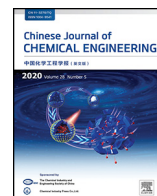




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## Review

Amine-based solvent for CO<sub>2</sub> absorption and its impact on carbon steel corrosion: A perspective reviewZhe Lun Ooi<sup>1</sup>, Pui Yee Tan<sup>2</sup>, Lian See Tan<sup>2,\*</sup>, Swee Pin Yeap<sup>1,\*</sup><sup>1</sup> Department of Chemical & Petroleum Engineering, Faculty of Engineering, Technology & Built Environment, UCSI University, 56000, Cheras Kuala Lumpur, Malaysia<sup>2</sup> Department of Chemical Process Engineering, Malaysia–Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

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## ABSTRACT

Carbon dioxide (CO<sub>2</sub>) is one of the commonly emitted gaseous by-products in industrial processes. While CO<sub>2</sub> gas is the main cause to greenhouse effect, various CO<sub>2</sub> capture technologies have been proposed and implemented to sequester the CO<sub>2</sub> before the waste gases being released into the atmosphere. One of the mature technologies for CO<sub>2</sub> absorption is by using amine-based solvents. In this regard, different single amine solvents or blended amine solvents have been proven for their capability to remove CO<sub>2</sub>. However, the dissolution and reaction of CO<sub>2</sub> gas with the amine solvents turn the solution corrosive. Such phenomenon is undesired as it posts corrosion problem to the absorption column, which normally built of carbon steel material. Henceforth, understanding the behaviour of different amine-based solvents in absorbing CO<sub>2</sub> and its subsequent impact on carbon steel corrosion is very significant. In this review article, we will outline some of the more commonly used solvents and their respective advantages and disadvantages, motivating further investigation into the corrosion tendency. Meanwhile, existing gaps in this research area are discussed for future investigation.

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## 1. Introduction

Fossil fuel consumption in power stations, industrial facilities as well as manufacturing processes have all contributed to the emission of CO<sub>2</sub> gas [1,2]. Releasing large amount of CO<sub>2</sub> gas into the environment is unacceptable as it is the main cause of greenhouse effect. Henceforth, post combustion CO<sub>2</sub> capture (PCCC) technology has been actively researched by many organisations with the aim to reduce the amount of CO<sub>2</sub> released into the environment. In this regard, CO<sub>2</sub> absorbers can be installed in the industrial facilities to remove the amount of CO<sub>2</sub> at large for the sake of the product quality besides the concerns for the environment. The idea implemented here is rather straightforward, whereby an absorbing agent is used to absorb the CO<sub>2</sub> gas before the waste gaseous product from the industries being released into the environment.

Most of the CO<sub>2</sub> absorbers are built of carbon steel owing to its relatively low costing and high tensile strength [3–5]. Carbon steel is a type

of steel that has an approximate carbon percentage of 0.1%–0.3% and up to 2.1% at most by weight. The categorisations of carbon steels comprised of low carbon steel, medium carbon steel and high carbon steel which are classified according to the amount of carbon containing in the carbon steel. Carbon steel exhibits very unique properties in which an increase in the carbon percentage would cause the ductility of the steel to decrease but the tensile strength and hardness to increase [6]. Unfortunately, utilisation of carbon steel as building material (especially for PCCC technology) is limited by corrosion issue [4].

Corrosion is a chemical reaction that occurs upon the interaction of a metal with its environment [7]. The rate of corrosion is dependent on the relative humidity, temperature, acidity and oxygen content in the environment. For the case of immersed carbon steel, the prime factor that affects the corrosion is the relative acidity of the solvent, especially upon dissolution of CO<sub>2</sub>. It is interesting to note that CO<sub>2</sub> itself is not corrosive when present in gaseous state; however, it turns corrosive upon dissolution in water and further dissociation into acidic ions [8]. In response to this, the properties of the metal materials especially the strength and hardness will undergo significant changes, making it more vulnerable to pits and cracks. This occurrence not only disrupts the entire production process but also causes some health-related issue [9]. Moreover, the impacts of the corrosion are very significant when it comes to costing [5]. For instance, it was reported that the direct and indirect costs of corrosion have been amounted to approximately

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6% of the total Gross National Products (GNP) in USA [10]. In other words, around 552 billion dollars have been spent on all the costs incurred on the corrosion.

As prescribed, one of the possible strategies to eliminate/reduce direct release of CO<sub>2</sub> into the environment is by means of absorption column. Amine-based solvents are the preferred agent employed for this purpose [11,12]. The commonly used amine-based solvents are monoethanolamine (MEA) [13,14], 2-amino-2-methylpropanol (AMP) [15], methyldiethanolamine (MDEA) [16], diglycolamine (DGA) [17] and piperazine (PZ) [13,18]. Despite presented different chemical structures as well as cost structures, all of these amine-based solvents have been experimentally proven for their CO<sub>2</sub> capture ability. Nevertheless, equipment corrosion caused by the amine solvent itself or the CO<sub>2</sub>-loaded amine solvent has been a major concern associated with this PCCC technique [12,19]. Some of the amine solvent, for instance MEA and its degraded products, are known to be corrosive [20,21]. Hence, recent investigation has been focussing the corrosion behaviour of carbon steel upon immersed in amine solvent or CO<sub>2</sub>-loaded amine solvent. More importantly, it is crucial to know how the corrosion of carbon steel can be varied by the type of amine solvent used. Considering this piece of information is important for the development of PCCC technology, the present review paper aims to provide an overview on (1) the mechanism involved in CO<sub>2</sub>-induced carbon steel corrosion, (2) the role of common amine-based solvent on CO<sub>2</sub> absorption and carbon steel corrosion rate, as well as (3) the research gaps urged for more investigations.

## 2. Mechanism of Corrosion

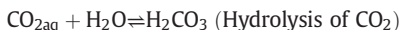
Corrosion involves an oxidation of a metal surface producing electrons and a reduction reaction that consumes the electrons which occurs simultaneously [22]. These oxidation and reduction reactions are known as redox reaction and can be correlated to electrochemical processes. On a general note, this redox reaction occurs upon interaction of three elements, namely the anode, the cathode, and the electrolyte. The electrolyte, in this case, refers to the corrosive solution (or the CO<sub>2</sub>-dissolved solvent). Upon interaction with this electrolyte, electrons are released from the anode (site of the corroding metal) and being transferred to the cathode [22,23]. The tendency of a metal to corrode may depend on the type of metal involved and the pH of the electrolyte [24].

The chemical reactions start with the dissolution of CO<sub>2</sub> gas in water as illustrated in Scheme (1). The dissolved CO<sub>2</sub> reacted with water forming carbonic acid, H<sub>2</sub>CO<sub>3</sub> (Scheme (2)). Further dissociation of the H<sub>2</sub>CO<sub>3</sub> forming acidic solution (Scheme (3)) [25].

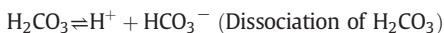
Scheme (1):



Scheme (2):

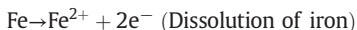


Scheme (3):



At the anode side, an oxidation reaction occurs involves the dissolution of iron as shown in Scheme (4).

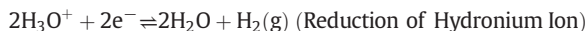
Scheme (4):



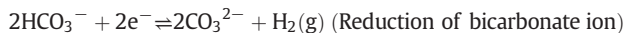
On the other hand, reduction reactions associated with the cathode involve the reduction of hydronium ion, bicarbonate ion as well as

undissociated water. The reduction of hydronium ion that takes place as illustrated in Scheme (5); while the equation representing the reduction of bicarbonate ion and the undissociated water are shown in Scheme (6) and Scheme (7), respectively [26].

Scheme (5):



Scheme (6):



Scheme (7):



The redox reactions then lead to two overall reactions comprising of the formation of ferrous hydroxide and ferrous carbonate. The formation of ferrous hydroxide is shown in Scheme (8) and the formation of ferrous carbonate is shown in Scheme (9) [25,27].

Scheme (8):



Scheme (9):



The final products formed are iron (ii) hydroxide and iron (ii) carbonate respectively. The iron (ii) ion is very unstable and it can be easily oxidised by the oxygen in the air to form iron (iii) ion, which is rust that exhibit reddish brown in colour. Fig. 1 shows the schematic of the corrosion mechanism [28].

## 3. Amine-Based Solvents: Roles in CO<sub>2</sub> Absorption and Carbon Steel Corrosion

Amine-based solvents have been discovered to have good absorbability to CO<sub>2</sub> gas. Accordingly, it is the most mature solvent used in CO<sub>2</sub> absorption [29,30]. Fig. 2 shows a typical process flow in amine-based CO<sub>2</sub> capture technology. The flue gas is first passing through an absorber column where lean amine is used to absorb CO<sub>2</sub> gas. The CO<sub>2</sub>-loaded amine (or rich amine) is then transferred to a stripper where the amine solvent is recovered via heating [31].

The amine-based solvents compose of N, O and C atoms which have high electron density. Amines can be furthered categorised into three classes on the basis of the number of hydrogen atom that adhered to the nitrogen atom [32]. These three classes are the primary, secondary, and tertiary amines which correspondingly contains two H atoms, one H atom, and no H atom adhered to the nitrogen atom [32,33]. Both the primary and secondary amines are weak base which tend to react with CO<sub>2</sub> to form carbamates [34]. This reaction is reversible and thus the amine solvent can be regenerated for next absorption usage [35]. As prescribed, there are few types of commonly used amine solvents, namely the MEA, AMP, MDEA, DGA and PZ. Each of this amine solvent has been investigated for their CO<sub>2</sub> absorption capacity as well as their impact on carbon steel corrosion. The following section will discuss the current research outputs on this field.

