


# Diamine based water-lean CO<sub>2</sub> solvent with extra high cyclic capacity and low viscosity


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**Abstract:** The industrial application of emerging water-lean solvents to CO<sub>2</sub> capture from flue gas is challenged by their high viscosity. In this work, we report a novel water-lean CO<sub>2</sub> solvent which possesses lower viscosity and higher CO<sub>2</sub> cyclic capacity than other water-lean solvents reported in the literature. The new solvent consists of *N*, *N*-dimethyl-1, 2-ethanediamine (DMEDA), physical cosolvent *N*-methyl-2-pyrrolidone (NMP) and up to 15% water (named ENH). We evaluated the effect of the solvent composition on the viscosity, CO<sub>2</sub> cyclic capacity and regeneration energy of ENH and compared it with the reference monoethanolamine (MEA) based solvents. It was found that ENH containing 5% H<sub>2</sub>O (ENH-5% H<sub>2</sub>O) with a CO<sub>2</sub> loading of 0.767 mol CO<sub>2</sub>·mol amine<sup>-1</sup> had a viscosity of 7.603 mPa·S at 40 °C, which was comparable with that of traditional blended amines. Excellent cyclic capacity performance was also observed, with ENH-5% H<sub>2</sub>O showing a 140% improvement compared to aqueous MEA. Regeneration energy of ENH-5% H<sub>2</sub>O was estimated to be 2.418 GJ·tCO<sub>2</sub><sup>-1</sup> which is 36% lower than the 30 wt. % aqueous MEA solvent. © 2021 Society of Chemical Industry and John Wiley & Sons, Ltd.

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**Keywords:** CO<sub>2</sub> capture; water-lean; diamine; viscosity; cyclic capacity

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## Introduction

Within the field of CO<sub>2</sub> capture, utilization, and storage (CCUS) for the mitigation of greenhouse gas emissions, CO<sub>2</sub> capture using aqueous amine-based absorbents is regarded as the most technically mature approach. Recently, water-lean solvents, which mix amines with organic diluents and contain low or no water, have gained considerable interests due to their lower energy requirement for regeneration and ability to be used in existing processes with minimal modification.

Previous investigations have found that water-lean solvents contribute to energy savings compared to traditional aqueous solvents. The regeneration energy of monoethanolamine (MEA) blended with ethylene glycol (EG) was found to be 23.8–31.3% lower than that of aqueous MEA.<sup>1</sup> Lv *et al.* found that a nonaqueous solvent containing 2-amino-2-methyl-1-propanol (AMP), (2-(2-aminoethylamino)ethanol and *N*-methyl-2-pyrrolidone (NMP) achieved a low regeneration energy (2.09 GJ·tCO<sub>2</sub><sup>-1</sup>) which was approximately half that of aqueous MEA.<sup>2</sup>

However, water-lean solvents are generally challenged by their high viscosity.<sup>3–6</sup> It was reported that water-lean solvents containing alcohol derivatives had high viscosity values, even up to ~1300 mPa·S at 40 °C with CO<sub>2</sub> loading<sup>7</sup> which would significantly reduce the mass and heat transfer efficiency in the CO<sub>2</sub> capture process. Moreover, alcohol derivatives were easily oxidized in an oxygen-containing environment, leading to a more severe degradation.<sup>8</sup> Thus, organic solvents, for example sulfolane (SFL), *N*-methyl-2-pyrrolidone (NMP) and poly (ethylene glycol) dimethylether (NHD), with high thermal stability and low vapor pressure were selected to form water-lean systems. SFL, NMP, and NHD based solvents can help lower the high viscosity of water-lean solvents to a certain extent<sup>9–11</sup> A relatively low viscosity (3.93 mPa·S) was achieved for the water-lean DETA/SFL solvent at a CO<sub>2</sub> loading of 2.21 mol·L<sup>-1</sup> (equal to 1.105 mol CO<sub>2</sub>·mol amine<sup>-1</sup>) at 348 K.<sup>9</sup> 7m MEA mixed with NMP and H<sub>2</sub>O in a mass ratio of NMP: H<sub>2</sub>O of 19:1 (equal to 3.5wt. % H<sub>2</sub>O) had a viscosity of 15.4 mPa·S with a CO<sub>2</sub> loading of 0.45 mol CO<sub>2</sub>·mol amine<sup>-1</sup>.<sup>10</sup> It was illustrated that multiple factors such as NMP fraction influenced on the viscosity performance of MEA-NMP-H<sub>2</sub>O. However, that is still 5 times more viscous than 30 wt% aqueous MEA. A viscosity of 37.4 mPa·S was achieved in the lower phase of biphasic solvent containing 1 M

