

# Study on absorption and regeneration performance of EHA-DMSO non-aqueous absorbent for CO<sub>2</sub> capture from flue gas

Fanli Meng <sup>a,1</sup>, Kun Fu <sup>b,1</sup>, Xueli Wang <sup>a</sup>, Yixiao Wang <sup>a</sup>, Lemeng Wang <sup>a</sup>, Dong Fu <sup>a,\*</sup>

<sup>a</sup> Hebei Key Lab of Power Plant Flue Gas Multi-Pollutants Control, Department of Environmental Science and Engineering, North China Electric Power University, Baoding, 071003, PR China

<sup>b</sup> College of Chemistry and Materials Science, Longyan University, Longyan, 364012, PR China

## ARTICLE INFO

Handling Editor: Krzysztof (K.J.) Ptasinski

### Keywords:

Carbon dioxide  
Non-aqueous absorbent  
Absorption/desorption  
Water resistance  
Cycle

## ABSTRACT

In previous work by Fu et al. (2021, 2022), the performance of 2-ethylhexylamine (EHA) and diglyme absorbents for carbon dioxide (CO<sub>2</sub>) capture from flue gas was demonstrated. In this study, dimethyl sulfoxide (DMSO) was selected as a replacement for diglyme due to its high boiling point, low viscosity, and environmentally friendly properties. The optimization of the mass fraction resulted in a composition of 60 wt% EHA and 40 wt% DMSO, considering factors such as absorption capacity, absorption rate, and viscosity. At a desorption temperature of 373 K, the CO<sub>2</sub>-loaded EHA-DMSO exhibited a desorption efficiency of approximately 98 %. The estimation of desorption energy ( $E_t$ ) consumption, using the method of electric energy consumption, revealed that EHA-DMSO achieved approximately a 50 % reduction in  $E_t$  compared to the MEA (30 wt%) absorbent. Even with a water content of 10 %,  $E_t$  was reduced by around 40 %. Additionally, the absorbent demonstrated notable advantages in terms of water resistance and cycle performance. The advantages of environmental friendliness and easy availability of raw materials suggest that the EHA-DMSO absorbent holds a promising potential for broader application in the field of CO<sub>2</sub> capture from flue gas.

## 1. Introduction

Many CO<sub>2</sub> emissions will greatly influence global climate change, but in daily life and the social economy, fossil fuels still play a very important role, and the CO<sub>2</sub> produced by their combustion is inevitable, so the development of CO<sub>2</sub> capture technology is particularly important [1–3]. CO<sub>2</sub> capture technology is divided into pre-combustion capture, post-combustion capture, and oxygen-enriched combustion [4,5] and other types. Post-combustion capture technology has been commercialized and allows existing plants to be retrofitted more easily than other technologies [6–9]. One of the regularly used technologies is solvent absorption [10], in which organic amine absorbent capture technology is considered to be the most economical technology [11,12], and has been applied to coal-fired power plants, etc [13].

As a primary amine, Monoethanolamine (MEA) is typically used in an aqueous solution in a concentration ranging from 15 wt% to 30 wt%. Although MEA absorbent is widely used [14,15], its regeneration energy consumption is very high [16,17]. Reducing energy consumption can be achieved by developing new absorbents and improving process

equipment [18]. The development of new absorbents can be roughly divided into three directions, one is to find amines with better performance than MEA, and the other is to blend with different kinds of amines, in addition is the single-atom solution, which has been reported in a lot of research work [19–27]. By improving the performance of the amine and reducing the water content in the absorbent, better absorption can be ensured and the regeneration energy consumption can be lowered. However, the continuous reduction of water content can cause a rapid growth in viscosity, so the reduction of energy consumption is limited [28–30] and affects mass transfer. Generally, the mass fraction of amine does not exceed 50 %. In addition to this scheme, water was replaced by organic solvent to form a non-water absorbent or water-lean absorbent is another effective way to reduce energy consumption [31–39]. Despite the rapid progress in this field in recent years, the choice of organic solvents is still an important constraint, so far there is no report about the use of non-aqueous absorbents in the actual industrial flue gas CO<sub>2</sub> capture.

In practical industrial applications, the solvent is water, the regeneration temperature of the CO<sub>2</sub>-loaded absorbent is high, sometimes as

\* Corresponding author.

E-mail addresses: [fanlimengncepu@163.com](mailto:fanlimengncepu@163.com) (F. Meng), [fudong@tsinghua.org.cn](mailto:fudong@tsinghua.org.cn) (D. Fu).

<sup>1</sup> Fanli Meng and Kun Fu contributed equally to this work.

high as 393.15K [40], and a great amount of energy is consumed by the evaporation of water, so the energy consumption can be greatly decreased by selecting organic solvents with high boiling points [41]. In addition, solvent losses are not negligible, but the evaporation rate of solvents with low vapor pressure is slower [42]. Common organic solvents include ethanol [43], diethylene glycol monomethyl ether [44], ethylene glycol [45], N-methyl pyrrolidone [46], sulfolane [47], dimethyl sulfoxide (DMSO) [48], n-propanol [49], ethylene glycol monohexyl ether [50]. Ethylene glycol, DMSO, and diethylene glycol monomethyl ether, these organic solvents have common features of high boiling point and low vapor pressure, they are suitable for compounding with amine to develop new non-aqueous absorbents.

Fu et al. [36] studied the performance of CO<sub>2</sub> capture with non-aqueous solutions composed of EHA and diglyme, and found that the low viscosity of such absorbents is very conducive to the mass transfer of CO<sub>2</sub>. Their research showed that this kind of absorbent has the feature of a fast absorption rate, good absorption capacity, fast desorption rate, and smaller energy required during regeneration. also has excellent water resistance and cycle performance [37]. Nevertheless, the organic solvent diglyme is classified by the European Chemicals Agency (ECHA) as having reproductive toxicity [51] and therefore has certain drawbacks in terms of environmental friendliness. In this work, we chose DMSO, which has no reproductive toxicity, as an alternative solvent for diglyme. Compared with diglyme, DMSO has a higher boiling point (101.3 kPa, 462.19K [52]), a lower viscosity (298 K, 1.99 mPa s [53]), a lower saturated vapor pressure (298 K, 75Pa [54]) and a lower specific heat capacity (298 K, 1.86J/(g·K) [55]). Given the above physicochemical properties, we expect that if diglyme is replaced by DMSO and EHA is blended to form a non-aqueous absorbent, satisfactory absorption and desorption performances can also be obtained, and it is suitable for capturing CO<sub>2</sub> in the flue gas.

The ideal CO<sub>2</sub> absorbent should have the characteristics of strong absorption capacity, high absorption rate, high stability, low corrosion, high regeneration rate, high regeneration efficiency and low energy consumption and cost [36]. In addition, for non-aqueous or water-lean absorbents, it is particularly necessary to point out that in practical industrial applications, water vapor must exist [41,56], so when selecting such absorbents, water resistance should also be considered [57,58], that is, it is very necessary to evaluate their absorption and desorption performance in the existing of water. Fu et al. [37] showed that with the growing water content in EHA-diglyme solutions, the absorption and desorption will be severely affected, and the regeneration energy consumption will be higher. As for the water content range, Fu et al. [37] considered 0–10 % since there was no specific case of industrial application. They believed that this range is sufficient to explain the influence of water content.

Therefore, the main contents of this work are: (1) constructing DMSO-EHA non-aqueous absorbents, (2) optimizing the composition of DMSO and EHA in absorbents using the experimental results of absorption amount, absorption rate and viscosity, to screen out absorbents with low viscosity and excellent absorption performance, (3) measuring the desorption performance, water resistance, cycle performance and energy consumption, comparing these important parameters with 30 wt % MEA absorbent such as. On this basis, the absorption performance and the desorption performance of DMSO-EHA absorbent and its industrial application potential will be expounded.

## 2. Materials and methods

### 2.1. Materials

The chemicals used in this work are detailed in Table 1.

### 2.2. Absorption and desorption

In a three-necked flask, absorption and desorption experiments were

**Table 1**  
Chemicals description.

Chemicals	CAS No.	Purity <sup>a</sup>	Molecular structures	Source
Ethanolamine	141-43-5	≥99 %		Aladdin Reagent
2-ethylhexan-1-amine	104-75-6	≥99 %		Macklin Reagent
Dimethyl sulfoxide	67-68-5	>99.8 %		Macklin Reagent
Water	7732-18-5	Electrical resistivity>15 MU cm at T = 298 K	—	Heal Force ROE -100 apparatus

<sup>a</sup> The purity is reported in mass percent and stated by the supplier.

executed, and the specific experimental steps were shown in the literature [34]. In this work, the total mass of the absorbent was 30 g, the temperature of the absorption experiment was 313 K, and the absorption time was 7200 s. In the absorption process, the gas composition was 30 ml/min CO<sub>2</sub> + 170 ml/min N<sub>2</sub>. The temperature of desorption experiments was divided into three temperatures: 363K, 368K and 373K, and the longest desorption time was not more than 5400 s. During desorption, 200 ml/min N<sub>2</sub> was used to assist purging.