### 3.1. Common Amine Solvents For CO<sub>2</sub> Absorption

#### 3.1.1. Monoethanolamine (Mea)

Monoethanolamine is an organic chemical compound that is both a primary amine and primary alcohol [36]. It is a weak base with the

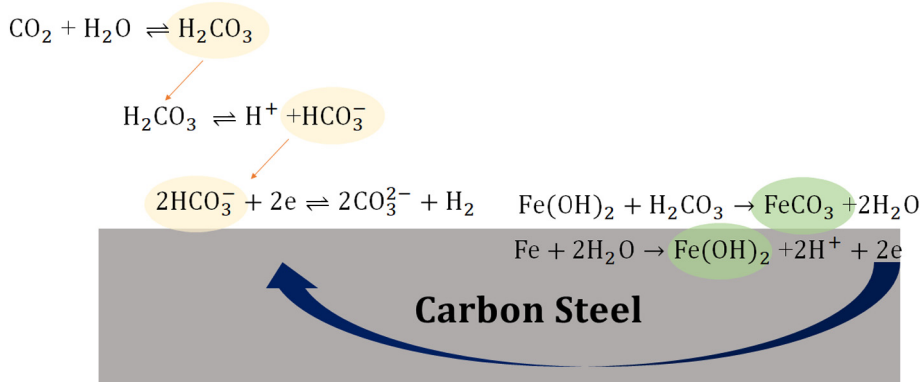


Fig. 1. Corrosion mechanism of carbon steel under  $\text{CO}_2$ - $\text{H}_2\text{O}$  environment.

formula of  $\text{NH}_2\text{CH}_2\text{CH}_2\text{OH}$ . MEA is widely applied for  $\text{CO}_2$  absorption due to its non-toxicity and economical cost. The reaction between MEA and  $\text{CO}_2$  in the aqueous solution is illustrated as below [32,35], Scheme (10):



where R represents the alcohol group. From the stoichiometry of reaction stated above, it is clearly shown that the loading capacity of the MEA is stoichiometrically  $0.5 \text{ mol CO}_2 \cdot \text{mol}^{-1}$  of MEA [37]. Experimentally, Choi *et al.* found that the  $\text{CO}_2$  absorption amount was approximately  $0.46 \text{ mol CO}_2/\text{mol}$  amine when aqueous 30 wt% of MEA was used. The absorption capacity can be further enhanced by increase the gas pressure. Tan *et al.* reported that the  $\text{CO}_2$  absorption performance increases gradually with the increase of pressure in an aqueous MEA solution. Their results showed that approximately 76% of  $\text{CO}_2$  removal was achieved when the pressure is at 0.1 MPa and go up to 95% when the pressure is increased to 1 MPa (see Fig. 3a) [38]. This phenomenon was ascribed to Marangoni effect, whereby the increase in the partial pressure increases the  $\text{CO}_2$  concentration at the gas/liquid-phase interface; such condition disrupts the interface and thus promote the absorption rate [38–40].

In addition, the solution temperature also will affect the  $\text{CO}_2$  capture efficiency; in this regard, Joel *et al.* reported that the  $\text{CO}_2$  capture efficiency increases with the increase in lean-MEA temperature. This observation is obvious especially when the temperature was increased from  $25^\circ\text{C}$  to  $50^\circ\text{C}$  (see Fig. 3b) [41]. At higher temperature, the viscosity of a gas will increase but the same lead to lower viscosity of lean MEA;

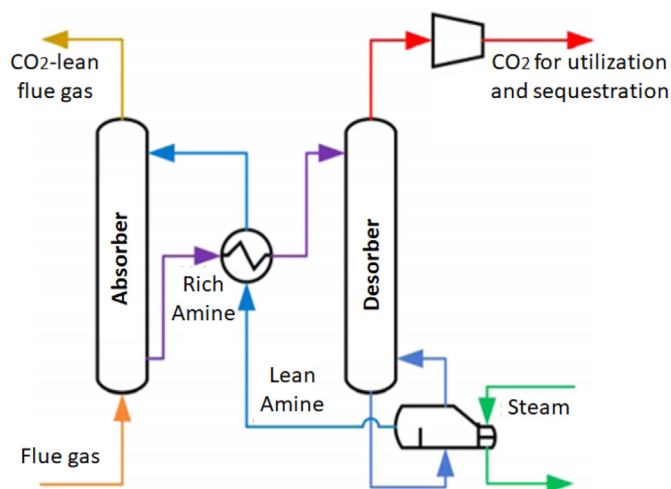


Fig. 2. A typical design of amine-based  $\text{CO}_2$  absorption and desorption columns. (Adapted with permission from [31]. Copyright (2015). American Chemical Society).

such condition enhances the mass transfer owing to thinner liquid film (note that  $\text{CO}_2$  absorption in amine solvent is a liquid film controlled process) [41–43]. Nevertheless, Joel *et al.* also found that temperature above  $50^\circ\text{C}$  has not much impact on the efficiency [41].

### 3.1.2. 2-Amino-2-Methylpropanol (AMP)

2-Amino-2-Methyl Propanol (AMP) is an organic compound that contains both amine and alcohol groups. It is also a primary amine with the chemical formula of  $(\text{CH}_3)_2\text{C}(\text{NH}_2)\text{CH}_2\text{OH}$  and has been extensively studied due to its promising alternatives for the capturing of  $\text{CO}_2$

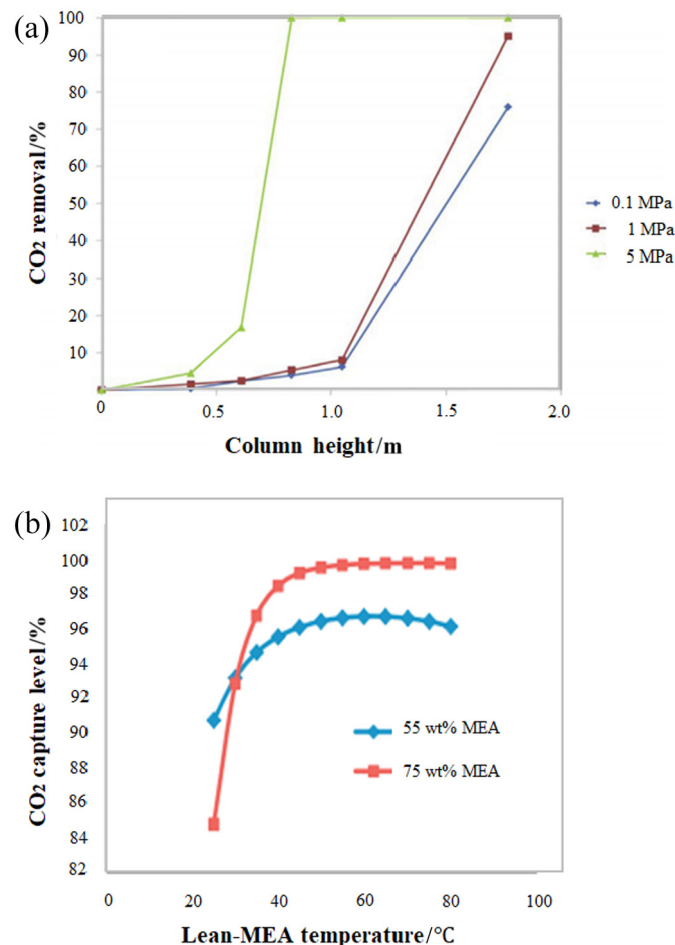
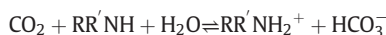


Fig. 3. (a)  $\text{CO}_2$  removal performance in a 20 wt% MEA aqueous solution (Adapted with permission from [38]. Copyright 2015. Elsevier). (b) Effect of operating temperature and MEA concentration on  $\text{CO}_2$  capture efficiency (in rotating packed bed (RPB) column). (Adapted with permission from [41] under CC BY).

gas in various fields. AMP is preferred owing to its unique sterically hindered characteristic [44,45]. Sterically hindered amines form an unstable carbamate intermediate and when mixing them along with organic solvents, the formation of this carbamate will be favoured since the formation of bicarbonate cannot take place with the absence of water [46]. The instability of the carbamate (due to steric hindrance) results in lower regeneration temperature of this amine as compared to other amine solvents. Hence, giving it an advantage in which the utility cost can be reduced. Additionally, AMP is preferred as it is degradation resistance [44].

According to Aroonwilas & Tontiwachwuthikul, a mole of CO<sub>2</sub> can be absorbed using 1 mol of AMP on a theoretical basis of stoichiometry. The overall reaction of CO<sub>2</sub> in AMP is illustrated in Scheme (11); note that in the present of water, bicarbonate can be formed too [47],

Scheme (11):



where R and R' represents the alcohol group, and -H, respectively.

Choi *et al.* reported that CO<sub>2</sub> absorption using 30 wt% AMP aqueous solution was found to be 0.84 mol·CO<sub>2</sub>·mol<sup>-1</sup> of amine. This value was about two times higher than the absorption capacity of 30 wt% MEA aqueous solution (0.46 mol·CO<sub>2</sub>·mol<sup>-1</sup> amine) [37]. Such variation is in fact, in line with the stoichiometry estimation. However, despite having greater absorption capacity, AMP was found to perform poorer in CO<sub>2</sub> removal as compared to MEA, probably due to greater reaction rate of MEA. Accordingly, the authors proposed the use blended MEA/AMP solution for CO<sub>2</sub> removal whereby the MEA/AMP is expected to have higher CO<sub>2</sub> loading than MEA alone and greater reaction rate than AMP alone. They found that the CO<sub>2</sub> removal efficiency decrease

with the increase in AMP concentration inside the blended solution (see Fig. 4a). On the other hand, Jahangiri & Hassankiadeh reported that AMP has a higher CO<sub>2</sub> absorption capacity at higher pressure. However, addition of small amount of piperazine (PZ) should be considered when the partial pressure of the CO<sub>2</sub> is high in order to enhance and promote CO<sub>2</sub> absorption (see Fig. 4b) [48].

### 3.1.3. Methyldiethanolamine (MDEA)

Methyldiethanolamine (MDEA) or more commonly known as N-methyldiethanolamine is an organic compound with the chemical formula CH<sub>3</sub>N(C<sub>2</sub>H<sub>4</sub>OH)<sub>2</sub>. MDEA has been receiving a considerable amount of attention in recent years in the area of PCCC due to its resistance towards corrosion and degradation [49].

Unlike MEA and AMP, the MDEA does not react directly with CO<sub>2</sub> because it cannot form a reaction product. In particular, no carbamate can be generated as the MDEA is a tertiary amine which contains no proton (H atom) to react with the CO<sub>2</sub> [50]. This tertiary amine can only function as a sink for the hydrogen ions produced from the hydrolysis of CO<sub>2</sub> in the water. The chemical reactions involved are described as follows [51]:

Scheme (12):



Scheme (13):



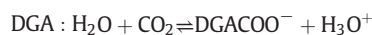
Even though MDEA has a higher ultimate absorption capacity as compared to primary amines, its absorption rate is rather slow [50–53]. This claim is supported by the reaction rate constant of CO<sub>2</sub> absorption determined at 298 K whereby the reaction rate constant for MDEA is 6.71 m<sup>3</sup>·kmol<sup>-1</sup>·s<sup>-1</sup>; while the one for MEA is 5939 m<sup>3</sup>·kmol<sup>-1</sup>·s<sup>-1</sup> [54–56]. Besides that, Mindaryani *et al.*, have conducted a CO<sub>2</sub> absorption study for initial gas content 40% using different concentrations of MDEA (20% and 35.3%) at various gas flow rates (1 L·min<sup>-1</sup>, 1.5 L·min<sup>-1</sup> and 1.8 L·min<sup>-1</sup>) [49]. Based on the experimental data, the outlet concentration of CO<sub>2</sub> falls in the range of 15% to 20% when 20% or 35.3% of MDEA was employed (see Fig. 5). The difference was rather insignificant despite the increase in MDEA concentration. Owing to the low performance, usage of MDEA normally coupled with promoters such as PZ, MEA, DEA, or ionic liquids [52,57,58].