3-dimethylaminopropylamine (DMAPA) mixed with NHD and H<sub>2</sub>O (volume ratio: 8:2). It was indicated that DMAPA with no hydroxyl group had weaker hydrogen bonding effect, leading to a relatively lower viscosity than MEA in the same volume ratio of NHD and H<sub>2</sub>O.<sup>11</sup>

In this work, we report a novel, high performing water-lean solvent with a lower viscosity than those reported water lean solvents in the literature. It is composed of a di-amine, *N,N*-dimethyl-1,2-ethanediamine (DMEDA), an organic physical solvent NMP and up to 15% water. Aqueous DMEDA was reported to exhibit a higher absorption rate and cyclic capacity compared with aqueous MEA.<sup>12</sup> We carried out several experiments to investigate the performance of water-lean solvents including viscosity, cyclic capacity, and regeneration energy. 30 wt% aqueous MEA solvent was used as a benchmark for comparison. To our knowledge, it is the first time that the DMEDA based water-lean solvent has been reported for CO<sub>2</sub> capture. The promising results shown in this work will stimulate more research work to further develop this solvent and water-lean solvents in general.

## Experimental

### Materials

Carbon dioxide (CO<sub>2</sub>, 99.9%) and nitrogen (N<sub>2</sub>, 99.9%) gases were supplied by BOC Australia. Monoethanolamine (MEA, 99% Merck), *N,N*-dimethyl-1,2-ethanediamine (DMEDA, 99% Sigma), 1-methyl-2-pyrrolidone (NMP, 99% Chem-supply) were used as received and their CAS numbers and molecular structures are provided in Table S1. Deionized water was used to prepare the water-lean solutions. The solvents in this study all contained 30 wt. % of amines, and the water content varied among 5, 10, 15, and 70%, with the balance made up by NMP (Table S2).

### Viscosity and CO<sub>2</sub> absorption enthalpy measurement

The details for viscosity and CO<sub>2</sub> absorption enthalpy measurement were previously presented by Xiao *et al.*<sup>12</sup> and Luo *et al.*<sup>13</sup>

### Desorption test

The CO<sub>2</sub> desorption device was described in our previous work.<sup>14</sup> All the materials used were weighed

by an analytical balance to the planned quantities in the preparation of the solvents. The weight percentage concentration was used in this work. The rich solvent was obtained after 24 hr absorption in a jacketed flask at 40 °C under 101kPa CO<sub>2</sub> partial pressure. The stirring rate was 800 rpm controlled by a magnetic stir plate. Prepared rich solvent was directly heated at 90 °C with the same stirring rate. Seven samples (0.5 mL) were collected during 60 min of desorption time and analyzed by NMR. The NMR facility and analysis procedure were described by Xiao *et al.*<sup>12</sup>

### Condensate water measurement

The regeneration energy of CO<sub>2</sub> solvent ( $Q_{\text{reg}}$ , GJ·tCO<sub>2</sub><sup>-1</sup>) was composed of three parts: reaction heat ( $Q_{\text{reac}}$ ), sensible heat ( $Q_{\text{sens}}$ ) and latent heat ( $Q_{\text{latent}}$ ), as given in Eq. 1. The calculation equation of each part is shown in Eqn 2.<sup>15–17</sup>

$$Q_{\text{reg}} = Q_{\text{reac}} + Q_{\text{sens}} + Q_{\text{latent}} \quad (1)$$

$$Q_{\text{reg}} = \frac{-H_{\text{abs}}}{M} + \frac{C_p m_{\text{sol}} \Delta T}{m_{\text{CO}_2}} + \frac{n_w}{M \times n_{\text{CO}_2}} \Delta H_w^{\text{vap}} \quad (2)$$