The absorption rate R<sub>ab</sub>(mol/kg·s) defined by equation (1):

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

in which Q<sub>CO<sub>2</sub></sub><sup>in</sup> and Q<sub>N<sub>2</sub></sub><sup>in</sup> are the CO<sub>2</sub> and N<sub>2</sub> volume flows at inlet (ml/s), x<sub>CO<sub>2</sub></sub><sup>out</sup> is the CO<sub>2</sub> concentration measured by the instrument, T<sub>s</sub> and T<sub>e</sub> are the standard temperature and experimental temperature (K); P<sub>s</sub> and P<sub>e</sub> are the standard pressure and experimental pressure (kPa).

The CO<sub>2</sub> absorption amount(m<sub>m,ab</sub>, mol/kg) is defined by equation (2):

$$m_{m,ab} = \sum_0^{7200} R_{ab} \quad (2)$$

The desorption rate R<sub>de</sub> (mol/kg·s) can be calculated from equation (3):

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

The CO<sub>2</sub> desorption amount(m<sub>m,de</sub>, mol/kg) is defined by equation (4):

$$m_{m,de} = \sum_0^{5400} R_{de} \quad (4)$$

The desorption efficiency( $\eta$ , %) can be calculated by equation (5):

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

### 2.3. Fitting of the time-dependent absorbance/desorption amount

The modified Avrami model [59] can be used to correlate and predict the absorbance versus time relationship as shown in equation (6):

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

in which m<sub>t,exp</sub> is the experimental absorption amount at a given time from experiments, m<sub>m,cal</sub> is the CO<sub>2</sub>-saturated absorption amount by calculations, k is the Avrami model rate constant (s<sup>-1</sup>) and n is the Avrami model index.

## 2.4. Calculation of activation energy

The activation energy ( $E_a$ ) is obtained by fitting the rate constants ( $k$ ) at different temperatures by the Arrhenius equation (Eq. (6)):

$$k = A \times \exp\left(\frac{-E_a}{RT}\right) \quad (7)$$

in which  $A$  ( $s^{-1}$ ) is the Arrhenius pre-exponential factor,  $E_a$  (kJ/mol) is the activation energy, and  $R$  ( $8.3145 \times 10^{-3}$  kJ/(mol·K)) is the universal ideal gas constant.

## 2.5. Desorption energy consumption

Desorption energy consumption  $E_t$  (GJ/tonCO<sub>2</sub>) can be determined from equation (8) [31]:

$$E_t = E_{de} \times 3600 / M_{de} \quad (8)$$

wherein  $E_{de}$  is the electric energy consumption (kW·h) of the device measured by the electricity meter during the desorption experiments, and  $M_{de}$  is the CO<sub>2</sub> desorption quality (g).

The relative energy consumption ( $E_{re}$ , %) is shown in formula (9) [31]:

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

wherein the  $E_{EHA}$  is the CO<sub>2</sub> desorption energy consumption (GJ/tonCO<sub>2</sub>) corresponding to the EHA + DMSO solution;  $E_{MEA}$  is the desorption energy consumption (GJ/ton CO<sub>2</sub>) for a 30 wt% MEA.

## 3. Results and discussion

### 3.1. Absorption performance and composition optimization

Variations in the composition of the solution can result in different absorption and desorption performances. Referring to the previous work [36,37], we comprehensively considered the absorption amount, the absorption rate, and the viscosity of the CO<sub>2</sub>-unloaded and the CO<sub>2</sub>-loaded absorbents, and determined an appropriate absorbent composition. The flue gas first undergoes desulfurization and denitrification, so the temperature in flue gas will be relatively low. From the current carbon dioxide capture process point of view, the absorption tower temperature is generally about 313 K. Therefore, we calculated the CO<sub>2</sub> absorption performance of EHA-DMSO absorbents with different mass fractions of EHA and DMSO at 313K, and compared it

with the commercial 30 wt% MEA absorption process. At the same time, the CO<sub>2</sub>-unloaded and CO<sub>2</sub>-loaded EHA-DMSO absorbents of viscosities were measured at this temperature.

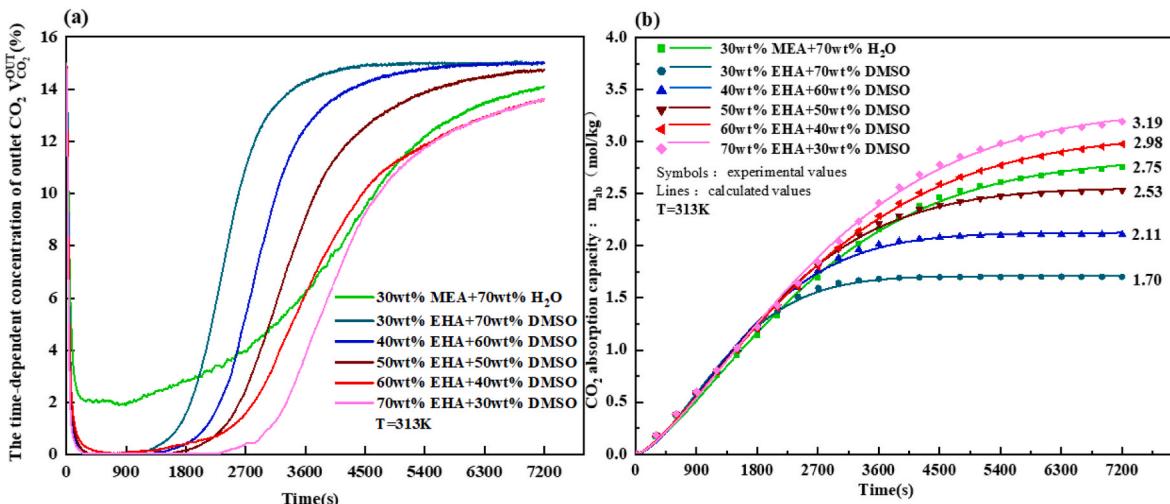
### 3.1.1. Experimental determination of absorption rate and absorption quantity

The dynamic absorption rate and absorption amount of CO<sub>2</sub> in various mass fractions ( $w_{EHA} = 0.3\text{--}0.7$ ) of EHA and DMSO are shown in Fig. 1. Fig. 1 (a) is impressive that 30 wt% MEA aqueous solution can not reduce the CO<sub>2</sub> outlet concentration to 0, but when the EHA mass fraction ( $w_{EHA}$ ) is between 0.3 and 0.7, the EHA-DMSO absorbent can maintain the CO<sub>2</sub> outlet concentration to 0 in a long time range. It implies that the CO<sub>2</sub> retention efficiency of EHA-DMSO is bigger than that of 30 wt% MEA water solution. As the  $w_{EHA}$  increases, the time for the absorbent to be penetrated becomes longer and longer, indicating that the CO<sub>2</sub> absorption amount increases. In Fig. 1 (b), when the  $w_{EHA}$  is from 0.4 to 0.7, the absorption amount(mol/kg) increases from 2.11 to 3.19. When  $w_{EHA} = 0.6$  and 0.7, the absorption capacity of EHA-DMSO for CO<sub>2</sub> is higher than that of 30 wt% MEA water solution. It should be noted that although DMSO has a certain physical solubility for CO<sub>2</sub>, its absorption capacity is not enough, the chemical reaction between EHA and CO<sub>2</sub> enhances the CO<sub>2</sub> absorption capacity of the solution.

### 3.1.2. Prediction of absorption rate and absorption amount

The absorption rate of EHA-DMSO for CO<sub>2</sub> can be expressed by various methods. For example, the apparent absorption rate (dM/dt) may express the absorption rate at a particular time. Besides, the Avrami model can be used to simulate the time-dependent absorption amount, and after obtaining the model parameters, the Avrami model can simultaneously predict the important parameters such as absorption capacity and absorption rate constant, in Table 2. The Avrami model rate constant  $k$  can also characterize the absorption rate of CO<sub>2</sub> by EHA-DMSO. The  $k$  became smaller with the increase of the absorption amount, which may be because the more CO<sub>2</sub> is absorbed, the viscosity of the absorbent also gradually increases, this makes the mass transfer of CO<sub>2</sub> molecules from the gas phase to the liquid phase more difficult. For this reason, the decrease in the rate constant with increasing  $w_{EHA}$  in Table 2 can be reasonably explained. The activation energy ( $E_a$ ) of CO<sub>2</sub> absorption in the 30 wt% MEA aqueous solution and 60 wt% EHA + 40 wt% DMSO solution derived from  $k_A$  are 2.9 kJ/mol and 1.6 kJ/mol, respectively. This suggests that the energy barrier that needs to be overcome for the two absorbents is not much different, the result is corroborated by the actual reaction rate relationships.