### 3.1.4. Diglycolamine (DGA)

Diglycolamine (DGA) or 2-(2-aminoethoxy)ethanol is a primary amine with the chemical formula of C<sub>4</sub>H<sub>11</sub>NO<sub>2</sub>. According to Material Safety Data Sheet (MSDS) provided by Silver Fern Chemical Inc., DGA is a slightly viscous, colourless liquid with very mild amine odour. DGA was found to have same reactivity as MEA but exhibits lower vapour pressure; thus, DGA can be employed in more concentrated solution with lesser flow rate of solvent [59].

Al-Juaied & Rochelle have conducted a CO<sub>2</sub> absorption study using aqueous solutions containing 65 wt% and 25 wt% of DGA solutions at 25 °C and 60 °C in a wetted wall column. Based on the absorption experiment, a rigorous model on the eddy diffusivity was done and it was found out that the reaction involving DGA and CO<sub>2</sub> is as follows [60]:

Scheme (14):



The findings of the experiment are that the reaction between DGA and CO<sub>2</sub> is dominant only at low loading whilst at high loading,

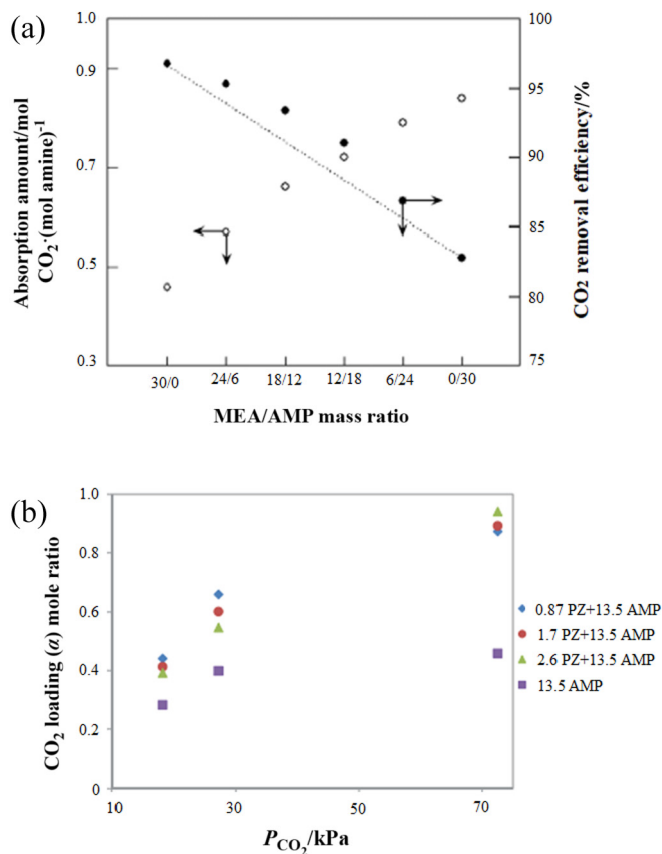


Fig. 4. (a) The CO<sub>2</sub> absorption amounts and removal efficiencies at different MEA/AMP blending amount (Adapted with permission from [37]. Copyright (2009). Elsevier). (b) Plot of CO<sub>2</sub> loading against different CO<sub>2</sub> partial pressure using AMP or PZ/AMP. (Adapted with permission from [48]. Copyright (2019). Taylor & Francis).

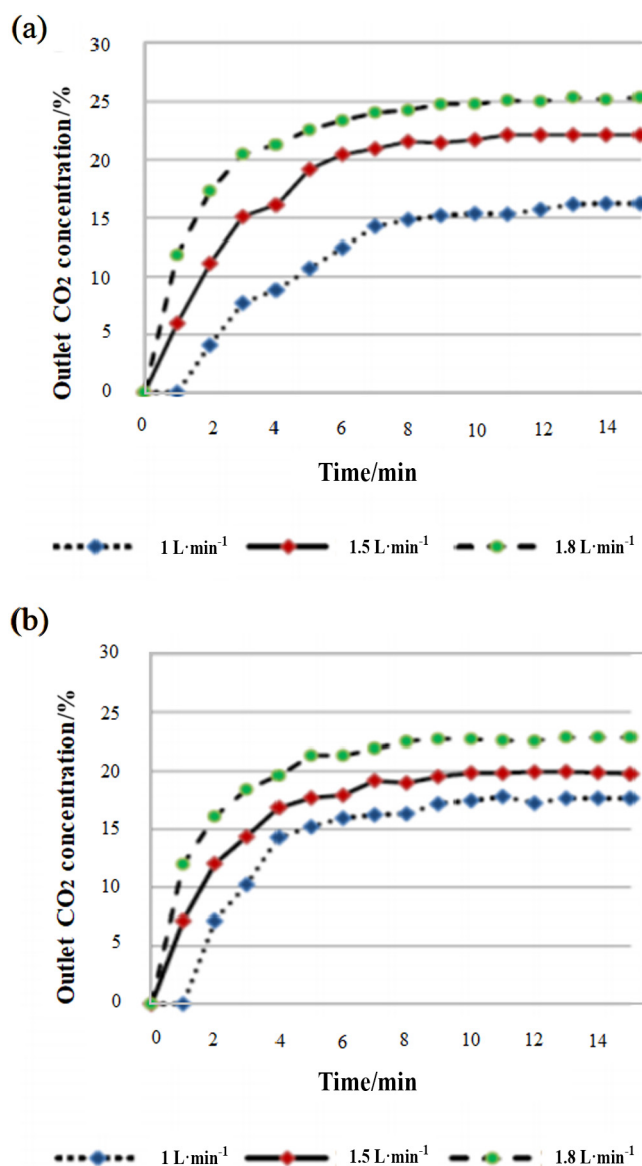


Fig. 5. Outlet CO<sub>2</sub> concentration for (a) 20% MDEA and (b) 35.3% MDEA. (Adapted with permission from [49] under CC BY).

instantaneous reactions tend to take place and the diffusion of reactants and products are the deciding factor for the absorption of CO<sub>2</sub>.

It is interesting to note that DGA posts advantage over MEA in term of the energy consumption during the recovery stage. In this regard, Salkuyeh & Mofarahi have conducted a study to compare the consumed energy duty during a stripping process to recover MEA or DGA solvent. Results showed that at low lean amine loadings, the DGA solvent reboiler duty is lower than that of MEA with equal and even lower amine mass flow. In this context, a large heat reduction can be achieved, and the operational cost can be reduced while the overall safety of the process can be attained. Another noticeable finding is that at equal lean amine loading, DGA requires lower flow and lower condenser duty than MEA, especially in the case where the feed stream contains a high CO<sub>2</sub> concentration [17]. The comparison of the MEA and DGA in term of the condenser duty is illustrated in the Fig. 6 below.

### 3.1.5. Piperazine (PZ)

Piperazine (PZ) or (1,4-hexahydropyrazine) is another amine solvent employed for CO<sub>2</sub> absorption. It is a cyclic organic molecule possessing two nitrogen atoms in opposite positions. Several studies

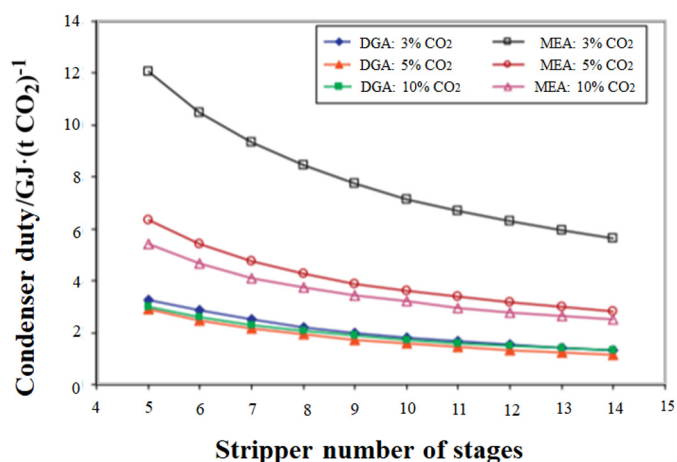
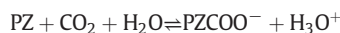
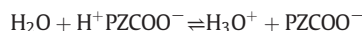


Fig. 6. The comparison between the MEA and DGA in term of the condenser duty in response to the number of stages. (Adapted with permission from [17]. Copyright (2011). John Wiley & Sons).

have been carried out on the rate of CO<sub>2</sub> absorption in piperazine. Bishnoi & Rochelle found that the rate constant of PZ with CO<sub>2</sub> is higher than MEA [61]. The primary chemical reaction involved is as follows [62]:



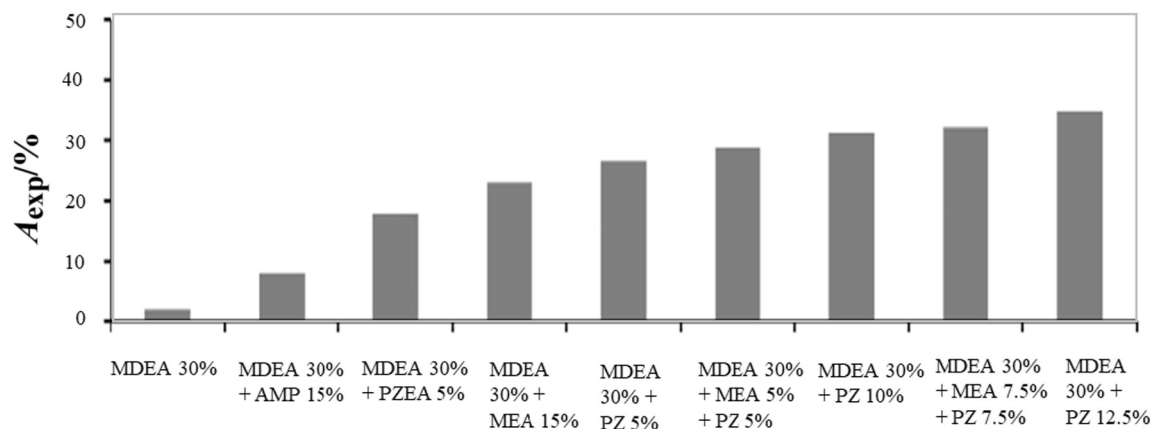
At low CO<sub>2</sub> loading, the dominant reaction product is piperazine carbamate (PZCOO<sup>-</sup>) and the reaction scheme is shown in Scheme (15). On the other hand, at high CO<sub>2</sub> loading, the dominant reaction product is protonated piperazine carbamate (H<sup>+</sup>PZCOO<sup>-</sup>) [63] and the reaction scheme is illustrated in the Scheme (16).