where,  $H_{\text{abs}}$  is the reaction heat of CO<sub>2</sub> absorption, kJ·mol·CO<sub>2</sub><sup>-1</sup>,  $M$  is the molecular weight of CO<sub>2</sub>, 44 g·mol<sup>-1</sup>,  $C_p$  is the heat capacity of rich solvents, kJ·kg<sup>-1</sup>·K<sup>-1</sup>,  $m_{\text{sol}}$  is the weight of rich solvents, kg,  $\Delta T$  is the temperature difference between lean and rich solvents which is assumed as 10K,  $m_{\text{CO}_2}$  is the weight of CO<sub>2</sub> absorbed, g,  $\Delta H_w^{\text{vap}}$  is the heat of water evaporation, kJ·mol<sup>-1</sup>,  $n_w$  and  $n_{\text{CO}_2}$  is the amount of water evaporated and CO<sub>2</sub> desorbed, mol which was determined using the apparatus shown in Fig. S1. Fresh solvent (500 g) was stirred with pure CO<sub>2</sub> gas presaturated with water flowing at a rate of 100 mL min<sup>-1</sup> for 6 hr. Then, 100g of the obtained rich solvent was injected into a 250 mL three necked flask and heated at 90 °C controlled by an oil bath for 1 hr. The stirring rate was maintained at 800 rpm during the whole experiment. Water vapor was condensed and collected by a condenser. A refrigerating circulator supplied cooling water at 3 °C to the condenser. An electronic soap film flowmeter (BL-1000, range 1–1000 mL min<sup>-1</sup>, accuracy 1%) was used to monitor the CO<sub>2</sub> desorption rate throughout the whole desorption process. The amount of CO<sub>2</sub> desorbed was measured by a CO<sub>2</sub> loading test device based on neutralization reaction, the detail of which was described by Zhu *et al.*<sup>18</sup>

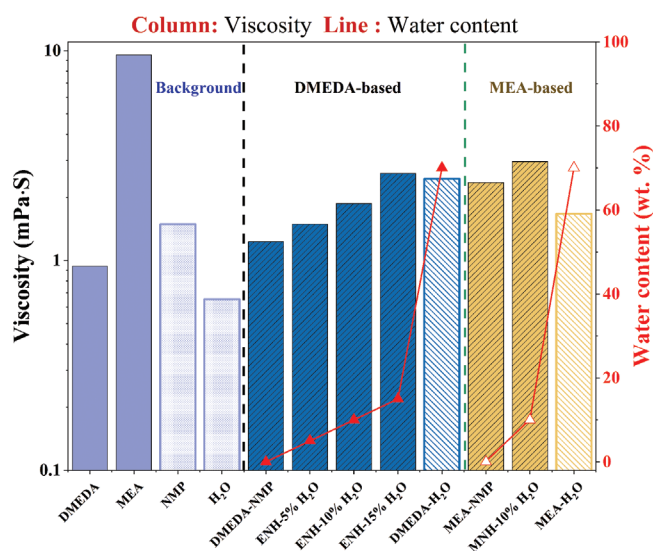


Figure 1. Viscosity of CO<sub>2</sub> free water-lean and aqueous solvents at 40 °C. The data for MEA-H<sub>2</sub>O is from reference.<sup>22</sup>

## Results and discussion

### Viscosity

The viscosity of fresh ENH water-lean solvents comprising different water content (0–15%) at 313 K is shown in Fig. 1. Aqueous MEA and MNH water-lean solvents were selected for comparison. It was found that the viscosity of the ENH solvent series dropped appreciably with a decrease in water content in the measured water fraction range (0–15%). A decline of 53% was achieved through decreasing water content of the ENH solvent from 15 to 0%, and DMEDA-NMP had a viscosity 26% lower than aqueous MEA.

It is known that the viscosity of a mixed solvent is strongly affected by the viscosity of each component (background viscosity) and interactions among molecules in the mixture. The results show that the co-solvent NMP (1.49 mPa·S) has a viscosity 56% higher than H<sub>2</sub>O (0.65 mPa·S). The measured viscosity of four DMEDA-based water-lean solvents was different from the expectation that the system viscosity would decrease as the fraction of water and NMP increased and decreased, respectively. In these cases, the impact of background viscosity changes attributed to the small change of water content (0–15%) was negligible. It is believed that the hydrogen bond between water and amine played a key role in the viscosity changes<sup>19</sup> of the DMEDA-based water-lean system. The increased water fraction enhanced hydrogen bond formation with the amine, resulting in an increase in viscosity. Whereas, the DMEDA-H<sub>2</sub>O

aqueous solvent had a relatively lower viscosity compared with that of ENH-15% H<sub>2</sub>O. This suggests that further addition of water contributed more to background viscosity after the amine was fully solvated by water to form hydrogen bonds.