In addition, we also compared the absorption capacity (mol/kg) and absorption rate constant ( $k \times 10^4$ ) of two non-aqueous absorbents, i.e.,



**Fig. 1.** (a) The time-dependent CO<sub>2</sub> outlet concentration; (b) The time-dependent CO<sub>2</sub> absorption amount.

**Table 2**  
Fitted parameters of Avrami kinetic model.<sup>a,b</sup>

absorbent composition	parameters				
	$m_{s,exp}$	$m_{s,cal}$	$k \times 10^3$	n	$R^2$
30 wt% MEA +70 wt% H <sub>2</sub> O	2.75	2.85	0.35	1.40	0.999
30 wt% EHA +70 wt% DMSO	1.70	1.71	0.64	1.60	0.998
40 wt% EHA +60 wt% DMSO	2.11	2.13	0.52	1.56	0.998
50 wt% EHA +50 wt% DMSO	2.53	2.56	0.43	1.48	0.999
60 wt% EHA +40 wt% DMSO	2.98	3.08	0.35	1.37	0.999
70 wt% EHA +30 wt% DMSO	3.19	3.32	0.33	1.42	0.999

<sup>a</sup>  $m_{s,exp}$  (mol/kg) is the values from experiments at 7200s,  $m_{s,cal}$  (CO<sub>2</sub>/kg) is the CO<sub>2</sub> absorption capacity saturation value from calculations,  $k(s^{-1})$  represents the Avrami kinetic model absorption rate constants, n represents the Avrami model exponent.

<sup>b</sup> Temperature (T, 313 K); Pressure (P, 101 kPa).

60 wt% EHA + 40 wt% DMSO in this work and 70 wt% EHA + 30 wt% diglyme in the work of Fu et al. [36,37]. The maximum absorption capacity values were 2.98 and 2.91, and the rate constants were 3.4 and 3.9, respectively, indicating that the absorption capacity values of EHA-DMSO were larger, but the absorption rate was slightly smaller.

### 3.1.3. Optimization of absorbent composition

The experimental results in the previous section show that the CO<sub>2</sub> absorption amount by 70 wt% EHA +30 wt% DMSO is 3.19 mol/kg, which is slightly higher than that by 60 wt% EHA +40 wt% DMSO, but the rate constant is slightly smaller. How to determine an appropriate composition is an important topic. We introduced the viscosity data after absorbing CO<sub>2</sub>. The viscosity values of the absorbent before and after CO<sub>2</sub> absorption, are shown in Table 3. In Table 3, the viscosity of the absorbent containing 70 wt% EHA after absorbing CO<sub>2</sub> is as high as 84.2 mPa s, which is much higher than that of the absorbent containing 60 wt% EHA. The mass fraction of EHA was set to 60 wt% in consideration of increasing the difficulty of mass transfer due to excessively high viscosity. In the following sections, unless otherwise specified, during the desorption experiment, the mass fraction of EHA was 60 wt%.

### 3.2. Desorption performance

To further investigate the desorption performance of CO<sub>2</sub>-loaded EHA + DMSO absorbent, we measured the time-dependent CO<sub>2</sub> concentration at the outlet at 363K, 368K and 373K, and calculated the time-dependent desorption amount and desorption efficiency and other important parameters, and then compared to those of 30 % MEA absorbent, as shown in Fig. 2. The desorption process can be roughly classified as three parts: 1) In the initial stage, in addition to the CO<sub>2</sub>-rich solution, there is a part of residual CO<sub>2</sub> gas in the three-mouth flask, and the residual CO<sub>2</sub> gas will be discharged with N<sub>2</sub> at the beginning of desorption, causing the concentration of CO<sub>2</sub> to rise temporarily, resulting in a small peak in Fig. 2 (a); 2) With the rapid rise of the solution temperature, the CO<sub>2</sub> in the CO<sub>2</sub>-rich solution is rapidly desorbed, and the desorption rate continues to increase until reaching a maximum; 3) slowly desorb that residual firmly combined CO<sub>2</sub>, and slowly reduce the rate until the desorption is finished. In Fig. 2 (a), when the temperature is as high as 373K, even in the vicinity of 5400 s, the concentration of CO<sub>2</sub> at the outlet corresponding to the CO<sub>2</sub>-loaded 30 % MEA

**Table 3**

Viscosity values of the absorbent before and after CO<sub>2</sub> absorption. Temperature (T, 313K). Pressure (P,101 kPa).

Sorbents	$\eta$ (mPa·s)	
	CO <sub>2</sub> -free	CO <sub>2</sub> -rich
50 wt% EHA+50 wt% DMSO	1.29	23.9
60 wt% EHA+40 wt% DMSO	1.24	40.6
70 wt% EHA+30 wt% DMSO	1.12	84.2

absorbent is not 0, which means that the desorption has not been completed. In contrast, CO<sub>2</sub>-loaded EHA + DMSO absorbent can achieve similar results at 363K, which means that will save a great amount of energy consumption At 373K, complete desorption of the CO<sub>2</sub>-loaded EHA + DMSO absorbent was achieved in less than 5000 s. Part of the reason may be related to the small heat capacity of the absorbent and the very huge heat capacity of water. The desorption temperature of the solution was measured every 10 min, the results are also shown in Fig. 2 (a). The isobaric heat capacity of EHA + DMSO is small, so at the same desorption temperature (approximately equal heat input value), the actual temperature of the solution is much higher, which is very conducive to the desorption of CO<sub>2</sub>.

The influence of desorption temperature on the desorption amount of the CO<sub>2</sub>-loaded EHA + DMSO absorbent in Fig. 2 (b), the desorption amount gradually bigger, with the growth of desorption temperature, and no matter what the regeneration temperature is, the corresponding desorption amount of EHA + DMSO is much higher than that of 30 % MEA in the same time. In addition, the corresponding desorption amount of EHA + DMSO is very close at 368K and 373K. Therefore, from the perspective of energy consumption, cost and absorbent recycling, it may be better to select the desorption temperature of 368K than that of 373K, but this needs to be verified by practical engineering. In this work, we take the maximum desorption quantity and the maximum desorption efficiency as the goal to complete the follow-up experimental work.

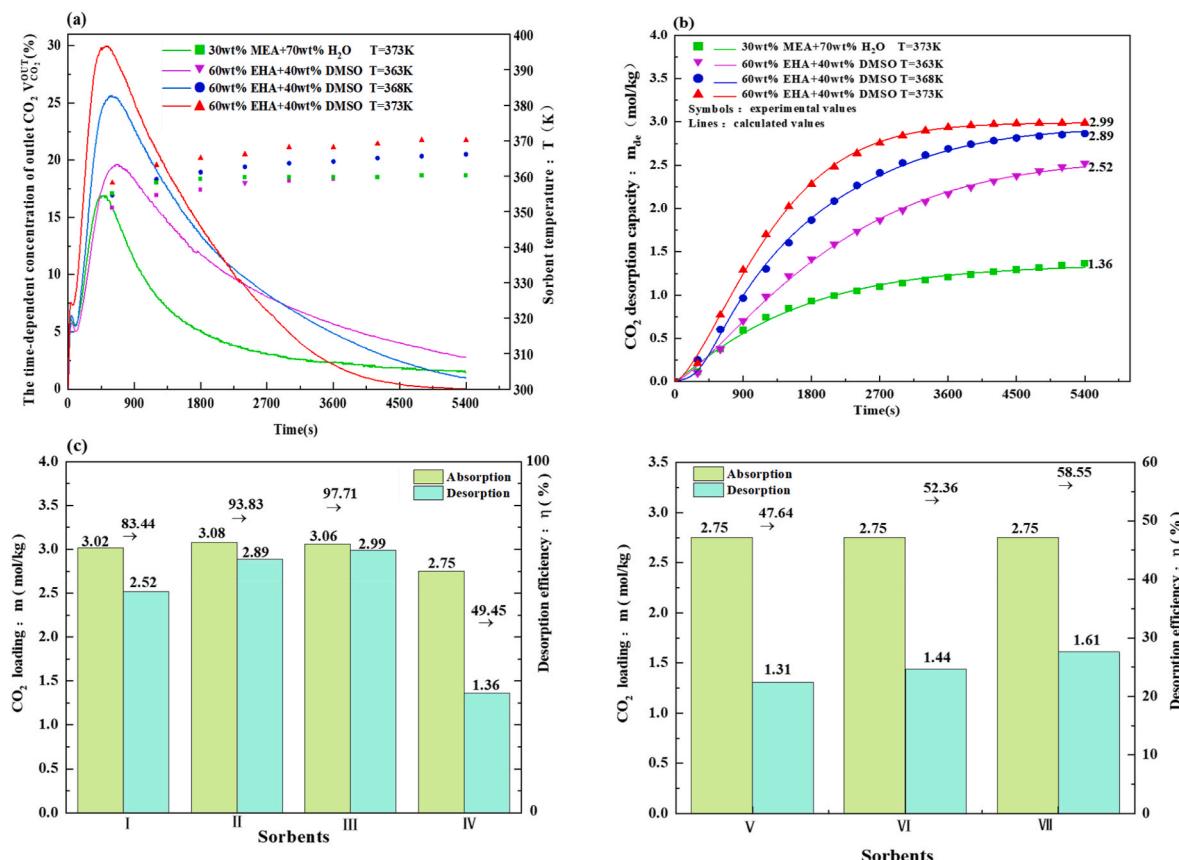
With the data in Fig. 2 (a) and 2 (b), we can calculate the desorption efficiency, as shown in Fig. 2 (c). At the same regeneration time (5400 s), the desorption efficiencies of EHA + DMSO absorbent were 83.44 %, 93.83 % and 97.71 % at 363K, 368K and 373K, respectively. The desorption efficiency gradually increases as the regeneration temperature increases. As can be seen in Fig. 2 (a), as the increasing of heating temperature, the actual temperature of the solution also becomes higher, so that the decomposition of the absorption product is more likely to occur. The regeneration efficiency was the highest at 373K, when the solution was almost completely desorbed.