The main finding of this study is that PZ is proven to be an effective promoter for the removal of CO<sub>2</sub> from the gas streams. This finding is well supported by Wong *et al.* which have also conducted a study on the CO<sub>2</sub> absorption by PZ-activated MDEA and PZ-activated AMP [64]. In this study, different weight percents of PZ (2% and 8%) was mixed with MDEA and AMP to aid as promoter. Results showed that the CO<sub>2</sub> loading capacity in MDEA and AMP increased substantially with the addition of PZ. More importantly, it was found that the solution with the largest amount of PZ (8%) has the highest CO<sub>2</sub> loading capacity. Fig. 7 is the results obtained by Dubois & Thomas which also showed that the addition of PZ further enhanced the CO<sub>2</sub> absorption in MEA or MDEA [65].

Noteworthy that PZ is commonly used as promoter instead of as sole solvent for CO<sub>2</sub> capture. This could ascribe to its limited solubility. In specific, increase in PZ concentration as the absorbed CO<sub>2</sub> is stripped off may lead to crystallisation of PZ [66]. Owing to this issue, PZ has been mainly employed at low quantity (<10 wt%) as promoter to aid other amine solvents with slow reaction rates [67].

In a nutshell, each of the amine-based solvent discussed in this section have their own advantages and disadvantages. Also, different amine-based solvents might be employed for different applications depending on their properties and the nature of the flue gases produced. However, MEA solvent which has been developed for approximately 60 years are typically used in industry for removing CO<sub>2</sub> in both physical or chemical absorption [68,69]. Also, MEA is typically considered as benchmark solvent for the comparison of other newly introduced alternative solvent.



### Amine solution

Fig. 7. CO<sub>2</sub> absorption in different blended amine solutions with PZ or (piperazinyl-1)-2-ethylamine (PZEA) as promoter. (Adapted with permission from [65]). Copyright (2011). Elsevier.

### 3.2. Corrosion of Carbon Steel Caused By CO<sub>2</sub>-Dissolved Amine Solvent

Despite being commonly used, MEA is not without limitation. One of the critical limitations of MEA is that it is more corrosive than other

amines [20,21,70]. Moreover, the corrosivity of MEA was further affected by (i) its own concentration, (ii) the CO<sub>2</sub> loading capacity, as well as (iii) the operating temperature [71]. Kittel *et al.* conducted a 4-year-long study to investigate the corrosion in a MEA pilot plant used

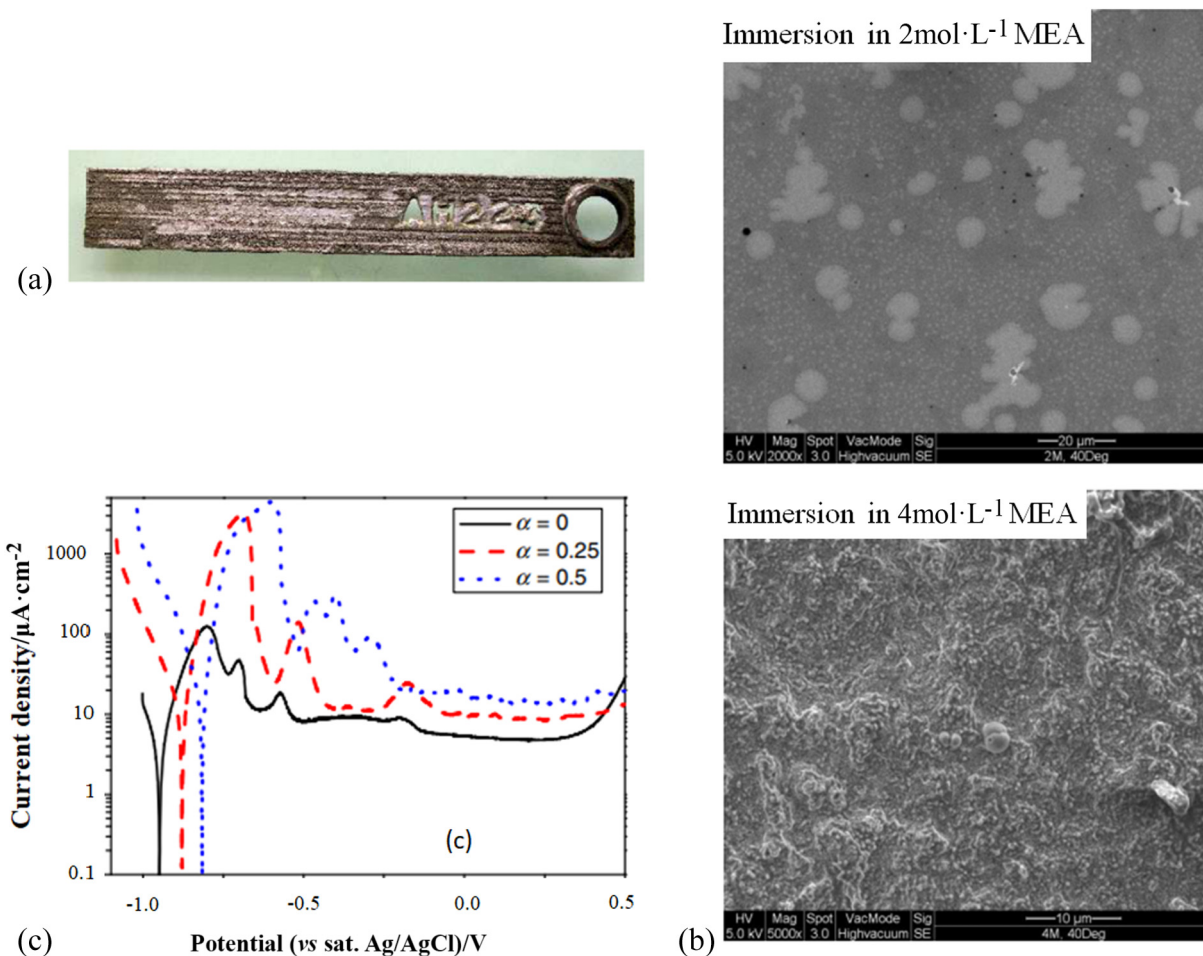


Fig. 8. (a) Photo of AISI 1018 carbon steel coupon upon 3 weeks of exposure in the lean solvent outlet of the stripper (Adapted with permission from [20]. Copyright (2009). Elsevier). (b) SEM images of carbon steel immersed in carbonated-2 mol·L<sup>-1</sup> and 4 mol·L<sup>-1</sup> MEA solutions; some pitting spots were seen on the 2 mol·L<sup>-1</sup> MEA-immersion sample, while dispersed islands of corrosion products were found on the 4 mol·L<sup>-1</sup> MEA-immersion sample (Adapted with permission from [72] under CC BY). (c) Polarisation curves of carbon steel in MEA loaded with different CO<sub>2</sub> amounts (0, 0.25, 0.50 mol CO<sub>2</sub>/mol MEA) (Adapted with permission from [73] under CC BY).

for CO<sub>2</sub> capture; they found that the AISI 1018 carbon steel installed at the outlet of the stripper experiences high corrosion rates (4.5 mm/year–8.5 mm/year) causing almost 80% lost in its initial weight [20]. Fig. 8(a) shows the photo of the corroded carbon steel; while Fig. 8(b) shows the scanning electron micrographic of a carbon steel exposed to different MEA concentrations at 40 °C [72].

The corrosiveness of carbon steel will increase with the increase of MEA concentration [74]. In particular, the corrosion risk is enhanced when the MEA concentration is >30%. Thus, 20%–30% MEA concentration has been set as the rule-of-thumb for industrial usage [71,73,75,76]. One of the possible reasons for this effect is that the amount of absorbed CO<sub>2</sub> will increase with the increase in MEA concentration. More H<sub>3</sub>O<sup>+</sup> is formed under high CO<sub>2</sub> content and thus resulting in higher corrosion rate [74].

The effect of CO<sub>2</sub> loading appears to be the most influencing factor on the corrosion rate. This is expectable as corrosion starts with the dissociation of CO<sub>2</sub> and its subsequent reaction with the amine solvent and metal surface. As illustrated in Fig. 8(c), about tenfold increase in the corrosion current density was observed when the CO<sub>2</sub> loading was increased from 0 to 0.5 [73]. Similarly, Kladaew *et al.* recorded a remarkable increase in corrosion rates from 12 mpy, to 79 mpy, 159 mpy, 192 mpy, for loading of 0, 0.2, 0.4, and 0.5 mol CO<sub>2</sub> · (mol MEA)<sup>-1</sup>, respectively [74].

A work done by Xiang *et al.* revealed that corrosion rate of carbon steel (which has been exposed to MEA/CO<sub>2</sub> solution) decreases with time [77]. Here, the corrosion rate was found to decrease from an initial value of ~0.9 mm/year to ≤0.1 mm/year after 24 h exposure to the MEA/CO<sub>2</sub> solution. Such remarkable reduction could be due to the formation of thin protective FeCO<sub>3</sub> layer and the adsorption of MEA. Meanwhile, the carbon steel that being exposed to MEA/CO<sub>2</sub>/O<sub>2</sub> solution experienced a high corrosion rate over time. This study also found that temperature has only mild impact on the corrosion rate as the solubility of both CO<sub>2</sub> and O<sub>2</sub> reduced with the increase in temperature. On the other hand, Veawab found that the corrosion rate of carbon steel in 2 kmol · m<sup>-3</sup> MEA solution rises from 2.6 mpy to 16.2 mpy when the operating temperature increases from 30 °C to 80 °C [78].