A different trend was observed in MEA-based solvents. The viscosity of MEA blends decreased sharply by the addition of water and/or NMP. MEA has one electron withdrawing hydroxyl group and one electron donating primary amino group. The two functional groups match well to form strong inter-molecular hydrogen bonds.<sup>20</sup> These hydrogen bonds could result in MEA molecules connected in linear, branched, or mixed ways, resulting in a viscous mixture. However, this intermolecular hydrogen bond is disrupted when water or NMP is introduced. The nitrogen and oxygen atoms in NMP are locked in an amide group, hence suppressing hydrogen bond formation with either amino or hydroxyl groups of MEA under general CO<sub>2</sub> capture process conditions. The hydroxyl group of MEA can behave as either hydrogen acceptor or donor in hydrogen bond formation.<sup>21</sup> The hydroxyl group in MEA (pK<sub>a</sub> 15.61) should behave as a hydrogen acceptor when fully solvated by water (pK<sub>a</sub> 14) to form much weaker hydrogen bonds compared to that formed with an amino group. Hence, a decrease of viscosity was observed in all MEA-based solvents, in which MEA formulated with H<sub>2</sub>O resulted in a lower viscosity than that with NMP.

Regarding the influence of amine structure, MEA based solvents always resulted in a higher viscosity than DMEDA based ones with the same water content (0 and 10%) in these water-lean systems. In addition to the background viscosity difference between MEA and DMEDA, the ability to form hydrogen bonds also plays a crucial role in viscosity performance. In nonaqueous systems, the intermolecular bonding interaction was preferred in MEA-NMP relative to DMEDA-NMP, leading to a higher viscosity of the MEA-NMP solvents. In the 10% H<sub>2</sub>O system, the hydroxyl group of MEA was regarded as a hydrogen acceptor from water and is more hydrophilic than tertiary amino group of DMEDA, which contributed to hydrogen bonding with water. As a consequence, a more extensive hydrogen bonding network was able to form in MNH-10%H<sub>2</sub>O leading to a larger viscosity.

Although DMEDA-NMP had the lowest viscosity without CO<sub>2</sub> loading, carbamate precipitated out as solid during CO<sub>2</sub> uptake, hence it is unsuitable for

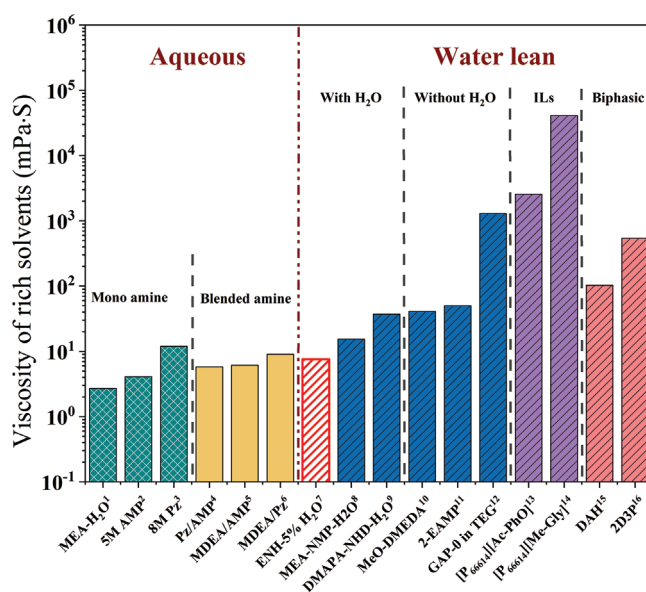


Figure 2. Comparison of viscosity of different solvents at 40 °C with rich loading (Except two ionic liquids which were tested at 30 °C). Rhombic pattern: aqueous solvent, no pattern: blended solvent, diagonal pattern: water-lean solvent.<sup>1</sup> loading: 0.5 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>2</sup> loading: 0.20 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>3</sup> loading: 0.10 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>4</sup> loading: 0.13 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>5</sup> loading: 0.75 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>6</sup> loading: 0.13 mol CO<sub>2</sub>·(mol N)<sup>-1</sup>,<sup>7</sup> loading: 0.767 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>8</sup> loading: 0.45 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>9</sup> loading: 1.06 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>10</sup> loading: 0.7 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>11</sup> loading: 0.43 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>12</sup> rich solvent,<sup>13</sup> loading: 1.20 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>14</sup> loading: 0.90 mol CO<sub>2</sub>·mol amine<sup>-1</sup>,<sup>15</sup> loading: lower phase with 3.9 mol CO<sub>2</sub>·kg<sup>-1</sup>,<sup>16</sup> loading: 0.564 mol CO<sub>2</sub>·mol amine<sup>-1</sup>.