As can be seen in Fig. 2 (d), when the desorption time of the CO<sub>2</sub>-loaded MEA absorbent was extended from 5400s to 9000s, an increase of only 0.13 mol/kg was observed in the desorption quantity. This suggests that at 373K, an increase in desorption time does not effectively enhance the desorption quantity. Potentially, this is because when the desorption time is 5400s, the CO<sub>2</sub> concentration at the outlet of the desorption device is only 1.18 %. With an increase in desorption time, the driving force gradually diminishes, causing the concentration of desorbed CO<sub>2</sub> to gradually decline with time. Therefore, the effect of further increasing the desorption time on enhancing the desorption quantity is very limited. To enhance the driving force of desorption, the oil bath temperature was increased to 383K. With the support of N<sub>2</sub> purging, a desorption efficiency of 58.55 % was achieved when the desorption time was 5400s. This is attributed to the need for CO<sub>2</sub> molecules in the absorption product, amine salt, to overcome the energy barrier of forming strong chemical bonds with the amine to transition from the liquid phase into the gas phase. An increase in the desorption temperature can raise the thermal energy of CO<sub>2</sub> molecules, aiding in overcoming these energy barriers and thus improving desorption efficiency. These findings indicate that desorption temperature significantly impacts desorption effectiveness, while merely extending desorption time does not necessarily lead to a substantial increase in desorption quantity.

It should be noted that the corresponding desorption amount (mol/kg) and desorption rate constant ( $\times 10^4$ ) of EHA + DMSO absorbent were 2.99 and 7.2 as shown in Table 4, respectively, while those of EHA + diglyme absorbent were 2.88 and 7.7 [37], respectively. As a result, the desorption performance of the two non-aqueous absorbents is very close.

### 3.3. Water resistance

The flue gas constantly contains a considerable amount of water,



**Fig. 2.** (a) The time dependent  $\text{CO}_2$  outlet concentration; (b) The time dependent  $\text{CO}_2$  desorption amount; (c) The desorption efficiency of  $\text{CO}_2$  loaded sorbent (absorption at 313 K for 7200s, I: 60 wt% EHA+ 40 wt% DMSO, desorption at 363 K for 5400s; II: 60 wt% EHA+ 40 wt% DMSO, desorption at 368 K for 5400s; III: 60 wt% EHA+ 40 wt% DMSO, desorption at 373 K for 5400s; IV: 30 wt% MEA+70 wt%  $\text{H}_2\text{O}$ , desorption at 373 K for 5400s; (d) The desorption efficiency of  $\text{CO}_2$  loaded 30 wt% MEA sorbent (absorption at 313 K for 7200s, V: desorption at 373 K for 5400s; VI: desorption at 373 K for 9000s; VII: desorption at 383 K for 5400s.).

**Table 4**  
Fitted parameters of Avrami kinetic model for desorption.<sup>a</sup>

Sorbents	T(K)	$k \times 10^3$	$n$
60 wt% EHA + 40 wt% DMSO	363	0.45	1.30
	368	0.57	1.35
30 wt% MEA + 70 wt% $\text{H}_2\text{O}$	373	0.72	1.43
	373	0.61	1.01

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

especially in coal-fired flue gas, the water vapor content can even reach 6 %. As the amine and the organic solvent have a certain solubility to water, in the absorption process, the non-aqueous absorbent certainly dissolves a small amount of water and forms a water-lean absorbent, thereby affecting the absorption and desorption of  $\text{CO}_2$ . To verify the water resistance of the EHA + DMSO absorbent, in this section, we tested the effect of 5 wt% and 10 wt% water on absorption and desorption, as shown in Figs. 3 and 4.

### 3.3.1. Effect of water content on absorbency

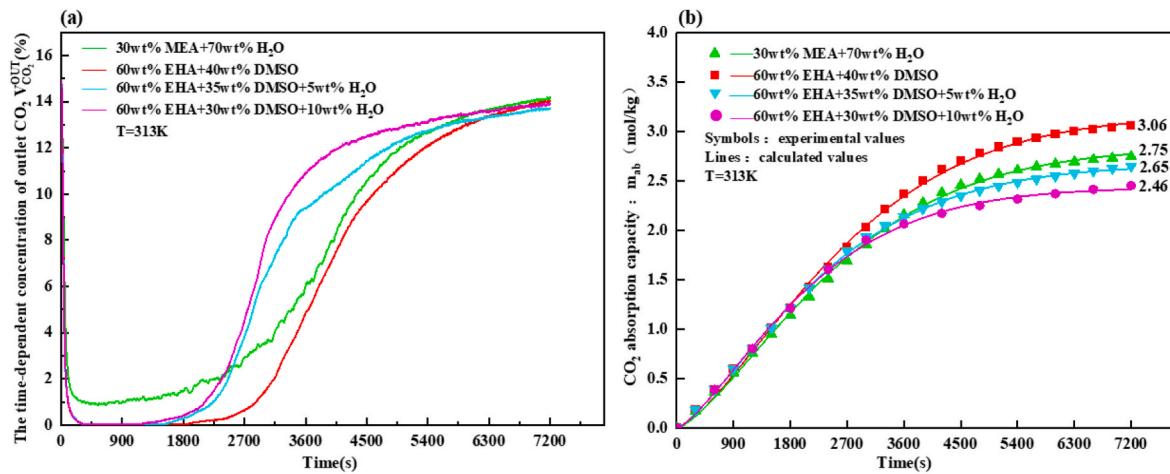
As shown in Fig. 3 (a), the EHA + DMSO absorbents with water contents of 0 wt%, 5 wt% and 10 wt% can nearly capture  $\text{CO}_2$  in a time range of 300 s–1200 s. When the water content is increasing, the penetration time of EHA + DMSO decreases, which indicates that water is not conducive to the absorption of  $\text{CO}_2$  of EHA + DMSO. On the one hand, by hydration, the nucleophilicity in the amino group of EHA is weakened, which is not conducive to the absorption of  $\text{CO}_2$ . This adverse effect is more fully manifested when the EHA molecule is insufficient.

Another reason may be that after adding water, the absorbent viscosity value increases, and high viscosity has a bad effect on the mass transfer of  $\text{CO}_2$ . In contrast, the aqueous MEA water solution does not completely absorb  $\text{CO}_2$  in this time range.

