 10.** CO<sub>2</sub> absorption amount, desorption amount, and the desorption efficiency in the three kinds of solutions EHA + DEGDEE absorbents, in the five absorption-desorption cycles.

% and 10 % for the water content. It can be seen from Table 8 that the water content of 70 wt% EHA + 25 wt% DEGDEE + 5 wt% H<sub>2</sub>O after the second desorption is as low as 0.06 wt%, the desorption efficiency of 70 wt% EHA + 25 wt% DEGDEE + 5 wt% H<sub>2</sub>O after the second absorption/desorption was 97.5 %, it was very close to the desorption efficiency of 70 wt% EHA + 30 wt% DEGDEE, which is very close to the water-free state, thus explaining why the desorption efficiency is close to that under water-free conditions. So before starting a new cycle, 1.5 g of water was added, in other words, 1.50 g of water was replenished to the regenerated solution, before the 3rd, 4th, and 5th cycles. Similarly, the water content of 70 wt% EHA + 20 wt% DEGDEE + 10 wt% H<sub>2</sub>O after the third desorption is only 0.16 wt%, therefore, the desorption efficiency is also close to that under water-free condition, 3.00 g of water was added to before the 4th and 5th cycles.

After multiple absorption and desorption, the capacity of CO<sub>2</sub> absorption and CO<sub>2</sub> desorption of EHA/DEGDEE decreased slightly. This may be due to the slight loss of both EHA and DEGDEE during the

heating process. Nevertheless, at the end of the fifth desorption, the desorption efficiency of 70 wt% EHA + 30 wt% DEGDEE was still 95.8 %, the desorption efficiency of 70 wt% EHA + 25 wt% DEGDEE + 5 wt% H<sub>2</sub>O was 84.2 %, and the desorption efficiency of 70 wt% EHA + 20 wt% DEGDEE + 10 wt% H<sub>2</sub>O was 80.9 %. It is difficult to accurately determine the water content in the absorbent, but in general, even under the limited condition of 10 % water content, the absorbent still has stable regeneration ability and recycling ability.

### 3.6. <sup>13</sup>NMR spectra

When the water content (e.g., 0 wt%, 5 wt% and 10 wt%) of the absorbent changes, the absorption and desorption performance will change significantly. This phenomenon has been found many times in our previous work [44,54], but the hidden reasons have not been analyzed in depth. To better understand the absorption and desorption behavior of absorbents with different water contents, <sup>13</sup>NMR spectra of

**Table 8**

Changes of water content with circulation cycle.

Sorbents	Cyclic numbers <sup>a</sup>	Water content ( wt% )
70 wt% EHA+ 25 wt% DEGDEE+ 5 wt% H <sub>2</sub> O	0 <sup>b</sup>	5.19
70 wt% EHA+ 25 wt% DEGDEE+ 5 wt% H <sub>2</sub> O	1	1.20
70 wt% EHA+ 25 wt% DEGDEE+ 5 wt% H <sub>2</sub> O	2	0.06
70 wt% EHA+ 25 wt% DEGDEE+ 5 wt% H <sub>2</sub> O	3 <sup>c</sup>	2.08
70 wt% EHA+ 25 wt% DEGDEE+ 5 wt% H <sub>2</sub> O	4 <sup>c</sup>	3.38
70 wt% EHA+ 25 wt% DEGDEE+ 5 wt% H <sub>2</sub> O	5 <sup>c</sup>	5.41
70 wt% EHA+ 20 wt% DEGDEE+ 10 wt% H <sub>2</sub> O	0 <sup>b</sup>	10.40
70 wt% EHA+ 20 wt% DEGDEE+ 10 wt% H <sub>2</sub> O	1	5.88
70 wt% EHA+ 20 wt% DEGDEE+ 10 wt% H <sub>2</sub> O	2	2.24
70 wt% EHA+ 20 wt% DEGDEE+ 10 wt% H <sub>2</sub> O	3	0.16
70 wt% EHA+ 20 wt% DEGDEE+ 10 wt% H <sub>2</sub> O	4 <sup>d</sup>	7.39
70 wt% EHA+ 20 wt% DEGDEE+ 10 wt% H <sub>2</sub> O	5 <sup>d</sup>	13.64

<sup>a</sup> The number of cycles refers to the number of times after desorption.<sup>b</sup> The number of cycles is zero, which means an unabsorbed solution.<sup>c</sup> Add 5 wt% water before absorption.<sup>d</sup> Add 10 wt% water before absorption.