application in common absorption and desorption equipment. This indicates that the presence of some water is important to ensure the system remains as a single phase upon reaction with CO<sub>2</sub>. Therefore, ENH-5%H<sub>2</sub>O which had the second smallest viscosity of the fresh solvents was chosen to test the viscosity after absorption of 15 kPa CO<sub>2</sub> at 40 °C for 5 hr and compared with published typical mono-amine solvents, blended solvents, and water-lean solvents (Fig. 2). Some CO<sub>2</sub> loading results of the published solvents quoted in Fig. 2 were displayed in different units in the original paper. They were converted to the unit of mol CO<sub>2</sub>·mol amine<sup>-1</sup> for unification. The abbreviation and composition of all solvents are listed in Table S3. ENH-5% H<sub>2</sub>O with a CO<sub>2</sub> loading of 0.767 mol CO<sub>2</sub>·mol amine<sup>-1</sup> had a viscosity of 7.603 mPa·S, which is the lowest viscosity among reported



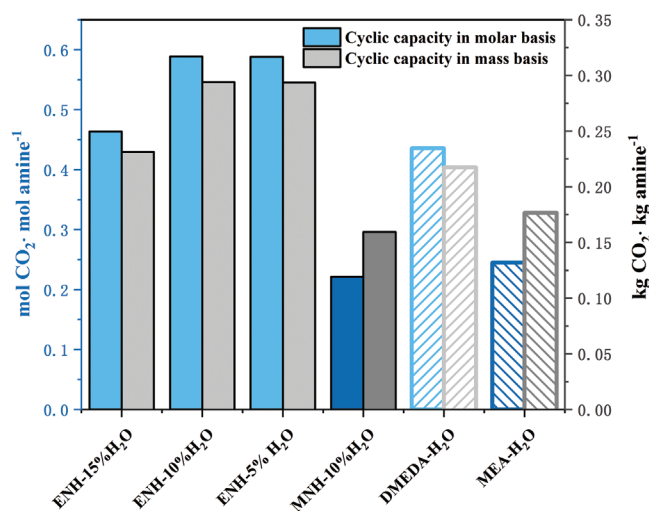


Figure 3. Cyclic capacity performances of different solvents.

water-lean solvents so far. Compared to aqueous amine systems, the viscosity of ENH-5% H<sub>2</sub>O solvent was close to MDEA/AMP blends and 36.6 % smaller than that of aqueous Pz. This enables the use of ENH in existing industrial absorber and heat exchanger equipment. Compared to water free solvents (e.g., GAP-0 in tri-ethylene glycol (TEG)) and Ionic Liquids (ILs), the determined viscosity of ENH-5% H<sub>2</sub>O is 2–5 orders of magnitude smaller. This is because that the background viscosity of GAP-0 and ILs is much bigger than small alkylamine molecules like DMEDA.

## Cyclic capacity

Cyclic capacity of DMEDA and MEA-based solvents is shown in Fig. 3. As the difference of cyclic capacity in two different units was unapparent, only cyclic capacity in mole basis was used below for an easy discussion.

Figure 3 shows that ENH solvents achieved improvements in cyclic capacity compared with aqueous DMEDA-H<sub>2</sub>O. ENH solvents with smaller water content (5%, 10%) resulted in higher cyclic capacity, in which ENH-5% H<sub>2</sub>O showed an improvement of 140% with respect to the aqueous MEA-H<sub>2</sub>O solvent.