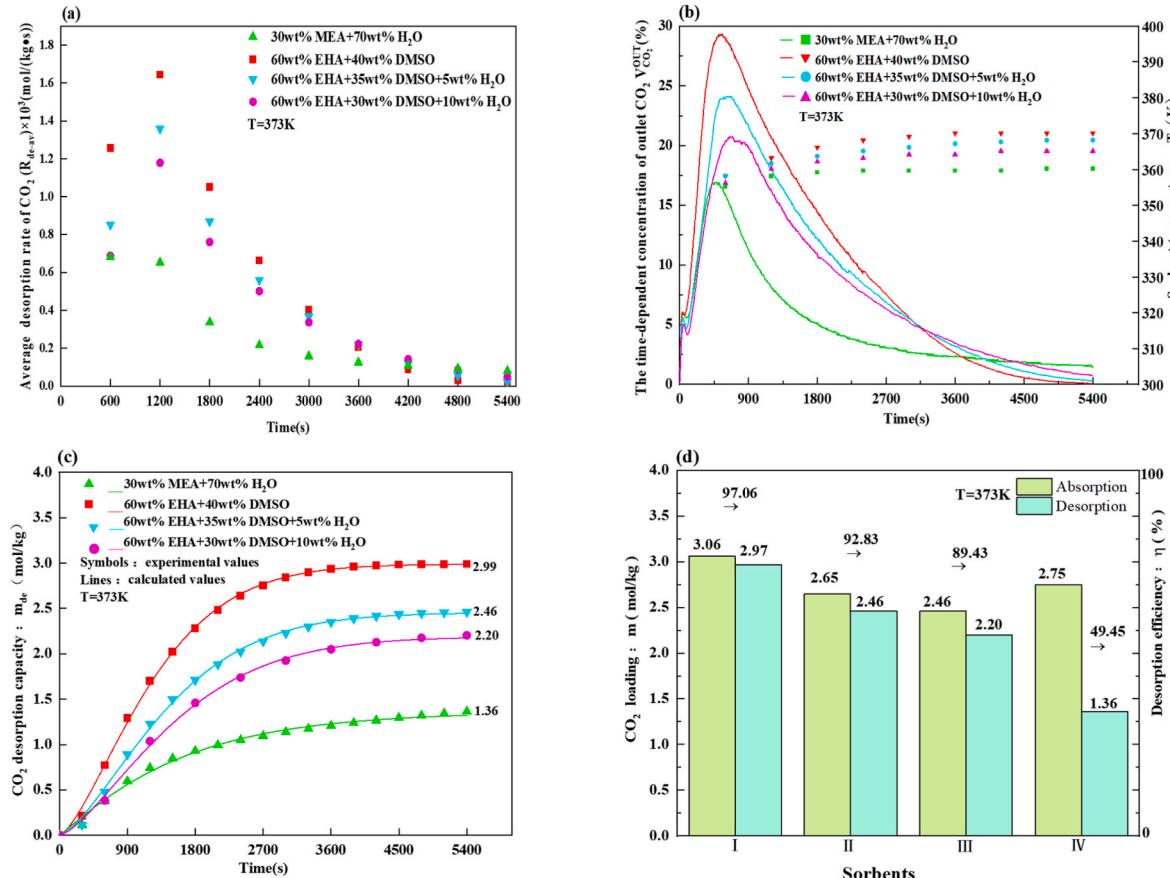
As shown in Fig. 3 (b), the absorbents with water contents of 0 wt%, 5 wt% and 10 wt% had almost the same absorption amount in the time range of 300 s–1200 s, while at 7200 s, the absorption amounts were significantly different, being 3.06 mol/kg, 2.65 mol/kg and 2.46 mol/kg. The reason for the decrease in the amount is as described above, as the absorption proceeds, the number of EHA molecules becomes less and less, and the adverse effect of the nucleophilicity of the amino group being weakened by hydration is more and more fully reflected. At the same time, with the water added, the increase of hydrogen bonds and the dissolution of  $\text{CO}_2$  might lead to the increase of viscosity, thus increasing the difficulty of  $\text{CO}_2$  mass transfer.

### 3.3.2. Effect of water content on desorption performance

The effect of water content on desorption is similar to that of absorption. As shown in Fig. 4 (a), the increase in water content could lead to a decrease in the desorption rate. Although the desorption rate decreased slightly, it was still higher than that of  $\text{CO}_2$ -loaded 30 wt% MEA water solution even when the water content was 10 %, that is to say, the desorption performance of EHA + DMSO was more excellent. In Fig. 4 (b), the desorption amount of  $\text{CO}_2$ -loaded EHA + DMSO reaches the maximum and is much higher than 30%MEA when the desorption time is 900 s. The  $\text{CO}_2$  desorbed at 5400 s was almost 0, while the  $\text{CO}_2$  concentration corresponding to 30 % MEA was still higher than 2 %. This indicated that the desorption rate of EHA + DMSO was faster than that of 30 % MEA at the same time. This phenomenon may also be



**Fig. 3.** (a) The time-dependent CO<sub>2</sub> outlet concentration; (b) The time-dependent CO<sub>2</sub> absorption amount.



**Fig. 4.** Comparison of non-aqueous and water-lean absorbent (a) The average apparent desorption rate of CO<sub>2</sub> (R<sub>de-av</sub>); (b) The time-dependent CO<sub>2</sub> outlet concentration; (c) The time-dependent CO<sub>2</sub> desorption amount; (d) The desorption efficiency: Sorbent I: 60 wt% EHA+ 40 wt% DMSO; II: 60 wt% EHA+ 35 wt% DMSO+ 5 wt% H<sub>2</sub>O; III: 60 wt% EHA+ 30 wt% DMSO+ 10 wt% H<sub>2</sub>O; IV: 30 wt% MEA+70 wt% H<sub>2</sub>O.

related to the actual temperature of the solution, as shown in Fig. 4(a), under the same heating temperature conditions, the smaller the water content, the actual temperature of the solution becomes higher, which is more conducive to the desorption of CO<sub>2</sub>.

Fig. 4 (c) and 4 (d) are comparisons of the desorption amount and desorption efficiency of four absorbents, respectively. An increase in water content is not conducive to the desorption of the CO<sub>2</sub>-loaded EHA-DMSO. For instance, as shown in Fig. 4 (d), the desorption efficiency can reach 97.06 % when it is water-free. When the water content is 10 %, the

desorption efficiency decreases to 89.43 %. The main reason might be that the heat capacity of water is too large. When the water content increases, the actual desorption temperature deviates from the heating temperature (373K). When there is no water, the desorption temperature is around 370K. When the water content is 10 %, it drops to around 365K. Therefore, it is not conducive to the breaking of the EHA-CO<sub>2</sub> chemical bond, which is not beneficial to regeneration. Additionally, water (polarity, dielectric constant = 78.30 at 298 K) is much more polar than DMSO (dielectric constant = 49.04 at 298 K [60]). Therefore, it can

be inferred that water has stronger solvation effects on the absorption product compared to DMSO. This leads to increased stability of the absorption product in the system with higher water content, which is unfavorable for absorption agent regeneration.

But the desorption efficiency of EHA + DMSO absorbent at 5 % and 10 % water content is still much higher than that of 30 % MEA water solution which is similar to that of EHA-diglyme absorbent reported by Fu et al. [37], although their desorption efficiency was 2 % higher than the values reported in this work. The reason for the easier desorption of CO<sub>2</sub>-loaded non-aqueous absorbents may be that, from a molecular perspective, the hydrogen bonds of water molecules are less likely to break or move due to temperature increase than the looser, weaker dipole-dipole bonds of organic solvents [61].

### 3.4. Desorption energy consumption

Desorption energy consumption is considered to be one of the key indicators to evaluate the applicability of absorbent. During the desorption process, we metered the energy consumption every 10 min, as shown in Fig. 5. The energy consumption was calculated with the relevant data, and the values are shown in Table 5. With the increase of desorption time, the lower electric energy consumption ( $E_c$ ) and the higher CO<sub>2</sub> desorption amount ( $M_{de}$ ) lead to the lowest energy consumption of non-aqueous absorbent. With the growing water content, the corresponding energy consumption of EHA + DMSO increased slightly, but the overall energy consumption was still lower than that of 30%MEA. This comparison further demonstrates the potential of EHA + DMSO as an energy-efficient alternative for CO<sub>2</sub> capture.

Under aqueous conditions, the reaction of MEA with CO<sub>2</sub> generates ionic species. These include charged carbamate anions, bicarbonate anions, and protonated amine cations. As a strong polar solvent, water significantly stabilizes these charged entities and enhances their stability via hydrogen bonding. In contrast, DMSO, at 298K, has a dielectric constant of 49.04 [60]. This value is significantly lower than water's dielectric constant of about 78.30 at the same temperature. This suggests that DMSO's solvation effect is weaker than that of water, inducing less stability for the absorption products in an anhydrous solution. Thus, when DMSO is the solvent, its reduced polarity weakens the solvation effect caused by electrostatic interactions. This helps to improve desorption performance and decrease energy consumption during regeneration. Additionally, within EHA molecules, steric hindrance around the amine can inhibit interactions between absorption products. This factor helps lower the stability of absorption products, leading to further reduction in regenerative energy consumption.

### 3.5. Cycle performance

CO<sub>2</sub> capture in the industry is usually an integrated process, and the absorbent needs to be repeatedly used in the absorption tower and desorption tower, so one of the necessary indicators to evaluate whether the absorbent is good or not is the ability to reuse. The desorption efficiency after multiple cycles is shown in Fig. 6.