different samples were characterized, and the characterization results can be seen in Fig. 11. In Fig. 11 (a), the possible carbon atoms during absorption and desorption are numbered. Fig. 11 (b) shows the <sup>13</sup>C NMR spectra of the absorption and desorption processes of the non-aqueous absorbent. From the figure, we found that when the absorption time was 900s and 5400s, a new carbon signal peak can be detected in 70 wt % EHA +30 wt% DEGDEE, and the chemical shift range is 160–170 ppm. This peak represents the carbon signal in the carbamate. It can be observed from the figure that the intensity of the peak increases with increasing CO<sub>2</sub> loading. In the process of desorption, the intensity of the peak corresponding to carbamate gradually decreases with the decrease of CO<sub>2</sub> loading. In particular, when the desorption time exceeds 3600 s, we can hardly observe the peak corresponding to carbamate, indicating that the loaded CO<sub>2</sub> has almost completely escaped from the absorbent. This phenomenon also gives an explanation for why the non-aqueous adsorbent desorption efficiency can be 99 %. As the water content of the absorbent increases, some changes are observed, for example, Fig. 11 (c) showed that when the desorption time was 840 s, 70 wt% EHA+25 wt% DEGDEE+5 wt% H<sub>2</sub>O was detected with two peaks in the chemical shift range from 160 to 170 ppm. The two peaks were approximately carbamate and HCO<sub>3</sub><sup>-</sup>, however, it can also be observed that the HCO<sub>3</sub><sup>-</sup> peak intensity is very small, this may be because the concentration of HCO<sub>3</sub><sup>-</sup> produced was too low. Fig. 11 (d) showed that when the absorption time was 5400 s, in the 70 wt% EHA+20 wt% DEGDEE+10 wt%H<sub>2</sub>O, two peaks were detected within the range from 160–170 ppm chemical shift, the two peaks were approximately carbamate and HCO<sub>3</sub><sup>-</sup>, similar experimental phenomena have been reported in the literature [28–31].

It's worth mentioning that when the water content of the absorbent was 5 wt% and 10 wt%, respectively, we did not find the peak of HCO<sub>3</sub><sup>-</sup> at the desorption time of 5400 s (that is, at the end of desorption). The reason for this phenomenon may be that HCO<sub>3</sub><sup>-</sup> decomposes more readily than carbamate [13,74,75]. However, we did observe the presence of a weak carbamate peak, which indicates that the CO<sub>2</sub>-loaded water lean absorbent cannot be fully regenerated. The above results can explain why the desorption efficiency of water lean absorbent is always lower than that of non-aqueous absorbent, and why the desorption efficiency generally decreases with the increase of water content. In addition, it has a slight shift in the carbon position of the carbamate during absorption and desorption, similar phenomena have been reported in the literature [74].

#### 4. Conclusion

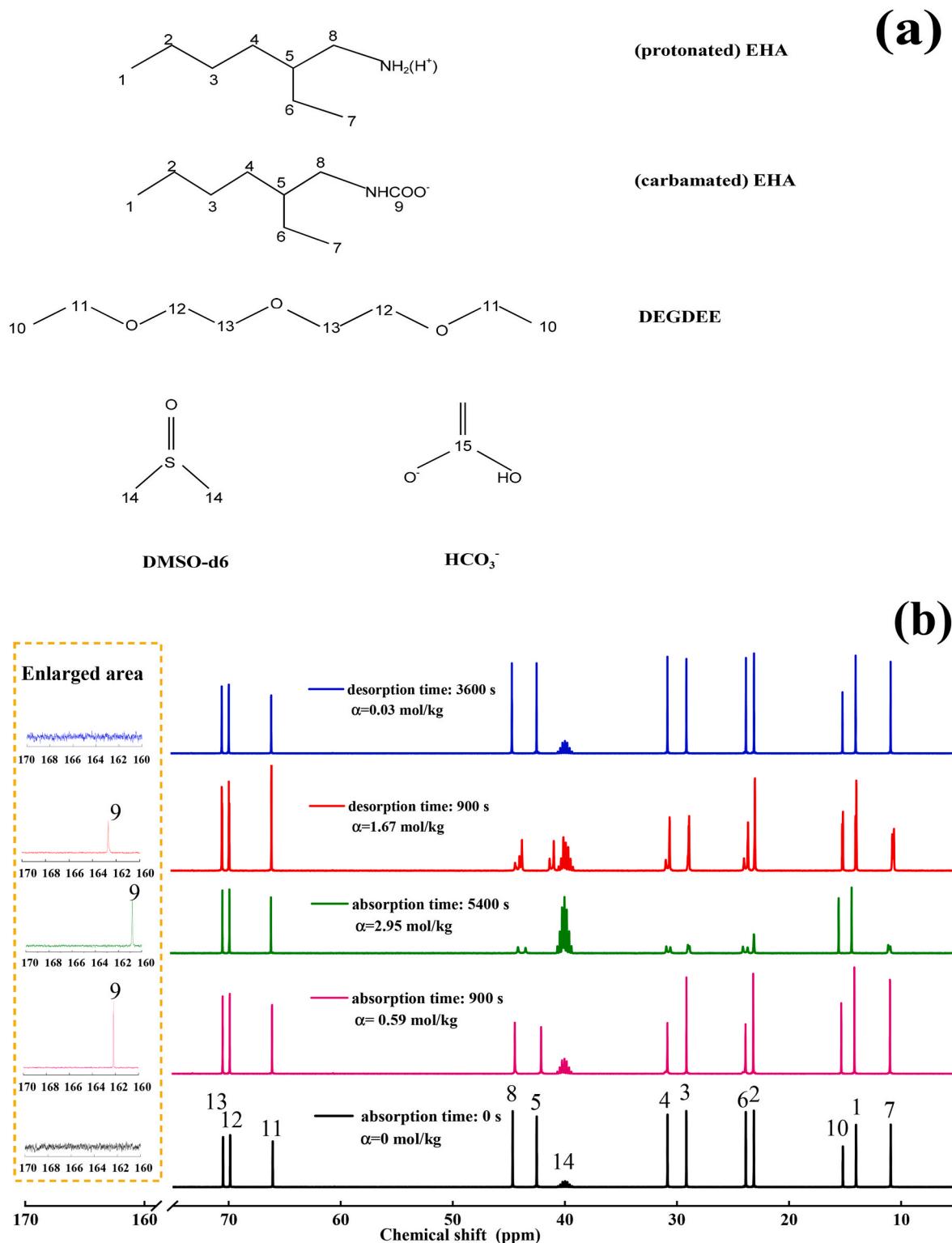
In this work, we first selected DEGDEE from a series of organic solvents with low prices and wide access and used it with EHA to form a non-aqueous absorbent. From the experimental results of absorbency and viscosity, we believe that the non-aqueous absorbent is suitable when EHA has a mass fraction of 70 wt% and the mass fraction of DEGDEE is 30 wt%. On this basis, we confirmed the good desorption efficiency and water resistance of the absorbent, the regeneration energy consumption of the absorbent was lower than that of 30 wt% MEA aqueous solution. At 373 K, the desorption efficiency of the absorbent was 99.0 %, and the energy consumption of desorption was only about 31 % of that of the 30 wt% MEA aqueous solution. Since the flue gas contains water vapor which can be dissolved in the absorbent, we also measured the absorption/desorption performance with water content of 5 wt% and 10 wt% of the water lean absorbents. In particular, it should be emphasized that, after the fifth absorption and desorption, even when the water content reaches 10 wt%, the desorption efficiency still reaches 80.9 %. Compared with the 30 wt% MEA, both water lean and non-aqueous absorbents have a much better performance in terms of absorption, desorption efficiency, water resistance, desorption energy consumption and cycling performance. Compared with the EHA-DMSO formed in our previous work, the absorption and desorption performance of EHA-DEGDEE are comparable, even better, or at least not worse. Most importantly, the cost of DEGDEE is much lower than that of DMSO, which is extremely important for the industrial application of absorbents. Given this, we have every reason to believe that the absorbent of EHA-DEGDEE will have excellent application prospects for capturing CO<sub>2</sub> in the field of flue gas.