The introduction of a nonprotonic polar co-solvent NMP greatly effects the cyclic capacity of the studied amines. It was reported that NMP can physically absorb CO<sub>2</sub> at higher pressure (> 2MPa). However, solubility of CO<sub>2</sub> at atmosphere pressure was quite small<sup>23</sup> which was considered negligible in this case. Thus, we postulate that the low

polarity of NMP is the key reason for the large cyclic capacity when it's used as a diluent in a water lean solvent based on a basic rule "like seeks like." Comparing to H<sub>2</sub>O, the nonprotonic polar co-solvent NMP has weak ability to stabilize the high-polarity product: bicarbonate/carbonate, resulting in a significant reduction of bicarbonate/carbonate amount. While for the carbamate comprising a lower polarity than bicarbonate/carbonate, NMP can stabilize it to a certain extent to ensure its formation during CO<sub>2</sub> absorption. Hence carbamate was detected as the major absorption product in water lean solvents by NMR analysis. However, in the desorption process, the weaker solvation ability of NMP was declined by the higher temperature and further reduced the stability of the polar carbamate molecule, resulting in an easier decomposition of carbamate to release more CO<sub>2</sub>. Hence, this is the reason why ENH-15% H<sub>2</sub>O with lowest NMP ratio gained lowest cyclic capacity compared with other two ENH solvents. However, comparable cyclic capacities were observed in ENH-5% H<sub>2</sub>O and ENH-10% H<sub>2</sub>O due to the differing contributions from bicarbonate and carbamate. The 5% higher water content in ENH-10% H<sub>2</sub>O allowed more bicarbonate formation while further stabilized the carbamate molecule. These two impacts made similar but opposite contribution to the cyclic capacity, resulting the similar overall cyclic capacities between ENH-5% H<sub>2</sub>O and ENH-10% H<sub>2</sub>O.

In contrast, MEA-H<sub>2</sub>O obtained a slightly higher cyclic capacity than MNH-10% H<sub>2</sub>O. This is because more bicarbonate/carbonate was formed in rich MEA-H<sub>2</sub>O and its decomposition dominated in the desorption process. MNH-10% H<sub>2</sub>O formed smaller amount of bicarbonate/carbonate than MEA-H<sub>2</sub>O, however achieved similar cyclic capacity. This also demonstrates that the introduction of NMP is able to boost cyclic capacity due to carbamate decomposition under mild conditions.

To further explain these results, the free energy barriers of CO<sub>2</sub> desorption in water-lean and aqueous systems were computed by Gaussian 09. The details of calculation method are given in the supporting information.

Optimized structures of reactant complex, transition state and free energy of CO<sub>2</sub> desorption reaction of aqueous and water-lean system are displayed in Fig. S2. It was found that the free energy barrier of CO<sub>2</sub> desorption in an aqueous system (91.18 kJ·mol<sup>-1</sup>) was significantly higher than that in the DMEDA-based

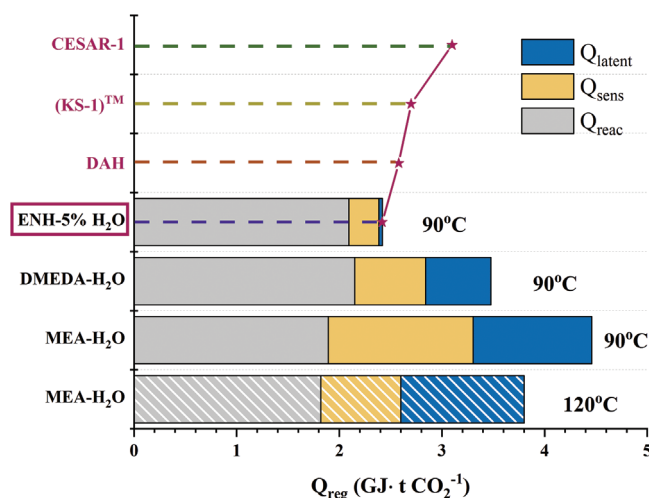


Figure 4. The regeneration energies of ENH-5% $\text{H}_2\text{O}$ , DMEDA- $\text{H}_2\text{O}$ , MEA- $\text{H}_2\text{O}$ , DAH, (KS-1)<sup>TM</sup> and CESAR-1 solvents.

water-lean system (78.30 kJ·mol<sup>-1</sup>). It is known that the reaction with a lower energy barrier requires less energy to proceed, which aligns to the results of larger cyclic capacity observed in the water-lean system.