As shown in Fig. 6 (a), the non-aqueous absorbent exhibited excellent stability, and after 5 cycles, the desorption efficiency remained above 96 %. For the absorbent with 5 wt% water content (1.50g), the CO<sub>2</sub> desorption efficiency of the first cycle is 92.83 % at 5400s. In the second cycle, the desorption efficiency is 95.39 % when the desorption time is 5400 s, which is not far from that of a non-aqueous absorbent. This means that after the first cycle, the water in the absorbent is essentially completely evaporated and lost. Because of this, the 1.50 g water was put into the absorbent before cycles 3, 4 and 5. Furthermore, for the same reason, before the beginning of the 4th and 5th cycles, 3.00 g of water was replenished to the absorbent containing 10 % by weight of water.

After the 5th cycle, the desorption efficiencies of the absorbents with 5 wt% and 10 wt% water content were 89.72 % and 83.08 %, respectively, which were indeed slightly lower than those after the first cycle (92.83 % and 89.43 %). During the cycling experiment, the EHA and the DMSO have some loss and evaporation, but these two substances have not been supplemented, which will have a negative impact on the desorption efficiency. In this work, that means the true desorption efficiency should be higher than the previously reported values.

In general, although the CO<sub>2</sub> uptake of the absorbent at the three water contents decreased slightly with the increase of the cycle number, possibly due to evaporation loss of the solution and amine degradation at high temperatures, the desorption efficiency of the non-aqueous absorbent remained above 96 % after 5 cycles, and the desorption efficiency of the 5 wt% H<sub>2</sub>O absorbent remained above 89 %. The desorption efficiency of the absorbent with 10 wt% H<sub>2</sub>O is kept above 83 %. That is to say, both non-aqueous absorbents and water-lean absorbents have stable regeneration abilities and can be reused after multiple absorption and desorption, which is one of the most popular properties in industrial applications.

Finally, a simple comparison of the regeneration efficiency and energy consumption between the EHA + DMSO absorbent developed in this work and the EHA + diglyme absorbent developed by Fu et al. [34, 35] is made. The water contents of the two absorbents are all taken as 0 wt%, 5 wt% and 10 wt%. After the first absorption-desorption cycles, the desorption efficiencies of the former were 97.0 %, 92.8 % and 89.4 %, respectively, while those of the latter were 99.0 %, 97.5 % and 86.4 %,

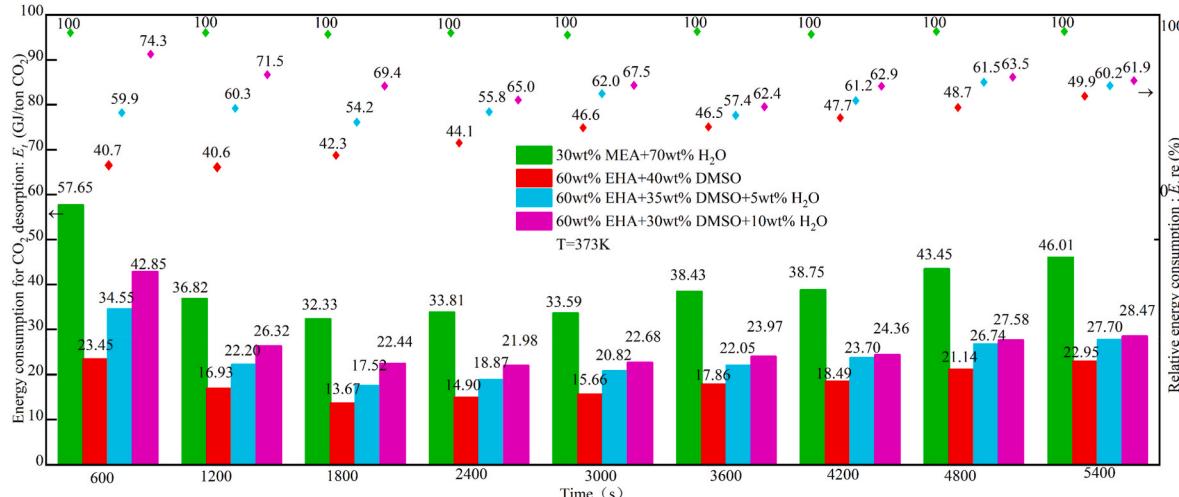
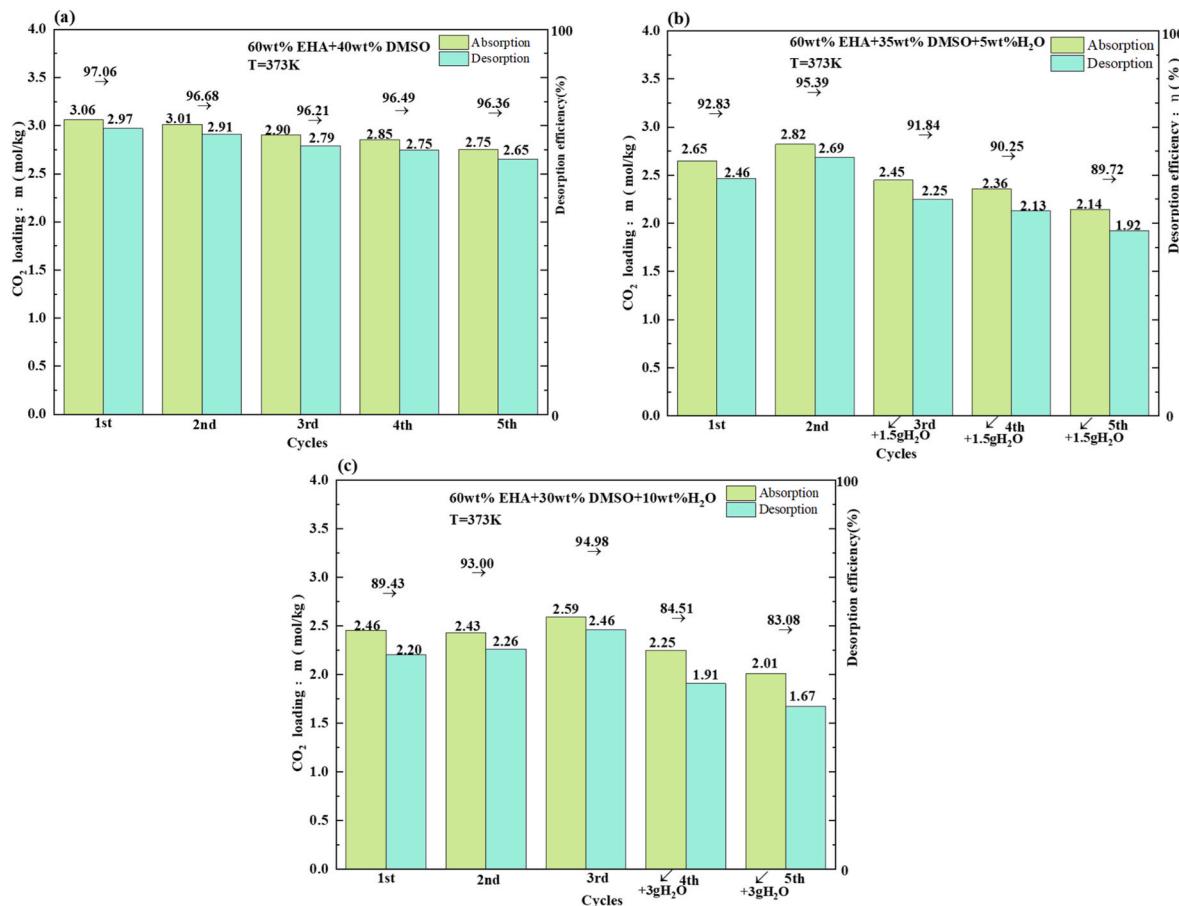


Fig. 5. The comparison of the CO<sub>2</sub> desorption energy consumption values ( $E_c$ ) based on electricity consumption, and the relative energy consumption values ( $E_{re}$ ).