#### CRediT authorship contribution statement

**Fanli Meng:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Kun Fu:** Visualization, Validation, Methodology, Investigation. **Xueli Wang:** Formal analysis. **Bonan Ye:** Validation. **Pan Zhang:** Validation. **Lemeng Wang:** Validation. **Dong Fu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



**Fig. 11.** (a): Molecular structures and carbon core types of the major species; The <sup>13</sup>C NMR spectra of EHA + DEGDEE absorbents (b) 0 wt%, (c) 5 wt% and (d) 10 wt% water.

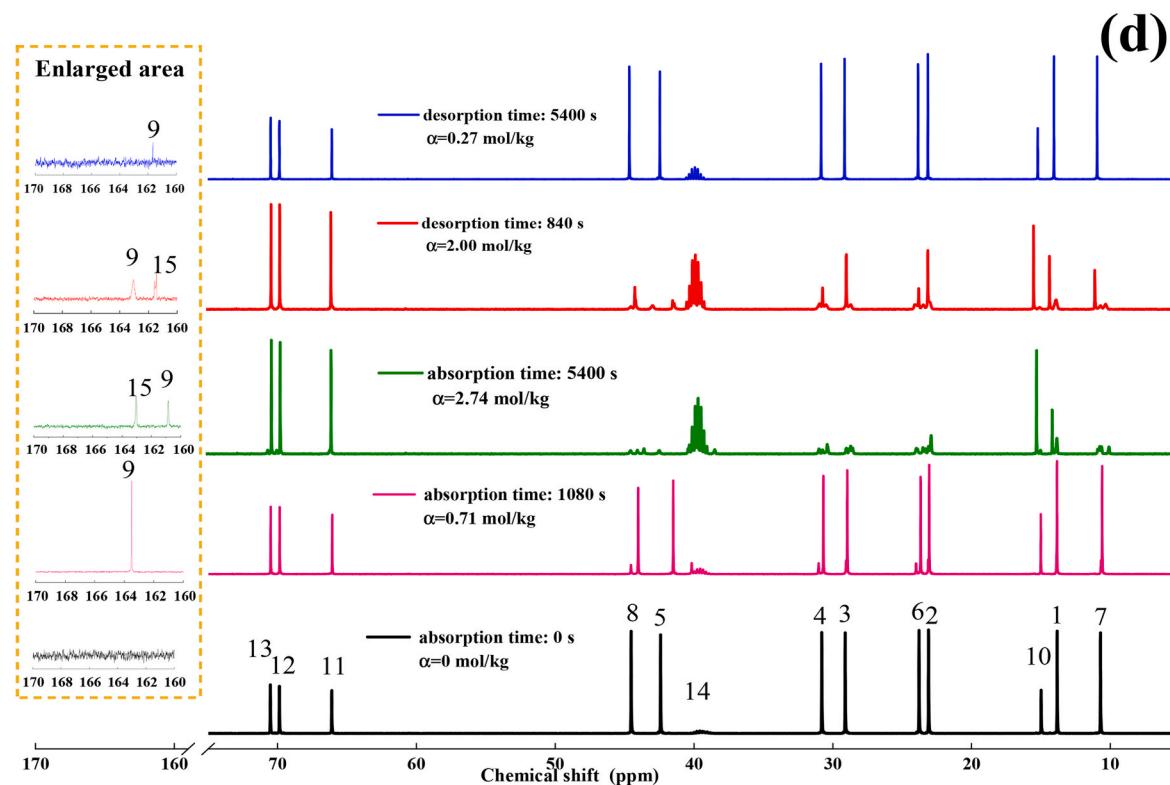
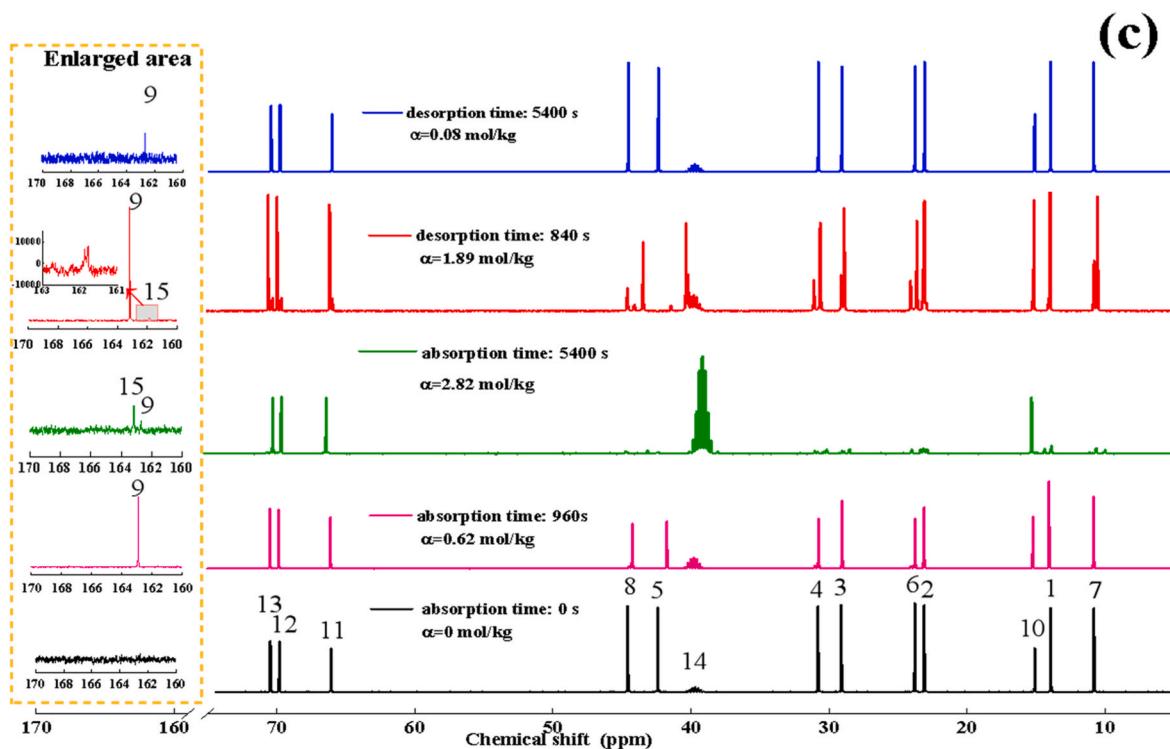