Erfani *et al.* found that the extent of temperature effect is depending on the presence of CO<sub>2</sub> in the amine solution [79]. The temperature effect is significant in lean amine solution and less significant in rich amine solution. In lean amine solution, the corrosion potential at 60 °C and 80 °C were recorded as -708 mV and -909.6 mV, respectively. In addition, the corrosion rate of the specimen at 80 °C was found to be 11.86 mpy; while the specimen at 60 °C has corrosion rate < 1 mpy. On the contrary, the same temperature change induced only a mild to negligible impact when come to rich amine solution. In this regard, the corrosion potential obtained for the temperature 60 °C and 80 °C in rich amine were -860.5 mV and -888.6 mV, respectively; while the corrosion rates were 10.20 mpy and 12.21 mpy, respectively. Polarisation profiles of the carbon steel shown in Fig. 9 clearly demonstrate this different.

Numerous studies have been done to compare the corrosiveness of different amine solvents over the carbon steel. One of this is the fascinating work by Gunasekaran *et al.* which showed that the corrosiveness of CO<sub>2</sub>-saturated amines decreases in the order of MEA > AMP > diethanolamine (DEA) > PZ > MDEA [80]. Nevertheless, in certain cases, the AMP was found leading to higher initial corrosion rate than MEA, probably due to preferable formation of HCO<sub>3</sub><sup>-</sup> in AMP [78,81]. While recent research has moving to the uses of blended amines for synergetic effect, the corrosion induced by the blended amines need to be known as well. In this regard, Gunasekaran *et al.* revealed that the corrosiveness of CO<sub>2</sub>-saturated blended amines following the order MEA-PZ ≥ MEA-AMP ≥ MEA-MDEA > MDEA-PZ > AMP-PZ [80]. Table 1 lists the corrosion rates reported by literature works using either sole amine solvent or blended of MEA with another solvent as CO<sub>2</sub> absorbent. Two information can be gained from Table 1; firstly, MEA appears

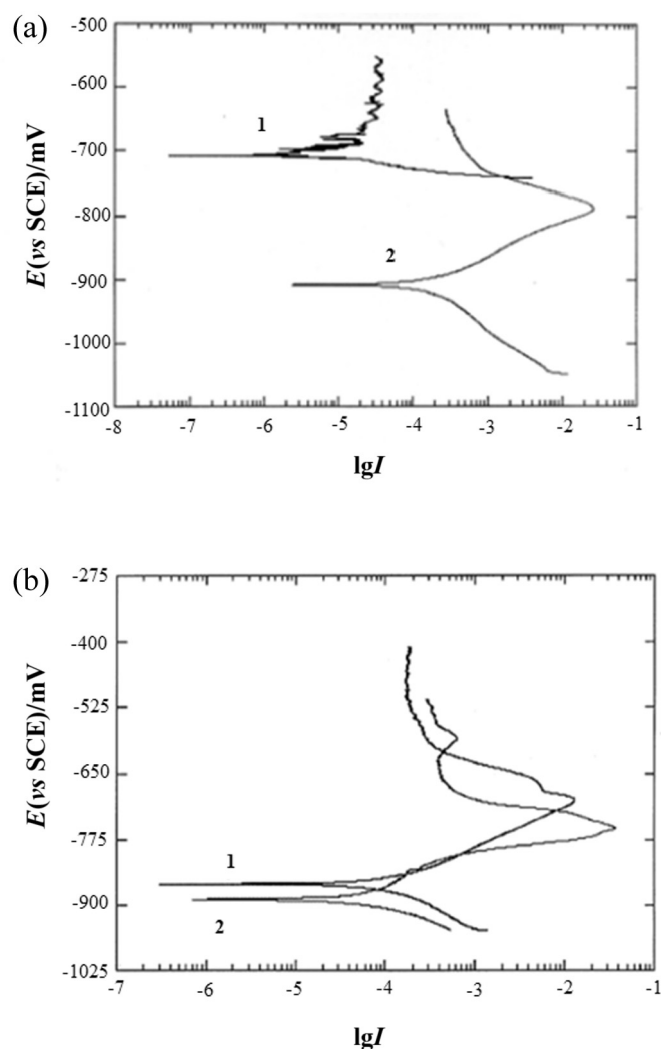


Fig. 9. Polarisation curve of carbon steel in (a) lean amine solution and (b) rich amine solution (Adapted with permission from [79]. Copyright (2015). VÚRUP, a. s.). [label 1 = 60 °C; label 2 = 80 °C] It is clearly seen that the corrosion potential is largely affected by temperature in lean amine solution and less affected by temperature in rich amine solution.

to be more corrosive than other solvents under the same study conditions. Secondly, mixing another amine solvent with MEA induces a lower corrosion rate as compared to the use of sole MEA.

Besides all the above mentioned factors, it is noteworthy that MEA tends to be degraded [14,86,87] whereby the degradation process is induced thermally under the presence of CO<sub>2</sub>, or via oxidative degradation [88]. The degraded products may also cause to corrosion effect [21].

### 3.3. Role of corrosion inhibitors in lean and rich amine solution

One of the possible ways to reduce the corrosion impact from CO<sub>2</sub>-dissolved amine solution will be to select stainless steel (instead of carbon steel) as the building material for the absorber column [73]. Nevertheless, this is expected to increase the capital cost. Corrosion inhibitor came into play if it is the aim to reduce the corrosion along with minimisation of costs.

Veawab *et al.* has conducted a study on the role of corrosion inhibitors in lean amine solution. It was determined that the addition of corrosion inhibitors such as sodium metavanadate (NaVO<sub>3</sub>) and sodium sulphite (Na<sub>2</sub>SO<sub>3</sub>) can effectively protect the metal from corrosion [89]. 10 μL · L<sup>-1</sup> of NaVO<sub>3</sub> demonstrates at least 93.8% of corrosion protection,

**Table 1**  
Summary on corrosion rates of carbon steel metal in sole and blended amine-based solvents

Solvent	Alloy	Study conditions	Corrosion rates/mpy	Ref.
<i>Single solvent</i>				
MEA	Carbon steel 1020 (C content: 0.20 wt%)	- 3 kmol·m <sup>-3</sup> amine solvent -Saturated with CO <sub>2</sub> - 80 °C	136.4	[78]
		- 5 kmol·m <sup>-3</sup> amine solvent -Saturated with CO <sub>2</sub> - 80 °C	164.17 <sup>Ⓢ</sup>	[80,82]
	Carbon steel 1018	- 4 mol·L <sup>-1</sup> amine solvent - Load with 0.55 mol CO <sub>2</sub> ·(mol MEA) <sup>-1</sup> - 80 °C	124.96 <sup>Ⓢ</sup>	[70]
		- 5 mol·L <sup>-1</sup> amine solvent -Load with 0.55 mol CO <sub>2</sub> ·(mol MEA) <sup>-1</sup> - 80 °C	166.35	[83]
AMP	Carbon steel 1020 (C content: 0.20 wt%)	- 3 kmol·m <sup>-3</sup> amine solvent -Saturated with CO <sub>2</sub> - 80 °C	125.9	[78]
		- 4 kmol·m <sup>-3</sup> amine solvent -Saturated with CO <sub>2</sub> - 80 °C	122.44 <sup>Ⓢ</sup>	[80,82]
	Carbon steel A106	- 30 wt% amine solvent - Load with 0.43 mol CO <sub>2</sub> ·(mol AMP) <sup>-1</sup> - 80 °C	78.74 <sup>Ⓢ</sup>	[81]
PZ	Carbon steel 1018	- 5 kmol·m <sup>-3</sup> amine solvent -Saturated with CO <sub>2</sub> - 80 °C	64.57 <sup>Ⓢ</sup>	[80,82]
	Carbon steel A106	- 30 wt% amine solvent - Load with 0.23–0.43 mol C·(mol N) <sup>-1</sup> - 80 °C	19.29–120.87 <sup>Ⓢ</sup>	[84]
MDEA	Carbon steel 1020 (C content: 0.20 wt%)	- 3 kmol·m <sup>-3</sup> amine solvent -Saturated with CO <sub>2</sub> - 80 °C	67.6	[78]
		- 5 kmol·m <sup>-3</sup> amine solvent -Saturated with CO <sub>2</sub> - 80 °C	35.04 <sup>Ⓢ</sup>	[80,82]
	Carbon steel A36 (C content: 0.23 wt%)	- 50 wt% amine solvent -Load with 0.13 mol CO <sub>2</sub> ·(mol MDEA) <sup>-1</sup> - 50 °C	8.27 <sup>Ⓢ</sup>	[85]
<i>Blended of MEA with another solvent</i>				
MEA/MDEA	Carbon steel 1020 (C content: 0.20 wt%)	- 3 kmol·m <sup>-3</sup> amine solvent -Saturated with CO <sub>2</sub> - 80 °C	77.6	[78]
MEA/MDEA	Carbon steel 1018	- 5 kmol·m <sup>-3</sup> amine solvent (1:1 mol ratio) - Saturated with CO <sub>2</sub> - 80 °C	112.60 <sup>Ⓢ</sup>	[80,82]
MEA/AMP	Carbon steel 1020 (C content: 0.20 wt%)	- 3 kmol·m <sup>-3</sup> amine solvent - Saturated with CO <sub>2</sub> - 80 °C	127.3	[78]
MEA/AMP	Carbon steel 1018	- 5 kmol·m <sup>-3</sup> amine solvent (1:1 mol ratio) - Saturated with CO <sub>2</sub> - 80 °C	118.50 <sup>Ⓢ</sup>	[80,82]
MEA/PZ	Carbon steel 1018	- 5 kmol·m <sup>-3</sup> amine solvent (1:1 mol ratio) - Saturated with CO <sub>2</sub> - 80 °C	122.84 <sup>Ⓢ</sup>	[80,82]

<sup>Ⓢ</sup> The original article provided data in mmpy. (taking 1 mmpy = 39.37 mpy).

resulting in <1 mpy corrosion rate. The protection can go up to 99.9% when the concentration of NaVO<sub>3</sub> increased to 75 μL<sup>-1</sup>. In addition to the NaVO<sub>3</sub>, Na<sub>2</sub>SO<sub>3</sub> is also another satisfactory corrosion inhibitor which induced 90%–93% protection even by just added in small quantity.

Erfani studied the effectiveness of a commercialised corrosion inhibitor in both lean and rich amine solution [79]. The experiment was conducted at 80 °C along with 200 μL<sup>-1</sup> corrosion inhibitor. It was found that the corrosion inhibitor works well in the lean amine solution by reducing the corrosion rate from 11.86 mpy to 8 mpy. Similarly, 200 μL<sup>-1</sup> of corrosion inhibitor was able to mix well in the rich amine solution and aid in reducing the corrosion rate down to 7.089 mpy. It shall be taken note that further increases the concentration of corrosion inhibitor >200 μL<sup>-1</sup> does not further reduce the corrosion rate but cause to a slight increase in corrosion rate. Hence, optimum concentration of corrosion inhibitor needs to be determined for effective protection. In fact, too high

concentration of corrosion inhibitor will cause issue such as plugging and eroding [89].

