

CO₂ absorption/desorption in aqueous DEEA/MDEA and their hybrid solutions with sulfolane

Ali Asghar Nozaeim^a, Ahmad Tavasoli^{a,*}, Hamid Reza Mortaheb^{b,*}, Morteza Mafi^b

^a School of Chemistry, College of Science, University of Tehran, Tehran, 11155-4563, Iran

^b Chemistry and Chemical Engineering Research Center of Iran, Tehran, P.O. Box 14335-186, Iran

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ABSTRACT

CO₂ absorption capacities in aqueous and hybrid solutions were investigated by applying a batch reactor under intermediate pressures up to 800 kPa. Tertiary alkanolamine of diethyl ethanol amine (DEEA), N-methyl di ethanol amine (MDEA), and physical solvent of sulfolane were used. Utilizing DEEA and sulfolane in the current research is considered as the first attempt to take the advantages of both chemical and physical solvents in CO₂ capturing. The absorption capacities were increased by increasing the reactant concentration, pressure, and by decreasing the temperature. A higher absorption capacity was observed for the aqueous DEEA solution compared to the other solutions except in high pressures, in which the DEEA hybrid solution represented a higher capacity. Regeneration of the solutions by desorption at 80 °C revealed the effective role of the physical solvent (sulfolane) that yields higher regeneration efficiencies of absorption capacities for the hybrid solutions. The regeneration efficiencies of absorption capacity of the hybrid DEEA solution were in the range of 88.1%–99.1% while those efficiencies for the aqueous DEEA solution were in the range of 50–83.1%. These values for the hybrid and aqueous MDEA solutions were 93.4–98.8% and 85.5–94.2%, respectively. In conclusion, adding sulfolane to the aqueous DEEA solution significantly improved the absorption capacity of the regenerated solution.

1. Introduction

Releasing massive amounts of carbon dioxide from various industries into atmosphere would worsen the greenhouse effect and causes numerous problems including climate change (Qiao et al., 2020).

CO₂ can be removed by means of membrane (Brunetti et al., 2010; Kai and Duan, 2014), adsorption (Pirngruber et al., 2013; Liu and Green, 2014; Hu et al., 2020), and absorption processes. Membrane processes are appropriate for the streams with low CO₂ concentrations (Brunetti et al., 2010). The widely studied adsorbents such as zeolites, silica, metal organic frameworks (Lee and Park, 2015), and N-functionalized solids (Hu et al., 2020) suffer from drawbacks such as low CO₂ selectivity, slow adsorption kinetic, and loss of sorption capacity over multiple cycles (Danaei Kenarsari et al., 2013). Carbon dioxide can be alternatively removed by physical and chemical absorbents in processes which are configured differently based on the physical solubility and chemical reactivity of the absorbent. Some new materials and processes have been investigated for absorption of carbon dioxide (Lepaumier et al., 2009; Murai et al., 2014; Ling et al., 2019; Baena-Moreno et al., 2020; Vega

et al., 2020). Among the commonly used chemical absorbent, the low-price alkanolamine solutions possess the ability to reduce the amount of acidic gases even at low pressures owing to their appropriate properties (Shakerian et al., 2015). CO₂ can be absorbed in either aqueous or blend alkanolamine solutions (Liu et al., 2017; Gao et al., 2020) to exploit the advantages of each amine (Zhang et al., 2017).

Although tertiary amines have restricted reaction rates with carbon dioxide, they are effective solvents for selective absorption of H₂S. On the other hand, tertiary amines require low energy for regeneration (Vega et al., 2020) along with appropriate resistances against corrosion and degradation at high temperatures (Macgregor and Mather, 1991). These advantages make them good candidates for applying as the chemical solvents.

Despite chemical solvents, the non-corrosive physical solvents have no stoichiometric limitation for absorption of acidic gases (Zhenhong et al., 2014). Also, the required heating energy for regeneration of a physical absorbing solution is less than that for a chemical solution (McKetta, 1978). Various physical solvents including dimethyl ether polyethylene glycols (Kapetaki et al., 2015), methanol (Sharma et al.,

* Corresponding author.

** Corresponding author.

E-mail addresses: tavasoli.a@ut.ac.ir (A. Tavasoli), mortaheb@ccerci.ac.ir (H.R. Mortaheb).

2016), propylene carbonate (Mokhtab and Poe, 2012), N-methyl 2-pyrrolidone, ionic liquids (Ahmady et al., 2010; Yan et al. 2020), and sulfolane (Jalili et al., 2015) are used to absorb carbon dioxide.