### Regeneration energy

ENH-5% $\text{H}_2\text{O}$  which has a satisfactory viscosity and large cyclic capacity has potential to reduce energy demand compared to aqueous solvents. Hence, ENH-5% $\text{H}_2\text{O}$  was chosen to compare the calculated regeneration energy with two aqueous solvents DMEDA- $\text{H}_2\text{O}$  and MEA- $\text{H}_2\text{O}$ . Parameters used for energy calculation are given in Table S4. The regeneration energy measured here was based on a lower desorption temperature (90 °C) which was not optimal for MEA- $\text{H}_2\text{O}$  so that the energy consumption result of MEA- $\text{H}_2\text{O}$  desorbed at 120 °C<sup>15</sup> was also displayed in Fig. 4.

An obvious decrease of sensible heat was obtained in the di-amine based solvents (DMEDA- $\text{H}_2\text{O}$  and ENH-5% $\text{H}_2\text{O}$ ), which was attributed to their larger cyclic capacity compared with aqueous MEA at both 90 and 120 °C. Moreover, organic co-solvent NMP has a significantly lower heat capacity than water. Hence, an extra decrease (57.9 %) of sensible heat was achieved in ENH-5% $\text{H}_2\text{O}$  compared with the DMEDA- $\text{H}_2\text{O}$  aqueous solvent. ENH-5% $\text{H}_2\text{O}$  with smaller water content further suppressed the water vaporization, achieving a quite low latent heat of 0.034 GJ·tCO<sub>2</sub><sup>-1</sup>. A regeneration energy of 2.418 GJ·t CO<sub>2</sub><sup>-1</sup> was calculated for the ENH-5% $\text{H}_2\text{O}$  case, which was 36% and 30%

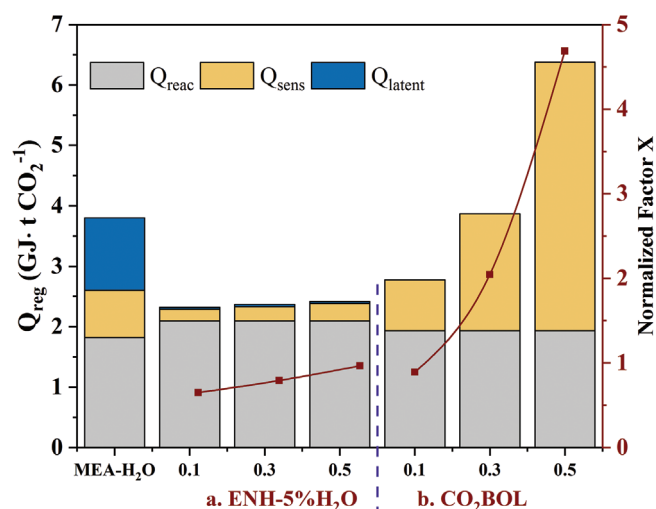


Figure 5. Normalized regeneration energies for ENH-5% $\text{H}_2\text{O}$  and CO<sub>2</sub>BOL with different parameters of the heat exchanger  $\alpha$ .

lower than MEA (120 °C) and DMEDA aqueous solvents, respectively. In Fig. 4, ENH-5% $\text{H}_2\text{O}$  was also compared for the regeneration energy with reported solvents such as proprietary solvents: (KS-1)<sup>TM</sup>,<sup>24</sup> biphasic solvents: DAH<sup>15</sup> and new benchmark<sup>25</sup>: CESAR-1.<sup>26</sup> ENH-5% $\text{H}_2\text{O}$  has the smallest regeneration energy suggesting good potential improved performance in industrial application.

In an industrial CO<sub>2</sub> capture process, higher viscosity of solvents can significantly reduce the heat transfer efficiency of lean/rich exchangers, which may result in a larger sensible heat requirement.<sup>27</sup> A normalized factor  $\chi$  was introduced<sup>28,29</sup> to correct the required sensible heat compared with MEA- $\text{H}_2\text{O}$  (Eqn S5).

CO<sub>2</sub>BOL (IPADM-2BOL).<sup>30–32</sup> which is a novel CO<sub>2</sub> binding organic liquid with high cyclic capacity but high viscosity, was chosen to illustrate the impact of viscosity on sensible heat together with ENH-5% $\text{H}_2\text{O}$  (Fig. 5). The parameters of CO<sub>2</sub>BOL used for the energy calculation are listed in Table S5. The regeneration energy of ENH-5% $\text{H}_2\text{O}$  was insignificantly affected by the parameters of the heat exchangers ( $\alpha$ ) and was approximately half of that of MEA- $\text{H}_2\text{O}$ .<sup>15</sup> In contrast, the CO<sub>2</sub>BOL performed differently in regeneration. Due to its more viscous property, the regeneration energy of CO<sub>2</sub>BOL rose rapidly with increasing  $\alpha$ . As  $\alpha$  increased from 0.1 to 0.5, the sensible heat of CO<sub>2</sub>BOL increased fivefold, resulting in a regeneration energy over 6.0 GJ·tCO<sub>2</sub><sup>-1</sup> which was far larger than that of aqueous MEA. It was

demonstrated that viscosity had a significant effect on regeneration energy and is an important property to be considered during solvent development.