#### 4. Comparison with Amino Acid Salt Solution as Alternative CO<sub>2</sub> Absorbing Agent

Besides amine-based solvents, recent works have ventured into the uses of amino acid salt (AAS) solutions as an alternative CO<sub>2</sub> absorbing agent [90–92]. Similar to amine-based solvents, the AAS also possess amine functional group; thus, able to react with CO<sub>2</sub> molecules. Potassium L-asparaginate, potassium lysinate, potassium taurinate, sodium glycinate, sodium L-phenylalaninate are some of the commonly studied AAS for CO<sub>2</sub> absorption [90]. In terms of advantages, AAS exhibits low toxicity, good biodegradability [93,94], and higher pKa value than amine-based solvents [90]. The latter



suggesting a higher reactivity with CO<sub>2</sub>. Meanwhile, the AAS has low volatility and ability to resist O<sub>2</sub> degradation [95]; this serves as an answer to the traditional amine solvents (e.g. MEA, MDEA) which are susceptible to CO<sub>2</sub> thermal degradation and are volatile at high operating temperatures [90,96].

Another unique feature of AAS is that they are able to form solid precipitates upon absorbing CO<sub>2</sub> [97–99]. The formation of solid precipitates helps to shift the reaction equilibrium to produce more carbamate or bicarbonate [98]. Such phase-change also induces higher driving force for absorption as the equilibrium CO<sub>2</sub> pressure are maintained while the CO<sub>2</sub>-loading of the solvent is further increases [97,98]. In terms of performance, Lerche *et al.* reported that 0.5 mol·L<sup>-1</sup> potassium glycinate has the same CO<sub>2</sub> loading capacity as 0.5 mol·L<sup>-1</sup> MEA (i.e. 0.8 mol CO<sub>2</sub> per mol amine) [100]. On the other hand, Sanchez-Fernandez *et al.* proven that AAS (by taking potassium salt of taurine as model) consume less energy and induce less corrosion impact as compared to MEA [99]. In particular, the regeneration energy required to recover potassium salt of taurine is lesser than MEA [99,101]. Moiolia *et al.* via a detail techno-economic analysis showed that the overall capital cost of the system using potassium taurate is ~20% lesser than the one using MEA [102].

## 5. Conclusions and Future Outlooks

Despite the well development of amine-based PCCC technology, there are still many undiscovered areas requires for exploration. First and foremost, ongoing research should focus on the strategies to reduce the environmental and health risks associated with the usage of amine solvents. In particular, available studies have allocated little attention on the potential risks upon degradation of amine solvent. Amine solvent may degrade via three mechanisms, namely the oxidative degradation, thermal degradation and atmospheric degradation. Oxidative degradation often takes place in the absorber while thermal degradation generally takes place in the stripper where it depends mainly on the operating temperature. For the case of atmospheric degradation, amines will start degrading and turn into other products once they are emitted from the CO<sub>2</sub> capture plant. There are a variety of degradation products such as amides, nitrosamines, nitramines and aldehydes [103]. The degraded products with the most negative impacts will probably be nitramines and nitrosamines as they are carcinogenic and mutagenic [103–105]. While the ultimate goal of PCCC is to reduce the adverse impact of industrial revolution on the environment by not introducing secondary pollution, the creation of various degraded amine wastes has to be reduced. Hence, it is necessary to investigate method to mitigate the degradation of amine solvents.

Secondly, available literatures mostly describe the role of single amine-based solvents in affecting the corrosion rates. On the other side, there is a lack of related information for the blended amine-based solvent. While it has been proven that blended amine solvents can provide a better performance in CO<sub>2</sub> removal as compared to single amine solvent, the absorption mechanism and the corrosion rate induced by these blended amine solvents are less reported. Meanwhile, other technical information such as whether this blended amine solvent can demonstrate high degree of CO<sub>2</sub> capture with least volume of usage, reduced energy requirement, reduced corrosion impact, as well as minimum environmental impact is scarcely available in open literature. To disclose this piece of information, research effort shall allocate on the process optimization to determine the optimum mixture ratio, optimum process temperature and *etc.* Meanwhile, regenerability of the blended amines is another factor that will directly reflect the cost incurred on the entire CO<sub>2</sub> capture process.

Another research area quest for more investigation is the contradict role of amine solvent as corrosion promoter or corrosion inhibitor. Taking MEA as an example, it has been reported that MEA is a

corrosive solvent especially at concentration > 30%; on the other hand, there are also studies showing that the adsorption of MEA on the metal surface can protect the metal from corrosion [106,107]. Apparently, there is a need to understand the working mechanisms of MEA and other amine solvents under both roles.

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## References

- [1] D. Cebrecan, V. Cebrecan, I. Ionel, CO<sub>2</sub> capture and storage from fossil fuel power plants, *Energy Procedia* 63 (2014) 18–26.
- [2] J. Liu, Q. Yang, Y. Zhang, W. Sun, Y. Xu, Analysis of CO<sub>2</sub> emissions in China's manufacturing industry based on extended logarithmic mean division index decomposition, *Sustainability* 11 (1) (2019) 1–28.
- [3] L.C.Y. Yu, K.L. Sedransk Campbell, D.R. Williams, Using carbon steel in the stripper and reboiler for post-combustion CO<sub>2</sub> capture with aqueous amine blends, *International Journal of Greenhouse Gas Control* 51 (2016) 380–393.
- [4] W. Li, J. Landon, B. Irvin, L. Zheng, K. Ruh, L. Kong, J. Pelgen, D. Link, J.D. Figueroa, J. Thompson, H. Nikolic, K. Liu, Use of carbon steel for construction of post-combustion CO<sub>2</sub> capture facilities: A pilot-scale corrosion study, *Ind. Eng. Chem. Res.* 56 (16) (2017) 4792–4803.
- [5] D. Dwivedi, K. Lepková, T. Becker, Carbon steel corrosion: A review of key surface properties and characterization methods, *RSC Adv.* 7 (8) (2017) 4580–4610.
- [6] M.F. Hasan, Analysis of mechanical behavior and microstructural characteristics change of ASTM A-36 steel applying various heat treatment, *J. Mater. Sci. Eng.* 5 (2) (2016) 227.
- [7] B.W. Darvell, in: B.W. Darvell (Ed.), Chapter 13 – Corrosion in materials science for dentistry, Woodhead Publishing, UK 2018, pp. 381–398.
- [8] A. Kahyarlian, B. Brown, S. Nescic, Mechanism of CO<sub>2</sub> corrosion of mild steel: A new narrative, *Corrosion* 2018, NACE International, Phoenix, Arizona, USA 2018, p. 16.
- [9] R. Javaherdashti, How corrosion affects industry and life, *Anti-Corrosion Methods and Materials* 47 (1) (2000) 30–34.
- [10] Corrosion Cost and Preventive Strategies in the United States. (FHWA-RD-01-156) (2002).
- [11] A. Nuchitprasittichai, S. Cremaschi, Sensitivity of amine-based CO<sub>2</sub> capture cost: The influences of CO<sub>2</sub> concentration in flue gas and utility cost fluctuations, *International Journal of Greenhouse Gas Control* 13 (2013) 34–43.
- [12] M. Oschatz, M. Antonietti, A search for selectivity to enable CO<sub>2</sub> capture with porous adsorbents, *Energy Environ. Sci.* 11 (1) (2018) 57–70.
- [13] D.H. Van Wagener, G.T. Rochelle, Stripper configurations for CO<sub>2</sub> capture by aqueous monoethanolamine and piperazine, *Energy Procedia* 4 (2011) 1323–1330.
- [14] P. Luis, Use of monoethanolamine (MEA) for CO<sub>2</sub> capture in a global scenario: Consequences and alternatives, *Desalination* 380 (2016) 93–99.
- [15] V. Barbarossa, F. Barzagli, F. Mani, S. Lai, P. Stoppioni, G. Vanga, Efficient CO<sub>2</sub> capture by non-aqueous 2-amino-2-methyl-1-propanol (AMP) and low temperature solvent regeneration, *RSC Adv.* 3 (30) (2013) 12349–12355.
- [16] S. Mudhasakul, H.-m. Ku, P.L. Douglas, A simulation model of a CO<sub>2</sub> absorption process with methyl-diethanolamine solvent and piperazine as an activator, *International Journal of Greenhouse Gas Control* 15 (2013) 134–141.
- [17] Y.K. Salkuyeh, M. Mofarahi, Comparison of MEA and DGA performance for CO<sub>2</sub> capture under different operational conditions, *Int. J. Energy Res.* 36 (2) (2012) 259–268.
- [18] J. Liu, X. Li, Z. Zhang, L. Li, Y. Bi, L. Zhang, Promotion of CO<sub>2</sub> capture performance using piperazine (PZ) and diethylenetriamine (DETA) bi-solvent blends, *Greenhouse Gases: Science and Technology* 9 (2) (2019) 349–359.
- [19] K.L.S. Campbell, Y. Zhao, J.J. Hall, D.R. Williams, The effect of CO<sub>2</sub>-loaded amine solvents on the corrosion of a carbon steel stripper, *International Journal of Greenhouse Gas Control* 47 (2016) 376–385.
- [20] J. Kittel, R. Idem, D. Gelowitz, P. Tontiwachwuthikul, G. Parrain, A. Bonneau, Corrosion in MEA units for CO<sub>2</sub> capture: Pilot plant studies, *Energy Procedia* 1 (1) (2009) 791–797.
- [21] G. Fytianos, A. Grimstvedt, H. Knuutila, H.F. Svendsen, Effect of MEA's degradation products on corrosion at CO<sub>2</sub> capture plants, *Energy Procedia* 63 (2014) 1869–1875.
- [22] L.T. Popoola, A.S. Grema, G.K. Latinwo, B. Gutti, A.S. Balogun, Corrosion problems during oil and gas production and its mitigation, *International Journal of Industrial Chemistry* 4 (1) (2013) 35.
- [23] S. Szabó, Metal corrosion and its relation to other fields of science, *Int. J. Corros. Scale Inhib.* 4 (1) (2015) 35–48.
- [24] R. Singh, R. Singh (Eds.), Chapter Six – Corrosion and Corrosion Protection, in Pipeline Integrity Handbook, 245–254, Gulf Professional Publishing, Boston, 2014.
- [25] J. Hernandez, A. Muñoz, J. Genesca, Formation of iron-carbonate scale-layer and corrosion mechanism of API X70 pipeline steel in carbon dioxide-saturated 3% sodium chloride, *Afinidad* 69 (560) (2012).