Fig. 11. (continued).

## Data availability

Data will be made available on request.

## Acknowledgments

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## References

- [1] Friedlingstein P, Andrew RM, Rogelj J, Peters GP, Canadell JG, Knutti R, et al. Persistent growth of CO<sub>2</sub> emissions and implications for reaching climate targets. *Nat Geosci* 2014;7:709–15. <https://doi.org/10.1038/ngeo2248>.
- [2] Osman AI, Hefny M, Abdel Maksoud MIA, Elgarahy AM, Rooney DW. Recent advances in carbon capture storage and utilisation technologies: a review. *Eviron Chem Lett* 2021;19:797–849. <https://doi.org/10.1007/s10311-020-01133-3>.
- [3] Idem R, Wilson M, Tontiwachwuthikul P, Chakma A, Veawab A, Aroonwilas A, et al. Pilot plant studies of the CO<sub>2</sub> capture performance of aqueousMEA and mixed MEA/MDEA solvents at the University of Regina CO<sub>2</sub> capture technology development plant and the boundary dam CO<sub>2</sub> capture demonstration plant. *Ind Eng Che Res* 2006;45:2414–20. <https://doi.org/10.1021/ie050569e>.
- [4] Mukhtar A, Saqib S, Mellon NB, Babar M, Rafiq S, Ullah S, et al. CO<sub>2</sub> capturing, thermo-kinetic principles, synthesis and amine functionalization of covalent organic polymers for CO<sub>2</sub> separation from natural gas: a review. *J Nat Gas Sci Eng* 2020;77:103203. <https://doi.org/10.1016/j.jngse.2020.103203>.
- [5] Song C, Liu Q, Deng S, Li H, Kitamura Y. Cryogenic-based CO<sub>2</sub> capture technologies: state-of-the-art developments and current challenges. *Renew Sustain Energy Rev* 2019;101:265–78. <https://doi.org/10.1016/j.rser.2018.11.018>.
- [6] Gautam A, Mondal MK. Review of recent trends and various techniques for CO<sub>2</sub> capture: special emphasis on biphasic amine solvents. *Fuel* 2023;334:126616. <https://doi.org/10.1016/j.fuel.2022.126616>.
- [7] Choubashani S, Rashidi H. CO<sub>2</sub> capture process intensification of water-lean methyl diethanolamine-piperazine solvent: experiments and response surface modeling. *Energy* 2023;267:126447. <https://doi.org/10.1016/j.energy.2022.126447>.
- [8] Kvamsdal HM, Hetland J, Haugen G, Svendsen HF, Major F, Kårstad V, et al. Maintaining a neutral water balance in a 450 MW<sub>e</sub> NGCC-CCS power system with post-combustion carbon dioxide capture aimed at offshore operation. *Int J Greenh Gas Con* 2010;4:613–22. <https://doi.org/10.1016/j.ijggc.2010.01.002>.
- [9] Huang B, Xu S, Gao S, Liu L, Tao J, Niu H, et al. Industrial test and techno-economic analysis of CO<sub>2</sub> capture in Huaneng Beijing coal-fired power station. *Appl Energy* 2010;87:347–54. <https://doi.org/10.1016/j.apenergy.2010.03.007>.
- [10] Olajire AA. CO<sub>2</sub> capture and separation technologies for end-of-pipe applications—a review. *Energy* 2010;35(6):2610–28. <https://doi.org/10.1016/j.energy.2010.02.030>.
- [11] Rezazadeh F, Gale WF, Rochelle GT, Sachde D. Effectiveness of absorber intercooling for CO<sub>2</sub> absorption from natural gas fired flue gases using monoethanolamine solvent. *Int J Greenh Gas Con* 2017;58:246–55. <https://doi.org/10.1016/j.ijggc.797>.
- [12] Jiang K, Li K, Yu H, Chen Z, Wardhaugh L, Feron P. Advancement of ammonia based post-combustion CO<sub>2</sub> capture using the advanced flash stripper process. *Appl Energy* 2017;202:496–506. <https://doi.org/10.1016/j.apenergy.2017.05.143>.
- [13] Zhang R, Zhang X, Yang Q, Yu H, Liang Z, Luo X. Analysis of the reduction of energy cost by using MEA-MDEA-PZ solvent for post-combustion carbon dioxide capture (PCC). *Appl Energy* 2017;205:1002–11. <https://doi.org/10.1016/j.apenergy.2017.08.130>.
- [14] Wai SK, Saiwan C, Idem R, Supap T, Nwaoha C. Carbon dioxide (CO<sub>2</sub>) solubility in diethylenetriamine and 2-amino-2-methyl-1-propanol (DETA-AMP) solvent system for amine-based CO<sub>2</sub> capture in flue gas from coal combustion. *Energy Proc* 2017;114:1973–9. <https://doi.org/10.1016/j.egypro.2017.03.1329>.