## Conclusion

Water-lean solvents consisting of DMEDA, organic physical co-solvent NMP and H<sub>2</sub>O (named ENH) were evaluated in this work. Several merits such as low viscosity, high cyclic capacity and low regeneration energy were demonstrated in ENH water-lean solvents. For ENH-5%H<sub>2</sub>O with CO<sub>2</sub> loading of 0.767 mol CO<sub>2</sub>·mol amine<sup>-1</sup>, the observed viscosity is only 7.603 mPa·S at 40 °C. Improvement in cyclic capacity of 140% for ENH-5%H<sub>2</sub>O was achieved in comparison with 30 wt% aqueous MEA. The regeneration energy of ENH-5%H<sub>2</sub>O was estimated to be 2.418 GJ·tCO<sub>2</sub><sup>-1</sup> which is 36 % lower than that of aqueous 30 wt% aqueous MEA. Normalized regeneration energy highlighted the impact of viscosity on sensible heat. ENH-5%H<sub>2</sub>O of lower viscosity showed a similar regeneration energy no matter the value of heat exchangers parameter ( $\alpha$ ) was, and this can significantly reduce the size/surface area requirement of heat exchangers.

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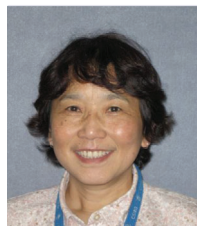
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Qi Yang has completed her PhD in chemistry in Monash University in 1994. She has then joined CSIRO as a postdoctoral fellow and later as a research scientist with CSIRO Manufacturing in Clayton, Australia. Her research in CSIRO has covered various scientific areas including focus on CO<sub>2</sub> capture from 2007. She has developed expertise in understanding the impact of compound structures on



their chemical reaction behaves and capacity in CO<sub>2</sub> capture process. She carried out studies to enhance the related fundamental knowledge and to address application concerns in CO<sub>2</sub> capture. She has also designed solvents with high efficiency and advanced properties to the CO<sub>2</sub> capture at large scales.

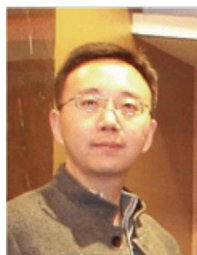
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Prof Tao Wang obtained his PhD degree in engineering and thermal physics from Zhejiang University in 2008. He has worked in the Department of Energy Engineering at Zhejiang University since 2012. His research field is CO<sub>2</sub> capture and utilization technology, including CO<sub>2</sub>

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Kexian Chen, born in November 12th 1983 in Zhejiang Province of China, received his BS (2006) and MS (2009) degrees from Zhejiang University of Technology, and PhD degree (2013) from the Department of Chemistry, Zhejiang University. After his postdoctoral study at the College of Chemical and Biological Engineering, Zhejiang University (2016), he is currently a researcher at the School of Food Science and Biotechnology, Zhejiang Gongshang University. His research interests concern the organocatalysis for aerobic oxidation, reaction mechanism, drug design, ionic liquid, and food colloid & flavour.

**Graeme Puxty**

Graeme studied chemistry and computer science at The University of Newcastle (AU). He then did his PhD in chemistry finishing in 2004. 2005–2007 were spent as a postdoc first in Sweden and then Switzerland. In 2007 Graeme returned to Newcastle and

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**Research Focus:** The chemical and physical processes involved in the separation of carbon dioxide and other acid gases from gas mixtures, and their potential transformation into valuable materials. Both from the perspective of measuring what is happening and building predictive models to simulate what is happening. By understanding in detail the mechanisms of these processes improvements can be made to the gas absorbing materials, chemical transformation steps and the design of the overall separation process. These improvements come from a combination of chemical insights and simulations used to guide the research focus. Carrying out this research couples chemical kinetics, equilibria and thermodynamics with mass and heat transfer processes.