**Table 5**

The electricity consumption and the desorption amount of CO<sub>2</sub> (M<sub>de</sub>). Sorbents: I: 30 wt% MEA+70 wt% H<sub>2</sub>O; II: 60 wt% EHA +40 wt% DMSO; III: 60 wt% EHA +35 wt % DMSO +5 wt% H<sub>2</sub>O; IV: 60 wt% EHA +30 wt% DMSO +10 wt% H<sub>2</sub>O.

sorbents		Time(s)								
		600	1200	1800	2400	3000	3600	4200	4800	5400
I	E <sub>blank</sub> (kW·h)	0.012	0.023	0.036	0.048	0.060	0.071	0.084	0.095	0.107
	E <sub>total</sub> (kW·h)	0.020	0.033	0.047	0.061	0.074	0.088	0.102	0.116	0.130
	E <sub>c</sub> (kW·h)	0.008	0.010	0.011	0.013	0.014	0.017	0.018	0.021	0.023
II	M <sub>de</sub> (g)	0.50	0.98	1.22	1.38	1.50	1.59	1.67	1.74	1.80
	E <sub>total</sub> (kW·h)	0.018	0.033	0.047	0.062	0.076	0.090	0.104	0.118	0.132
	E <sub>c</sub> (kW·h)	0.006	0.010	0.011	0.014	0.016	0.019	0.020	0.023	0.025
III	M <sub>de</sub> (g)	0.92	2.13	2.90	3.38	3.68	3.83	3.89	3.92	3.92
	E <sub>total</sub> (kW·h)	0.018	0.033	0.047	0.062	0.077	0.090	0.105	0.119	0.132
	E <sub>c</sub> (kW·h)	0.006	0.010	0.011	0.014	0.017	0.019	0.021	0.024	0.025
IV	M <sub>de</sub> (g)	0.63	1.62	2.26	2.67	2.94	3.10	3.19	3.23	3.25
	E <sub>total</sub> (kW·h)	0.018	0.033	0.048	0.062	0.076	0.089	0.103	0.117	0.130
	E <sub>c</sub> (kW·h)	0.006	0.010	0.012	0.014	0.016	0.018	0.019	0.022	0.023
	M <sub>de</sub> (g)	0.50	1.37	1.93	2.29	2.54	2.70	2.81	2.87	2.91



**Fig. 6.** In Five absorption-desorption cycles, the variations of CO<sub>2</sub> absorption and desorption amount in the three different EHA + DMSO solutions and the desorption efficiency of the three solutions.

respectively. In terms of the estimated regeneration energy consumption based on electric energy consumption, we compared it in the form of relative energy consumption, that is, the actual energy consumption after 3600 s of regeneration divided by the energy consumption corresponding to 30 wt% MEA, the former were 47 %, 57 % and 62 % respectively, while the latter were 20 %, 25 % and 45 %. It can be seen from the comparison that the former has a slight advantage in regeneration efficiency, but the energy consumption of the former is much higher than that of the latter, which is a very puzzling phenomenon. It sounds reasonable that the energy consumption of EHA-DMSO should be relatively small because the heat capacity of DMSO is slightly less than

that of diglyme and the regeneration temperature is the same, but the fact is just the opposite. It may be related to the complex molecular configuration of DMSO and the linear molecular configuration of diglyme, or it may be caused by equipment or environmental inconsistencies, such as we do not have particularly good thermal insulation equipment or cold and heat exchange, indoor temperature and humidity are different in different seasons, and so on. We will further study the reasons for this difference in the future.

#### 4. Conclusion

Non-aqueous absorbents show excellent absorption and regeneration performance in the CO<sub>2</sub> capture process, and the energy consumption is very low, so it is a topic worthy of study. But the choice of a suitable organic solvent is not a particularly simple matter. From the point of view of environmental friendliness and easy availability of raw materials, we chose the so-called universal solvent DMSO to replace diglyme which we chose in the previous work [36,37], and blended it with EHA to form a non-aqueous absorbent. According to the results, the CO<sub>2</sub> absorption capacity and absorption rate, the viscosity of both CO<sub>2</sub>-unloaded and CO<sub>2</sub>-loaded EHA-DMSO solutions, and the mass fractions of EHA and DMSO were optimized. On this basis, we verified that this absorbent has good desorption performance, water resistance and low regeneration energy consumption. When the desorption temperature is set at 373K, the desorption efficiency of the CO<sub>2</sub>-loaded non-aqueous absorbent is as high as 97 %, and the regeneration energy consumption is only about half of that of 30 % MEA. Even if 10 % of water is dissolved, the desorption efficiency is still above 83 % after five absorption-desorption cycles, and the regeneration energy consumption is only about 60 % of that of 30 % MEA. Whether from the absorption capacity, absorption rate, desorption efficiency, desorption rate point of view, or from the regeneration energy point of view, compared with the traditional 30 % MEA absorbent, EHA-DMSO absorbent has significant advantages. These advantages make it become a very promising prospect in the field of CO<sub>2</sub> capture from flue gas.

#### CRediT authorship contribution statement

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

#### 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.

#### Data availability

Data will be made available on request.

#### Acknowledgments

The authors appreciate the financial support from the National Natural Science Foundation of China (No. 51776072).

#### References

- [1] Zoghi AT, Rahimi A, Feyzi F, Jalili AH. Measuring and modeling equilibrium solubility of carbon dioxide in aqueous solution of dimethylaminoethanol and 3-methylaminopropylamine. *Thermochim. Acta* 2020;686:178565. <https://doi.org/10.1016/j.tca.2020.178565>.
- [2] Karadas F, Atilhan M, Aparicio S. Review on the use of ionic liquids (ILs) as alternative fluids for CO<sub>2</sub> capture and natural gas sweetening. *Energy Fuels* 2010; 24(11):5817–28. <https://doi.org/10.1021/ef1011337>.
- [3] Babu P, Linga P, Kumar R, Englezos P. A review of the hydrate based gas separation (HGBS) process for carbon dioxide pre-combustion capture. *Energy* 2015;85: 261–79. <https://doi.org/10.1016/j.energy.2015.03.103>.
- [4] Leung DYC, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. *Renew Sustain Energy Rev* 2014; 39:426–43.
- [5] Kim YE, Yun SH, Choi JH, Nam SC, Park SY, Jeong SK, et al. Comparison of the CO<sub>2</sub> absorption characteristics of aqueous solutions of Diamines: absorption capacity, specific heat capacity, and heat of absorption. *Energy Fuels* 2015;29(4):2582–90. <https://doi.org/10.1021/ef500561a>.
- [6] Haszeldine RS. Carbon capture and storage: how green can black be. *Science* 2009; 325(5948):1647–52. <https://doi.org/10.1126/science.1172246>.
- [7] Wang M, Lawal A, Stephenson P, Sidders J, Ramshaw C. Post-combustion CO<sub>2</sub> capture with chemical absorption: a state-of-the-art review. *Chem Eng Res Des* 2011;89(9):1609–24. <https://doi.org/10.1016/j.cherd.2010.11.005>.
- [8] Cho S, Yu H-R, Kim K-D, Yi KB, Lee Y-S. Surface characteristics and carbon dioxide capture characteristics of oxyfluorinated carbon molecular sieves. *Chem Eng Res Des* 2012;211–212:89–96. <https://doi.org/10.1016/j.cej.2012.09.047>.
- [9] Liang Z, Rongwong W, Liu H, Fu K, Gao H, Cao F, et al. Recent progress and new developments in post-combustion carbon-capture technology with amine based solvents. *Int. J. Greenh. Gas. Con* 2015;40:26–54. <https://doi.org/10.1016/j.ijggc.2015.06.017>.
- [10] Vega F, Baena-Moreno FM, Gallego Fernández LM, Portillo E, Navarrete B, Zhang Z. Current status of CO<sub>2</sub> chemical absorption research applied to CCS: towards full deployment at industrial scale. *Appl Energy* 2020;260:114313. <https://doi.org/10.1016/j.apenergy.2019.114313>.
- [11] Rochelle GT. Amine scrubbing for CO<sub>2</sub> capture. *Science* 2009;325(5948):1652–4. <https://doi.org/10.1126/science.1176731>.
- [12] Dutcher B, Fan M, Russell AG. Amine-based CO<sub>2</sub> capture technology development from the beginning of 2013—a review. *ACS Appl Mater Interfaces* 2015;7(4): 2137–48. <https://doi.org/10.1021/am507465f>.
- [13] Abotaleb A, El-Naas MH, Amhammed A. Enhancing gas loading and reducing energy consumption in acid gas removal systems: a simulation study based on real NGL plant data. *J Nat Gas Sci Eng* 2018;55:565–74. <https://doi.org/10.1016/j.jngse.2017.08.011>.
- [14] Rochelle G, Chen E, Freeman S, Van Wagener D, Xu Q, Voice A. Aqueous piperazine as the new standard for CO<sub>2</sub> capture technology. *Chem Eng J* 2011;171 (3):725–33. <https://doi.org/10.1016/j.cej.2011.02.011>.
- [15] Reynolds AJ, Verheyen TV, Adelaja SB, Meuleman E, Feron P. Towards commercial scale postcombustion capture of CO<sub>2</sub> with monoethanolamine solvent: key considerations for solvent management and environmental impacts. *Environ Sci Technol* 2012;46(7):3643–54. <https://doi.org/10.1021/es204051s>.
- [16] Samanta A, Zhao A, Shimizu GK, Sarkar P, Gupta R. Post-combustion CO<sub>2</sub> capture using solid sorbents: a review. *Ind Eng Chem Res* 2012;51(4):1438–63. <https://doi.org/10.1021/ie200686q>.
- [17] Goto K, Yogo K, Higashii T. A review of efficiency penalty in a coal-fired power plant with post-combustion CO<sub>2</sub> capture. *Appl Energy* 2013;111:710–20. <https://doi.org/10.1016/j.apenergy.2013.05.020>.
- [18] Wang J, Sun T, Zhao J, Deng S, Li K, Xu Y, et al. Thermodynamic considerations on MEA absorption: whether thermodynamic cycle could be used as a tool for energy efficiency analysis. *Energy* 2019;168:380–92. <https://doi.org/10.1016/j.energy.2018.11.084>.
- [19] 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>.
- [20] 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;233:468–77. <https://doi.org/10.1016/j.apenergy.2018.10.007>.
- [21] Liu J, Li X, Zhang Z, Li L, Bi Y, Zhang L. Promotion of CO<sub>2</sub> capture performance using piperazine (PZ) and diethylenetriamine (DETA) bi-solvent blends. *Greenh. Gases* 2019;9(2):349–59. <https://doi.org/10.1002/ghg.1851>.
- [22] 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>.
- [23] Hu X, Huang J, He X, Luo Q, Li Ce, 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>.
- [24] 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>.
- [25] He X, He H, Barzaghi F, Amer MW, Li Ce, 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>.
- [26] Zhou C, Zhang C, Zhang T, Zhang J, Ma P, et al. Single-atom solutions promote carbon dioxide capture. *Appl Energy* 2023;332:120570. <https://doi.org/10.1016/j.apenergy.2022.120570>.
- [27] Zhang C, Zhou C, Li Y, Yu Y, Zhang Z, et al. Single atom solutions for carbon dioxide capture. *J Chem Phys* 2023;158(8):084309. <https://doi.org/10.1063/5.0132627>.
- [28] Fu D, Zhang P, Wang L. Absorption performance of CO<sub>2</sub> in high concentrated [Bmim][Lys]-MDEA aqueous solution. *Energy* 2016;113:1–8. <https://doi.org/10.1016/j.energy.2016.07.049>.
- [29] Wang L, Fang C, Du X, Fu K, Tian X, Zhang P, et al. Surface thermodynamics and viscosity of 1-dimethylamino-2-propanol+1-(2-aminoethyl)piperazine and 1-dimethylamino-2-propanol+1,5-diamino-2-methylpentane aqueous solutions. *J Chem Thermodyn* 2020;151:106242. <https://doi.org/10.1016/j.jct.2020.106242>.
- [30] Zhang P, Ji Y, Li W, Xu L, Wang L, Fu D. Investigation of viscosity, activation energy and CO<sub>2</sub> diffusion coefficient for N-methyl-1,3-propane-diamine, N-(2-aminoethyl)ethanolamine and 1,4-butanediamine activated 2-diethylaminoethanol aqueous solutions. *J Chem Thermodyn* 2022;168:106740. <https://doi.org/10.1016/j.jct.2022.106740>.