- [15] Zhou X, Jing G, Lv B, Liu F, Zhou Z. Low-viscosity and efficient regeneration of carbon dioxide capture using a biphasic solvent regulated by 2-amino-2-methyl-1-propanol. *Appl Energy* 2019;235:379–90. <https://doi.org/10.1016/j.apenergy.2018.10.118>.
- [16] Liu F, Fang M, Dong W, Wang T, Xia Z, Wang Q, et al. Carbon dioxide absorption in aqueous alkanolamine blends for biphasic solvents screening and evaluation. *Appl Energy* 2019;233–234:468–77. <https://doi.org/10.1016/j.apenergy.2018.10.007>.
- [17] Liu F, Fang M, Yi N, Wang T, Wang Q. Biphasic behaviors and regeneration energy of a 2-(diethylamino)-ethanol and 2-((2-aminoethyl) amino) ethanol blend for CO<sub>2</sub> capture. *Sustain Energy Fuels* 2019;3:3594–602. <https://doi.org/10.1039/c9se00821g>.
- [18] Wang R, Liu S, Li Q, Zhang S, Wang L, An S. CO<sub>2</sub> capture performance and mechanism of blended amine solvents regulated by N-methylcyclohexylamine. *Energy* 2021;215:119209. <https://doi.org/10.1016/j.energy.2020.119209>.
- [19] Zhou X, Shen Y, Liu F, Ye J, Wang X, Zhao J, et al. A novel dual-stage phase separation process for CO<sub>2</sub> absorption into a biphasic solvent with low energy penalty. *Environ Sci Technol* 2021;55:15313–22. <https://doi.org/10.1021/acs.est.1c01622>.
- [20] Hu X, Huang J, He X, Luo Q, Li C, Zhou C, et al. Analyzing the potential benefits of trio-amine systems for enhancing the CO<sub>2</sub> desorption processes. *Fuel* 2022;316:123216. <https://doi.org/10.1016/j.fuel.2022.123216>.
- [21] Chen G, Chen G, Peruzzini M, Zhang R, Barzaghi F. Understanding the potential benefits of blended ternary amine systems for CO<sub>2</sub> capture processes through <sup>13</sup>C NMR speciation study and energy cost analysis. *Sep Purif Technol* 2022;291:120939. <https://doi.org/10.1016/j.seppur.2022.120939>.
- [22] Zhang R, Li Y, He X, Niu Y, Li C, Amer MW, et al. Investigation of the improvement of the CO<sub>2</sub> capture performance of aqueous amine sorbents by switching from dual-amine to trio-amine systems. *Sep Purif Technol* 2023;316:123810. <https://doi.org/10.1016/j.seppur.2023.123810>.
- [23] He X, He H, Barzaghi F, Amer MW, Li C, Zhang R. Analysis of the energy consumption in solvent regeneration processes using binary amine blends for CO<sub>2</sub> capture. *Energy* 2023;270:126903. <https://doi.org/10.1016/j.energy.2023.126903>.
- [24] Zhou X, Liu C, Zhang J, Fan Y, Zhu Y, Zhang L, et al. Novel 2-amino-2-methyl-1-propanol-based biphasic solvent for energy-efficient carbon dioxide capture using tetraethylenepentamine as a phase change regulator. *Energy* 2023;270:126930. <https://doi.org/10.1016/j.energy.2023.126930>.
- [25] Zhao Z, Xing X, Tang Z, Zheng Y, Fei W, Liang X, et al. Experiment and simulation study of CO<sub>2</sub> solubility in dimethyl carbonate, 1-octyl-3-methylimidazolium tetrafluoroborate and their mixtures. *Energy* 2018;143:35–42. <https://doi.org/10.1016/j.energy.2017.10.116>.
- [26] Zhao Z, Gao J, Luo M, Liu X, Zhao Y, Fei W. Molecular simulation and experimental study on low-viscosity ionic liquids for high-efficient capturing of CO<sub>2</sub>. *Energy & Fuels* 2022;36:1604–13. <https://doi.org/10.1021/acs.energyfuels.1c02928>.
- [27] Machida H, Ando R, Esaki T, Yamaguchi T, Horizoe H, Kishimoto A, et al. Low temperature swing process for CO<sub>2</sub> absorption-desorption using phase separation CO<sub>2</sub> capture solvent. *Int J Greenh Gas Control* 2018;75:1–7. <https://doi.org/10.1016/j.ijggc.2018.05.010>.
- [28] Li H, Guo H, Shen S. Low-energy-consumption CO<sub>2</sub> capture by liquid-solid phase change absorption using water-lean blends of amino acid salts and 2-alkoxyethanol. *Accts Sustain Chem Eng* 2020;8:12956–67. <https://doi.org/10.1021/acssuschemeng.0c03525>.