- [26] A. Kahyarlan, M. Achour, S. Nesić, in: A.M. El-Sherik (Ed.), 7 – CO<sub>2</sub> corrosion of mild steel, in *Trends in Oil and Gas Corrosion Research and Technologies*, Woodhead Publishing, Boston 2017, pp. 149–190.
- [27] J. Kotz, P. Treichel, J. Townsend, *Chemistry and Chemical Reactivity*, Cengage Learning, 2008.
- [28] J. Banaś, U. Lelek-Borkowska, B. Mazurkiewicz, W. Solarski, Effect of CO<sub>2</sub> and H<sub>2</sub>S on the composition and stability of passive film on iron alloys in geothermal water, *Electrochim. Acta* 52 (18) (2007) 5704–5714.
- [29] C. Nwaoha, T. Supar, R. Idem, C. Saiwan, P. Tontiwachwuthikul, M.J. Al-Marri, A. Benamor, Advancement and new perspectives of using formulated reactive amine blends for post-combustion carbon dioxide (CO<sub>2</sub>) capture technologies, *Petroleum* 3 (1) (2017) 10–36.
- [30] R. Rowland, Q. Yang, P. Jackson, M. Attalla, Amine mixtures and the effect of additives on the CO<sub>2</sub> capture rate, *Energy Procedia* 4 (2011) 195–200.
- [31] B. Dutcher, M. Fan, A.G. Russell, Amine-based CO<sub>2</sub> capture technology development from the beginning of 2013—A review, *ACS Appl. Mater. Interfaces* 7 (4) (2015) 2137–2148.
- [32] I.M. Bernhardsen, H.K. Knuutila, A review of potential amine solvents for CO<sub>2</sub> absorption process: Absorption capacity, cyclic capacity and pKa, *International Journal of Greenhouse Gas Control* 61 (2017) 27–48.
- [33] 1998 Freshman Achievement Award, CRC Press LLC, 1998.
- [34] G.F. Versteeg, W.P.M. van Swaaij, On the kinetics between CO<sub>2</sub> and alkanolamines both in aqueous and non-aqueous solutions—I, *Primary and Secondary Amines. Chemical Engineering Science* 43 (3) (1988) 573–585.
- [35] N. McCann, D. Phan, X. Wang, W. Conway, R. Burns, M. Attalla, G. Puxty, M. Maeder, Kinetics and mechanism of carbamate formation from CO<sub>2</sub>(aq), carbonate species, and monoethanolamine in aqueous solution, *J. Phys. Chem. A* 113 (17) (2009) 5022–5029.
- [36] R.E. Reitmeyer, V. Sivertz, H.V. Tartar, Some properties of monoethanolamine and its aqueous solutions, *J. Am. Chem. Soc.* 62 (8) (1940) 1943–1944.
- [37] W.-J. Choi, J.-B. Seo, S.-Y. Jang, J.-H. Jung, K.-J. Oh, Removal characteristics of CO<sub>2</sub> using aqueous MEA/AMP solutions in the absorption and regeneration process, *J. Environ. Sci.* 21 (7) (2009) 907–913.
- [38] L.S. Tan, A.M. Shariff, K.K. Lau, M.A. Bustam, Impact of high pressure on high concentration carbon dioxide capture from natural gas by monoethanolamine/N-methyl-2-pyrrolidone solvent in absorption packed column, *International Journal of Greenhouse Gas Control* 34 (2015) 25–30.
- [39] J. Buzek, J. Podkański, K. Warmuziński, The enhancement of the rate of absorption of CO<sub>2</sub> in amine solutions due to the Marangoni effect, *Energy Convers. Manag.* 38 (1997) S69–S74.
- [40] L.S. Tan, A.M. Shariff, K.K. Lau, M.A. Bustam, Factors affecting CO<sub>2</sub> absorption efficiency in packed column: A review, *J. Ind. Eng. Chem.* 18 (6) (2012) 1874–1883.
- [41] A.S. Joel, M. Wang, C. Ramshaw, E. Oko, Process analysis of intensified absorber for post-combustion CO<sub>2</sub> capture through modelling and simulation, *International Journal of Greenhouse Gas Control* 21 (2014) 91–100.
- [42] M.S. Jassim, G. Rochelle, D. Eimer, C. Ramshaw, Carbon dioxide absorption and desorption in aqueous monoethanolamine solutions in a rotating packed bed, *Ind. Eng. Chem. Res.* 46 (9) (2007) 2823–2833.
- [43] T. Sema, A. Naami, P. Usubharatana, X. Wang, R. Gao, Z. Liang, R. Idem, P. Tontiwachwuthikul, Mass transfer of CO<sub>2</sub> absorption in hybrid MEA-methanol solvents in packed column, *Energy Procedia* 37 (2013) 883–889.
- [44] F. Bougie, M.C. Iliuta, Sterically hindered amine-based absorbents for the removal of CO<sub>2</sub> from gas streams, *J. Chem. Eng. Data* 57 (3) (2012) 635–669.
- [45] P.D. Vaidya, S.G. Jadhav, Absorption of carbon dioxide into sterically hindered amines: Kinetics analysis and the influence of promoters, *Can. J. Chem. Eng.* 92 (12) (2014) 2218–2227.
- [46] H. Svensson, C. Hultheberg, H.T. Karlsson, Precipitation of AMP carbamate in CO<sub>2</sub> absorption process, *Energy Procedia* 63 (2014) 750–757.
- [47] A. Aroonwilas, P. Tontiwachwuthikul, High-efficiency structured packing for CO<sub>2</sub> separation using 2-amino-2-methyl-1-propanol (AMP), *Sep. Purif. Technol.* 12 (1) (1997) 67–79.
- [48] A. Jahangiri, M. Nabipoor Hassankiadeh, Effects of piperazine concentration and operating conditions on the solubility of CO<sub>2</sub> in AMP solution at low CO<sub>2</sub> partial pressure, *Sep. Sci. Technol.* 54 (6) (2019) 1067–1078.
- [49] A. Mindaryani, W. Budhijanto, S.S. Ningrum, Continuous absorption of CO<sub>2</sub> in packed column using MDEA solution for biomethane preparation, *IOP Conference Series: Materials Science and Engineering* 162 (1) (2016), 012006.
- [50] S. Babamohammadi, A. Shamiri, K. Aroua Mohamed, A review of CO<sub>2</sub> capture by absorption in ionic liquid-based solvents, *Reviews in Chemical Engineering* 2015, p. 383.
- [51] J. Seagraves, R.H. Weiland, *Treating High CO<sub>2</sub> Gases with MDEA*, Crambeth Allen Publishing Ltd, UK, 2009.
- [52] S. Mirzaei, A. Shamiri, K. Aroua Mohamed, A review of different solvents, mass transfer, and hydrodynamics for postcombustion CO<sub>2</sub> capture, *Reviews in Chemical Engineering* 2015, p. 521.
- [53] J.G. Speight, 8 – Gas cleaning processes, in: J.G. Speight (Ed.), *Natural Gas*, Second edition, Gulf Professional Publishing, Boston 2019, pp. 277–324.
- [54] M. Edali, A. Aboudheir, R. Idem, Kinetics of carbon dioxide absorption into mixed aqueous solutions of MDEA and MEA using a laminar jet apparatus and a numerically solved 2D absorption rate/kinetics model, *International Journal of Greenhouse Gas Control* 3 (5) (2009) 550–560.
- [55] E.B. Rinker, S.A. Sami, O.C. Sandall, Kinetics and modelling of carbon dioxide absorption into aqueous solutions of N-methyldiethanolamine, *Chem. Eng. Sci.* 50 (5) (1995) 755–768.
- [56] T. Sema, A. Naami, Z. Liang, G. Chen, R. Gao, R. Idem, P. Tontiwachwuthikul, A novel reactive 4-diethylamino-2-butanol solvent for capturing CO<sub>2</sub> in the aspect of absorption capacity, cyclic capacity, mass transfer, and reaction kinetics, *Energy Procedia* 37 (2013) 477–484.
- [57] Z. Feng, F. Cheng-Gang, W. You-Ting, W. Yuan-Tao, L. Ai-Min, Z. Zhi-Bing, Absorption of CO<sub>2</sub> in the aqueous solutions of functionalized ionic liquids and MDEA, *Chem. Eng. J.* 160 (2) (2010) 691–697.
- [58] A. Gladis, M.T. Gundersen, K. Thomsen, P.L. Fosbol, J.M. Woodley, N. von Solms, Comparison of the kinetic promoter piperazine and carbonic anhydrase for CO<sub>2</sub> absorption, *Energy Procedia* 114 (2017) 719–725.
- [59] M.A. Pacheco, S. Kaganoi, G.T. Rochelle, CO<sub>2</sub> absorption into aqueous mixtures of diglycolamine® and methyldiethanolamine, *Chem. Eng. Sci.* 55 (21) (2000) 5125–5140.
- [60] M. Al-Juaied, G.T. Rochelle, Absorption of CO<sub>2</sub> in aqueous diglycolamine, *Ind. Eng. Chem. Res.* 45 (8) (2006) 2473–2482.
- [61] S. Bishnoi, G.T. Rochelle, Thermodynamics of piperazine/methyldiethanolamine/water/carbon dioxide, *Ind. Eng. Chem. Res.* 41 (3) (2002) 604–612.
- [62] S. Bishnoi, G.T. Rochelle, Absorption of carbon dioxide in aqueous piperazine/methyldiethanolamine, *AIChE J.* 48 (12) (2002) 2788–2799.
- [63] S. Bishnoi, G.T. Rochelle, Absorption of carbon dioxide into aqueous piperazine: Reaction kinetics, mass transfer and solubility, *Chem. Eng. Sci.* 55 (22) (2000) 5531–5543.
- [64] M.K. Wong, G. Murshid, M.A. Bustam, S. Tyutyu, A.M. Shariff, Solubility of carbon dioxide in piperazine-activated methyldiethanolamine and 2-amino-2-methyl-1-propanol, *J. Appl. Sci.* 14 (2012) 3114–3117.
- [65] L. Dubois, D. Thomas, Carbon dioxide absorption into aqueous amine based solvents: Modeling and absorption tests, *Energy Procedia* 4 (2011) 1353–1360.
- [66] I. Kim, X. Ma, J.-P. Andreassen, Study of the solid-liquid solubility in the piperazine-H<sub>2</sub>O-CO<sub>2</sub> system using FBRM and PVM, *Energy Procedia* 23 (2012) 72–81.
- [67] L. Li, A.K. Voice, H. Li, O. Namjoshi, T. Nguyen, Y. Du, G.T. Rochelle, Amine blends using concentrated piperazine, *Energy Procedia* 37 (2013) 353–369.
- [68] D. Aaron, C. Tsouris, Separation of CO<sub>2</sub> from flue gas: A review, *Sep. Sci. Technol.* 40 (1–3) (2005) 321–348.
- [69] A.A. Olajire, CO<sub>2</sub> capture and separation technologies for end-of-pipe applications – A review, *Energy* 35 (6) (2010) 2610–2628.
- [70] B. Hamah-Ali, B.S. Ali, R. Yusoff, M.K. Aroua, Corrosion of carbon steel in aqueous carbonated solution of MEA/ [bmim] [DCA], *Int. J. Electrochem. Sci.* 6 (2011) 181–198.
- [71] J. Kittel, E. Fleury, B. Vuillemin, S. Gonzalez, F. Ropital, R. Oltra, Corrosion in alkanolamine used for acid gas removal: From natural gas processing to CO<sub>2</sub> capture, *Mater. Corros.* 63 (3) (2012) 223–230.
- [72] B.S. Ali, B.H. Ali, R. Yusoff, M.K. Aroua, Carbon steel corrosion behaviors in carbonated aqueous mixtures of monoethanolamine and 1-n-butyl-3-methylimidazolium tetrafluoroborate, *Int. J. Electrochem. Sci.* 7 (2012) 3835–3853.
- [73] J. Kittel, S. Gonzalez, Corrosion in CO<sub>2</sub> post-combustion capture with Alkanolamines – A review, *Oil Gas Sci. Technol. – Rev. IFP Energies Nouvelles* 69 (5) (2014) 915–929.
- [74] N. Kladkaew, R. Idem, P. Tontiwachwuthikul, C. Saiwan, Corrosion behavior of carbon steel in the monoethanolamine – H<sub>2</sub>O – CO<sub>2</sub> – O<sub>2</sub> – SO<sub>2</sub> system, *Ind. Eng. Chem. Res.* 48 (19) (2009) 8913–8919.
- [75] R.B. Nielsen, K.R. Lewis, J.G. McCullough, D.A. Hansen, Controlling corrosion in amine treating plants, *Proceedings of the Laurance Reid Gas Conditioning Conference*, Norman, Oklahoma, 1985.
- [76] R.J.B. Wagner, *Fundamentals – Gas sweetening*, *Proceedings of the 56th Laurance Reid Gas Conditioning Conference*, Norman, 2006.
- [77] Y. Xiang, M. Yan, Y.-S. Choi, D. Young, S. Nesić, Time-dependent electrochemical behavior of carbon steel in MEA-based CO<sub>2</sub> capture process, *International Journal of Greenhouse Gas Control* 30 (2014) 125–132.
- [78] A. Veawab, P. Tontiwachwuthikul, A. Chakma, Corrosion behavior of carbon steel in the CO<sub>2</sub> absorption process using aqueous amine solutions, *Ind. Eng. Chem. Res.* 38 (10) (1999) 3917–3924.
- [79] A. Erfani, S. Boroojerdi, A. Dehghani, M. Yarandi, Investigation of carbon steel and stainless steel corrosion in a MEA based CO<sub>2</sub> removal plant, *Petroleum & Coal* 57 (1) (2015) 48–55.
- [80] P. Gunasekaran, A. Veawab, A. Aroonwilas, Corrosivity of single and blended amines in CO<sub>2</sub> capture process, *Energy Procedia* 37 (2013) 2094–2099.
- [81] L. Zheng, N.S. Matin, J. Thompson, J. Landon, N.E. Holubowitch, K. Liu, Understanding the corrosion of CO<sub>2</sub>-loaded 2-amino-2-methyl-1-propanol solutions assisted by thermodynamic modeling, *International Journal of Greenhouse Gas Control* 54 (2016) 211–218.
- [82] P. Gunasekaran, Corrosion evaluation for absorption – Based CO<sub>2</sub> capture process using single and blended amines, *Process Systems Engineering*, 206, University of Regina, Regina, Saskatchewan, Canada, 2012.
- [83] P. Wattanaphan, T. Sema, R. Idem, Z. Liang, P. Tontiwachwuthikul, Effects of flue gas composition on carbon steel (1020) corrosion in MEA-based CO<sub>2</sub> capture process, *International Journal of Greenhouse Gas Control* 19 (2013) 340–349.
- [84] L. Zheng, J. Landon, N. Matin, Z. Li, G. Qi, K. Liu, Corrosion behavior of carbon steel in piperazine solutions for post-combustion CO<sub>2</sub> capture, *ECS Trans.* 61 (20) (2014) 81–95.
- [85] Y.-S. Choi, D. Duan, S. Nešić, F. Vitse, S.A. Bedell, C. Worley, Effect of oxygen and heat stable salts on the corrosion of carbon steel in MDEA-based CO<sub>2</sub> capture process, *Corrosion* 66 (12) (2010) 125004-125004-10.
- [86] M. Gupta, S.J. Vevelstad, H.F. Svendsen, Mechanisms and reaction pathways in MEA degradation; A computational study, *Energy Procedia* 63 (2014) 1115–1121.
- [87] S.B. Fredriksen, K.-J. Jens, Oxidative degradation of aqueous amine solutions of MEA, AMP, MDEA, Pz: A Review, *Energy Procedia* 37 (2013) 1770–1777.