- [31] 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>.
- [32] Wang R, Liu S, Wang L, Li Q, Zhang S, Chen B, et al. Superior energy-saving splitter in monoethanolamine-based biphasic solvents for CO<sub>2</sub> capture from coal-fired flue gas. *Appl Energy* 2019;242:302–10. <https://doi.org/10.1016/j.apenergy.2019.03.138>.
- [33] 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(11): 11389–98. <https://doi.org/10.1021/acs.energyfuels.9b02392>.
- [34] 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>.
- [35] 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. *ACS Sustainable Chem Eng* 2020;8(38):14493–503. <https://doi.org/10.1021/acsschemeng.0c04616>.
- [36] 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>.
- [37] 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>.
- [38] Shen S, Shi X, Li C, Guo H, Long Q, Wang S, et al. Nonaqueous (amine+glycol ether) solvents for energy-efficient CO<sub>2</sub> capture: new insights into phase change behaviors and assessment of capture performance. *Sep Purif Technol* 2022;300: 121908. <https://doi.org/10.1016/j.seppur.2022.121908>.
- [39] Luo Q, Yoon B, Gao H, Lv J, Hwang GS, Xiao M, et al. Combined experimental and computational study 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>.
- [40] Zhang J, Agar DW, Zhang X, Geuzebroek F. CO<sub>2</sub> absorption in biphasic solvents with enhanced low temperature solvent regeneration. *Energy Proc* 2011;4:67–74. <https://doi.org/10.1016/j.egypro.2011.01.024>.
- [41] 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>.
- [42] Heldebrant DJ, Koech PK, Glezakou VA, Rousseau R, Malhotra D, Cantu DC. Water-lean solvents for post-combustion CO<sub>2</sub> capture: fundamentals, uncertainties, opportunities, and outlook. *Chem Rev* 2017;117(14):9594–624. <https://doi.org/10.1021/acs.chemrev.6b00768>.
- [43] Liu F, Jing G, Zhou X, Lv B, Zhou Z. Performance and mechanisms of Triethylene Tetramine (TETA) and 2-Amino-2-methyl-1-propanol (AMP) in aqueous and nonaqueous solutions for CO<sub>2</sub> capture. *ACS Sustainable Chem Eng* 2018;6(1): 1352–61. <https://doi.org/10.1021/acsschemeng.7b03717>.
- [44] 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>.
- [45] Li R, Wu C, Yang D. CO<sub>2</sub> absorption mechanism by the nonaqueous solvent consisting of Hindered amine 2-[{1,1-dimethylethyl}amino]ethanol and ethylene glycol. *Molecules* 2020;25(23):5743. <https://doi.org/10.3390/molecules25235743>.
- [46] Alipour M, Hafizi A, Kanani M, Dara A. Biphasic systems of mutual amine solution with tunable phase separation for CO<sub>2</sub> capture: optimal compositions and volume of rich phase. *J Mol Liq* 2023;385:122433. <https://doi.org/10.1016/j.molliq.2023.122433>.
- [47] Wang R, Jiang L, Li Q, Gao G, Zhang S, Wang L. Energy-saving CO<sub>2</sub> capture using sulfolane-regulated biphasic solvent. *Energy* 2020;211:118667. <https://doi.org/10.1016/j.energy.2020.118667>.
- [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] 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>.
- [51] <https://echa.europa.eu/substance-information/-/substanceinfo/100.003.568>.
- [52] Radhamma M, Hsieh CT, Venkatesu P, Rao MVP, Lee MJ, Lin HM. Isobaric vapor-liquid equilibrium for Dimethylsulfoxide with chloroethanes and chloroethenes. *J Chem Eng Data* 2008;53(2):374–7. <https://doi.org/10.1021/je700408x>.
- [53] Yin X, Dong Y, Ping T, Shen S. Densities, viscosities, and Excess/Deviation properties of the ternary system 2-(methylamino)ethanol + dimethyl sulfoxide + water and the binary subsystems. *J Chem Eng Data* 2021;66(9):3543–56. <https://doi.org/10.1021/acs.jcd.1c00414>.
- [54] Grigoryan ZL, Kazoyan EA, Markaryan SA. Thermodynamics of liquid-vapor phase equilibrium in dimethyl sulfoxide–alkanol systems in the range of 293.15–323.15 K. *Russ J Phys Chem A* 2015;89(10):1790–4. <https://doi.org/10.1134/S0036024415100131>.
- [55] Comelli F, Francesconi R, Bigi A. Excess molar Enthalpies, molar heat capacities, Densities, viscosities, and refractive indices of dimethyl sulfoxide + Esters of carbonic acid at 308.15 K and atmospheric pressure. *J Chem Eng Data* 2006;52(2): 665–70. <https://doi.org/10.1021/je050444g>.
- [56] House KZ, Harvey CF, Aziz MJ, Schrag DP. The energy penalty of post-combustion CO<sub>2</sub> capture & storage and its implications for retrofitting the U.S. installed base. *Energy Environ Sci* 2009;2(2):193–205. <https://doi.org/10.1039/B811608c>.
- [57] Chowdhury FA, Goto K, Yamada H, Matsuzaki Y. A screening study of alcohol solvents for alkanolamine-based CO<sub>2</sub> capture. *Int. J. Greenh. Gas. Con* 2020;99: 103081. <https://doi.org/10.1016/j.ijggc.2020.103081>.
- [58] Raganati F, Miccio F, Ammendola P. Adsorption of carbon dioxide for post-combustion capture: a review. *Energy Fuels* 2021;35(16):12845–68. <https://doi.org/10.1021/acs.energyfuels.1c01618>.
- [59] 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 (1–2):182–90. <https://doi.org/10.1016/j.cej.2010.04.042>.
- [60] Jie Q, Guo-Zhu J. Dielectric constant of polyhydric alcohol-DMSO mixture solution at the microwave frequency. *J Phys Chem A* 2013;117(48):12983–9. <https://doi.org/10.1016/j.jfluid.2013.12.014>.
- [61] 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>.