- [29] Zhao Y, Zhang Y, Liu Q, Guo X, Cao Y, Xu N, et al. Energy-efficient carbon dioxide capture using piperazine(PZ)-activated EMEA+DEEA water lean solvent: performance and mechanism. *Sep Purif Technol* 2023;316:123761. <https://doi.org/10.1016/j.seppur.2023.123761>.
- [30] Yin X, Shen S. Water-lean monophasic absorbents containing secondary alkanolamines and dimethyl sulfoxide for energy-efficient CO<sub>2</sub> capture. *Energy* 2023;281:128352. <https://doi.org/10.1016/j.energy.2023.128352>.
- [31] Long Q, Wang S, Shen S. CO<sub>2</sub> capture using EGHE-based water-lean solvents with novel water balance design. *Chem Eng Sci* 2023;273:118658. <https://doi.org/10.1016/j.ces.2023.118658>.
- [32] Barzaghi F, Mani F, Peruzzini M. Novel water-free biphasic absorbents for efficient CO<sub>2</sub> capture. *Int J Greenh Gas Con* 2017;60:100–9. <https://doi.org/10.1016/j.ijggc.2017.03.010>.
- [33] Barzaghi F, Giorgi C, Mani F, Peruzzini M. Reversible carbon dioxide capture by aqueous and non-aqueous amine-based absorbents: a comparative analysis carried out by <sup>13</sup>C NMR spectroscopy. *Appl Energy* 2018;220:208–19. <https://doi.org/10.1016/j.apenergy.2018.03.076>.
- [34] Guo H, Li C, Shi X, Li H, Shen S. Nonaqueous amine-based absorbents for energy efficient CO<sub>2</sub> capture. *Appl Energy* 2019;239:725–34. <https://doi.org/10.1016/j.apenergy.2019.02.019>.
- [35] Bougie F, Pokras D, Fan X. Novel non-aqueous MEA solutions for CO<sub>2</sub> capture. *Int J Greenh Gas Con* 2019;86:34–42. <https://doi.org/10.1016/j.ijggc.2019.04.013>.
- [36] 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 CO<sub>2</sub> capture. *Environ Sci Technol* 2019;53:12873–81. <https://doi.org/10.1021/acs.est.9b02787>.
- [37] Lv B, Yang K, Zhou X, Zhou Z, Jing G. 2-Amino-2-methyl-1-propanol based non-aqueous absorbent for energy-efficient and non-corrosive carbon dioxide capture. *Appl Energy* 2020;264:114703. <https://doi.org/10.1016/j.apenergy.2020.114703>.
- [38] Jiang C, Chen H, Wang J, Shen Y, Ye J, Zhang S, et al. Phase splitting agent regulated biphasic solvent for efficient CO<sub>2</sub> capture with a low heat duty. *Environ Sci Technol* 2020;54:7601–10. <https://doi.org/10.1021/acs.est.9b07923>.
- [39] Zhou X, Li X, Wei J, Fan Y, Liao L, Wang H. Novel nonaqueous liquid-liquid biphasic solvent for energy-efficient carbon dioxide capture with low corrosivity. *Environ Sci Technol* 2020;54:16138–46. <https://doi.org/10.1021/acs.est.0c05774>.
- [40] Chen Z, Jing G, Lv B, Zhou Z. An efficient solid-liquid biphasic solvent for CO<sub>2</sub> capture: crystalline powder product and low heat duty. *Accts Sustain Chem Eng* 2020;8:14493–503. <https://doi.org/10.1021/acssuschemeng.0c04616>.
- [41] Liu F, Shen Y, Shen L, Sun C, Chen L, Wang Q, et al. Novel AminoFunctionalized ionic liquid/organic solvent with low viscosity for CO<sub>2</sub> capture. *Environ Sci Technol* 2020;54:3520–9. <https://doi.org/10.1021/acs.est.9b06717>.
- [42] Wang Y, Dong Y, Zhang L, Chu G, Zou H, Sun B, et al. Carbon dioxide capture by non-aqueous blend in rotating packed bed reactor: absorption and desorption investigation. *Sep Purif Technol* 2021;269:118714. <https://doi.org/10.1016/j.seppur.2021.118714>.
- [43] Li X, Zhou X, Wei J, Fan Y, Liao L, Wang H. Reducing the energy penalty and corrosion of carbon dioxide capture using a novel nonaqueous monoethanolamine-based biphasic solvent. *Sep Purif Technol* 2021;265:118481. <https://doi.org/10.1016/j.seppur.2021.118481>.
- [44] Fu K, Zheng M, Wang H, Fu D. Effect of water content on the characteristics of CO<sub>2</sub> capture processes in absorbents of 2-ethylhexan-1-amine+ diglyme. *Energy* 2022;244:122656. <https://doi.org/10.1016/j.energy.2021.122656>.
- [45] Bai L, Lu S, Zhao Q, Chen L, Jiang Y, Jia C, et al. Low-energy-consuming CO<sub>2</sub> capture by liquid-liquid biphasic absorbents of EMEA/DEEA/PX. *Chem Eng J* 2022;450:138490. <https://doi.org/10.1016/j.cej.2022.138490>.