- [88] S.J. Vevelstad, I. Eide-Haugmo, E.F. da Silva, H.F. Svendsen, Degradation of MEA; a theoretical study, *Energy Procedia* 4 (2011) 1608–1615.
- [89] A. Veawab, P. Tontiwachwuthikul, S.D. Bhole, Studies of corrosion and corrosion control in a CO<sub>2</sub> – 2-amino-2-methyl-1-propanol (AMP) environment, *Ind. Eng. Chem. Res.* 36 (1) (1997) 264–269.
- [90] Z. Zhang, Y. Li, W. Zhang, J. Wang, M.R. Soltanian, A.G. Olabi, Effectiveness of amino acid salt solutions in capturing CO<sub>2</sub>: A review, *Renew. Sust. Energ. Rev.* 98 (2018) 179–188.
- [91] A.F. Ciftja, A. Hartono, H.F. Svendsen, Selection of amine amino acids salt systems for CO<sub>2</sub> capture, *Energy Procedia* 37 (2013) 1597–1604.
- [92] S. Matsunaga, Molecular dynamics study on carbon dioxide absorbed potassium glycinate aqueous solution, *J. Solut. Chem.* 46 (12) (2017) 2268–2280.
- [93] R. Shao, A. Stangeland, Amines Used in CO<sub>2</sub> Capture – Health and Environmental Impacts, The Bellona Foundation, Oslo, Norway, 2009.
- [94] I. Eide-Haugmo, O.G. Brakstad, K.A. Hoff, K.R. Sørheim, E.F. da Silva, H.F. Svendsen, Environmental impact of amines, *Energy Procedia* 1 (1) (2009) 1297–1304.
- [95] F. He, T. Wang, M. Fang, Z. Wang, H. Yu, Q. Ma, Screening test of amino acid salts for CO<sub>2</sub> absorption at flue gas temperature in a membrane contactor, *Energy Fuel* 31 (1) (2017) 770–777.
- [96] H. Lepaumier, S. Martin, D. Picq, B. Delfort, P.-L. Carrette, New amines for CO<sub>2</sub> capture. III. Effect of alkyl chain length between amine functions on polyamines degradation, *Industrial & Engineering Chemistry Research* 49 (10) (2010) 4553–4560.
- [97] M.E. Majchrowicz, D.W.F. Brilman, M.J. Groeneveld, Precipitation regime for selected amino acid salts for CO<sub>2</sub> capture from flue gases, *Energy Procedia* 1 (1) (2009) 979–984.
- [98] X. Wang, B. Li, in: F. Shi, B. Morreale (Eds.), Chapter 1 – Phase-change solvents for CO<sub>2</sub> Capture, in *Novel Materials for Carbon Dioxide Mitigation Technology*, Elsevier, Amsterdam 2015, pp. 3–22.
- [99] E. Sanchez-Fernandez, F.d.M. Mercader, K. Misiak, L. van der Ham, M. Linders, E. Goetheer, New process concepts for CO<sub>2</sub> capture based on precipitating amino acids, *Energy Procedia* 37 (2013) 1160–1171.
- [100] B.M. Lerche, E.H. Stenby, K. Thomsen, CO<sub>2</sub> capture from flue gas using amino acid salt solutions, PhD Thesis, Danmarks Tekniske Universitet, Denmark, 2012.
- [101] E. Sanchez-Fernandez, K. Heffernan, L. van der Ham, M.J.G. Linders, E.L.V. Goetheer, T.J.H. Vlucht, Precipitating amino acid solvents for CO<sub>2</sub> capture. Opportunities to Reduce Costs in Post Combustion Capture, *Energy Procedia* 63 (2014) 727–738.
- [102] S. Moiola, G. Lodi, L. Pellegrini, M. Ho, W. D., Amino acid based solvent vs. traditional amine solvent: a comparison, *Chemical Engineering Transactions* 69 (2018) 157–162.
- [103] T. Spietz, S. Dobras, L. Więclaw-Solny, A. Krótki, Nitrosamines and nitramines in carbon capture plants, *Environmental Protection and Natural Resources* 28 (4) (2017) 43–50.
- [104] E.D. Wagner, J. Osiol, W.A. Mitch, M.J. Plewa, Comparative in vitro toxicity of nitrosamines and nitramines associated with amine-based carbon capture and storage, *Environmental Science & Technology* 48 (14) (2014) 8203–8211.
- [105] K. Yu, W.A. Mitch, N. Dai, Nitrosamines and nitramines in amine-based carbon dioxide capture systems: Fundamentals, engineering implications, and knowledge gaps, *Environmental Science & Technology* 51 (20) (2017) 11522–11536.
- [106] I. Jevremović, V. Misković-Stanković, The Inhibitive effect of ethanolamine on corrosion behavior of aluminium in NaCl solution saturated with CO<sub>2</sub>, *Metallurgical & Materials Engineering* 18 (4) (2012) 241–257.
- [107] K.T. Kim, Y.S. Kim, H.Y. Chang, B.T. Lim, H.B. Park, Effect of ethanolamines on corrosion inhibition of ductile cast Iron in nitrite containing solutions, *Corrosion Science and Technology* 15 (4) (2016) 171–181.