- [46] Chen M, Li M, Zhang F, Hu X, Wu Y. Fast and efficient CO<sub>2</sub> absorption in non-aqueous tertiary amines promoted by ethylene glycol. *Energy Fuels* 2022;36: 4830–6. <https://doi.org/10.1021/acs.energyfuels.2c00215>.
- [47] Gao X, Li X, Cheng S, Lv B, Jing G, Zhou Z. A novel solid-liquid ‘phase controllable’ biphasic amine absorbent for CO<sub>2</sub> capture. *Chem Eng J* 2022;430:132932. <https://doi.org/10.1016/j.cej.2021.132932>.
- [48] Zhou X, Liu C, Fan Y, Zhang L, Tang S, Mo S, et al. Energy-efficient carbon dioxide capture using a novel low-viscous secondary amine-based nonaqueous biphasic solvent: performance, mechanism, and thermodynamics. *Energy* 2022;255: 124570. <https://doi.org/10.1016/j.energy.2022.124570>.
- [49] Ma M, Liu Y, Chen Y, Jing G, Lv B, Zhou Z, et al. Regulatory mechanism of a novel non-aqueous absorbent for CO<sub>2</sub> capture using 2-amino-2-methyl-1-propanol: low viscosity and energy efficient. *J CO<sub>2</sub> Util* 2023;67:102277. <https://doi.org/10.1016/j.jcou.2022.102277>.
- [50] Kassim MA, Sulaiman NA, Yusoff R, Aroua MK. Non-aqueous solvent mixtures for CO<sub>2</sub> capture: choline hydroxide-based deep eutectic solvents absorbent performance at various temperatures and pressures. *Sustainability* 2023;15:9191. <https://doi.org/10.3390/su15129191>.
- [51] Wang C, Xiao G, Zhou X, Zhu Q, Chen Y, Gao Z, et al. The Formation of high CO<sub>2</sub> loading solid phase from 1, 4-butanediamine/ethylene glycol biphasic solvent: phase-changing behavior and mechanism. *Sep Purif Technol* 2023;323:124397. <https://doi.org/10.1016/j.seppur.2023.124397>.
- [52] Lu G, Wang Z, Yue Z, Wei W, Huang Y, Zhang X, et al. Development of novel AMP-based absorbents for efficient CO<sub>2</sub> capture with low energy consumption through modifying the electrostatic potential. *Chem Eng J* 2023;474:145929. <https://doi.org/10.1016/j.cej.2023.145929>.
- [53] Li S, Fu L, Dong Z, Que L, Ma M, Lv B, et al. Theoretical and experimental analysis of CO<sub>2</sub> capture into 1,5-diamino-2-methyl-pentane/n-propanol non-aqueous absorbent regulated by ethylene glycol. *Sep Purif Technol* 2024;330:125408. <https://doi.org/10.1016/j.seppur.2023.125408>.
- [54] Meng F, Fu K, Wang X, Wang Y, Wang L, et al. Study on absorption and regeneration performance of EHA-DMSO non-aqueous absorbent for CO<sub>2</sub> capture from flue gas. *Energy* 2024;286:129631. <https://doi.org/10.1016/j.energy.2023.129631>.
- [55] Lail M, Tanthana J, Coleman L. Non-aqueous solvent (NAS) CO<sub>2</sub> capture process. *Energy Proc* 2014;63:580–94. <https://doi.org/10.1016/j.egypro.2014.11.063>.
- [56] Wang W, Yun Z, Tang Z, Gui X. Fast determination of binary vapor–liquid equilibrium of CO<sub>2</sub>-based mixtures at elevated pressures. *J Chem Eng Data* 2015; 60:1642–7. <https://doi.org/10.1021/je501023n>.
- [57] Roux G, Perron G, Desnoyers JE. The heat capacities and volumes of some low molecular weight amides, ketones, esters, and ethers in water over the whole solubility range. *Can J Chem* 1978;56:2808–14. <https://doi.org/10.1139/v78-464>.
- [58] Ku HC, Tu CH. Densities and viscosities of seven glycol ethers from 288.15 K to 343.15 K. *J Chem Eng Data* 2000;45:391–4. <https://doi.org/10.1021/je990281u>.
- [59] Herreros JM, Schroer K, Sukjit E, Tsolakis A. Extending the environmental benefits of ethanol–diesel blends through DGE incorporation. *Appl Energy* 2015;146: 335–43. <https://doi.org/10.1016/j.apenergy.2015.02.075>.
- [60] Han SM, Kim JH, Kim DW. Evaluation of the electrochemical performance of a lithium-air cell utilizing diethylene glycol diethyl ether-based electrolyte. *J Electrochem Soc* 2014;161(6):A856–62. <https://doi.org/10.1149/2.022406jes>.
- [61] Carvalho PJ, Fonseca CHG, Moita MLCJ, Santos AFS, Coutinho JAP. Thermophysical properties of glycols and glymes. *J Chem Eng Data* 2015;60: 721–37. <https://doi.org/10.1021/acs.jced.5b00662>.
- [62] Machida H, Oba K, Tomikawa T, Esaki T, Yamaguchi T, Horizoe H. Development of phase separation solvent for CO<sub>2</sub> capture by aqueous (amine+ether) solution. *J Chem Thermodyn* 2017;113:64–70. <https://doi.org/10.1016/j.jct.2017.05.043>.
- [63] Machida H, Esaki T, Oba K, Tomikawa T, Yamaguchi T, Horizoe H. Phase separation solvent for CO<sub>2</sub> capture. *Energy Proc* 2017;114:823–6. <https://doi.org/10.1016/j.egypro.2017.03.1224>.
- [64] Liu F, Fang M, Yi N, Wang T. Research on alkanolamine-based physical–chemical solutions as biphasic solvents for CO<sub>2</sub> capture. *Energy Fuels* 2019;33:11389–98. <https://doi.org/10.1021/acs.energyfuels.9b02392>.
- [65] Machida H, Ando R, Esaki T, Yamaguchi T, Norinaga K. Modelling of CO<sub>2</sub> solubility in phase separation solvent composed of amine/ether/water system for CO<sub>2</sub> capture. *J Mol Liq* 2019;292:111411. <https://doi.org/10.1016/j.molliq.2019.111411>.
- [66] Tran KVB, Ando R, Yamaguchi T, Machida H, Norinaga K. Carbon dioxide absorption heat in liquid–liquid and solid–liquid phase-change solvents using continuous calorimetry. *Ind Eng Chem Res* 2020;59:3475–84. <https://doi.org/10.1021/acs.iecr.9b04672>.
- [67] Nakaoaka M, Tran KVB, Yanase K, Machida H, Norinaga K. Prediction of phase behavior of CO<sub>2</sub> absorbents using conductor-like screening model for real solvents (COSMO-RS): an approach to identify phase separation solvents of amine/ether/water systems upon CO<sub>2</sub> absorption. *Ind Eng Chem Res* 2020;59:19020–9. <https://doi.org/10.1021/acs.iecr.0c03233>.
- [68] Hung YC, Hsieh CM, Machida H, Lin ST, Shimoyama Y. Modeling of phase separation solvent for CO<sub>2</sub> capture using COSMO-SAC model. *J Taiwan Inst Chem E* 2022;135:104362. <https://doi.org/10.1016/j.jtice.2022.104362>.
- [69] Fu K, Liu C, Wang L, Huang X, Fu D. Performance and mechanism of CO<sub>2</sub> absorption in 2-ethylhexan-1-amine+glyme non-aqueous solutions. *Energy* 2021; 220:119735. <https://doi.org/10.1016/j.energy.2020.119735>.
- [70] Wu Z, Liu S, Gao H, Yin Q, Liang Z. A study of structure-activity relationships of aqueous diamine solutions with low heat of regeneration for post-combustion CO<sub>2</sub> capture. *Energy* 2019;167:359–68. <https://doi.org/10.1016/j.energy.2018.10.194>.
- [71] Luo Q, Yoon B, Gao H, Lv J, Hwang GS, Xiao M, et al. Combined experimental and computational studies on the promising monoethanolamine + 2-(ethylamino) ethanol + sulfolane biphasic aqueous solution for CO<sub>2</sub> absorption. *Chem Eng J* 2022;446:136674. <https://doi.org/10.1016/j.cej.2022.136674>.
- [72] Serna-Guerrero R, Sayari A. Modeling adsorption of CO<sub>2</sub> on amine-functionalized mesoporous silica. 2: kinetics and breakthrough curves. *Chem Eng J* 2010;161: 182–90. <https://doi.org/10.1016/j.cej.2010.04.042>.
- [73] Wanderley RR, Pinto DDD, Knuutila HK. From hybrid solvents to water-lean solvents—A critical and historical review. *Sep Purif Technol* 2021;260:118193. <https://doi.org/10.1016/j.seppur.2020.118193>.
- [74] Wang R, Zhao H, Qi C, Yang X, Zhang S, Li M, et al. Novel tertiary amine-based biphasic solvent for energy-efficient CO<sub>2</sub> capture with low corrosivity. *Energy* 2022;260:125045. <https://doi.org/10.1016/j.energy.2022.125045>.
- [75] Shi H, Naami A, Idem R, Tontiwachwuthikul P. Catalytic and non catalytic solvent regeneration during absorption-based CO<sub>2</sub> capture with single and blended reactive amine solvents. *Int J Greenh Gas Con* 2014;26:39–50. <https://doi.org/10.1016/j.ijggc.2014.04.007>.