Utilizing mixed solvents consisting of physical and chemical absorbents is a promising attempt to take the advantages of both chemical and physical solvents. The hybrid solutions such as Sulfinol (Isaacs et al., 1977; Torabi Angaji et al., 2013) may effectively remove the acidic gases as they exploit the merits of either physical or chemical solvents in the following ways: (1) the CO₂ absorption capacity is not limited by the stoichiometry of the reactions especially at high CO₂ partial pressures; (2) a higher purity for the treated gas can be yielded; (3) the circulation flow rate of the solution as well as the energy required for regenerating the solution are lower (Xu et al., 1991); (4) the costs of gas pressure amplification is reduced due to avoiding formation of hydrates at low temperatures; (5) the corrosion is controlled and a permissible limit of contaminant dispersion can be attained (Torabi Angaji et al., 2013).

One of the main factors in selecting amines for gas sweetening is foaming. This phenomenon might be occurred due to degradation of the amine as well as adding corrosion inhibitors in the absorption solution. Applying hybrid solutions reduces the requirement for adding anti-corrosive agents. It also decreases the regeneration temperature that not only reduces the formation of side products due to degrading of amine but also slightly increases the solution viscosity resulting in less foaming (Thitakamol and Veawab, 2008).

Isaacs et al. measured the solubilities of H₂S and CO₂ individually in a Sulfinol solution (40 wt% di-isopropanol amine (DIPA), 40 wt% sulfolane, 20 wt% water) at 40 and 100 °C with H₂S partial pressures of 5–3900 kPa while the partial pressures of CO₂ was in the range of 2.4–5700 kPa. It was found that at high partial pressures, the effect of the physical solvent, sulfolane, becomes dominant and leads to high solubilities of the acidic gases in the liquid. Also, the absorption of Sulfinol solution was significant at partial pressures of 760 kPa or greater (Isaacs et al., 1977). Torabi Angaji et al. simulated the removal of gas impurities (CO₂ and H₂S) by Aspen Plus using Sulfinol-M (37.7 wt % MDEA, 40.2 wt% sulfolane, 21.2 wt% H₂O). It was predicted that replacement of DIPA in Sulfinol by MDEA in Sulfinol-M results in a better performance as well as that compared to the other amine solvents (Torabi Angaji et al., 2013). In another research by Ghanbarabadi and Khoshandam, simulation of gas treatment process was carried out for removal of acidic gases (CO₂ and H₂S) and sulfur compounds (methyl and ethyl mercaptans, dimethyl-sulfide, and COS) by several solutions comprising Sulfinol-M (sulfolane + MDEA + H₂O), DGA, and the mixture of MDEA + AMP. The results were compared with that by MDEA. It was shown that more than 30–40% of mercaptans along with the sour gas are absorbed by Sulfinol-M at lower flow rates where 10–25% lower energy is required for the solvent regeneration. Furthermore, little solvent waste is produced compared to the operation with amine solvents (MDEA + AMP, DGA, and MDEA). The operation parameters for mercaptan and acidic gas absorption can be controlled more easily by using Sulfinol-M than those by amine solvents where energy consumption i.e. the operation costs can be lowered (Ghanbarabadi and Khoshandam, 2015). Macgregor and Mather studied the solubility of hydrogen sulfide, carbon dioxide, and their mixtures at 40° and 100 °C in a mixed solvent comprising 20.9 wt% MDEA, 30.5 wt% sulfolane, and 48.6 wt% water. The results have been compared with those for aqueous 2.0 M MDEA and an analogous mixed solvent containing AMP (Macgregor and Mather, 1991). Nabipour et al. measured and compared CO₂ absorption in the nanofluids containing Fe₃O₄ and MWNT. They found that the presence of both nanoparticles in the based solvent can enhance the rate of absorption and also the equilibrium solubility to the maximum amounts of 46.7% and 23.2%, respectively (Nabipour et al., 2017).

It can be seen that conventional alkanolamines have been commonly used to remove carbon dioxide whereas these alkanolamines can cause high corrosive effects and also have less degradation resistance. Furthermore, majority of the reports have merely studied the absorption

while both absorption and desorption should be considered in a separation process. Accessing the experimental data about solubility of acidic gases in the liquid solvents and optimization of solvent ratio in a hybrid solvent, which are of great importance, have received less attentions.

The purposes of present research are to study the capacities of CO₂ absorption in the hybrid solutions as well as assessing the cyclic CO₂ absorption capacities since an increase in the cyclic capacity will lead to decrease in the solvent circulation rate and thus the operating costs.

The study will focus on the tertiary alkanolamine of DEEA (diethyl ethanol amine) as the chemical absorbent, which has been less investigated compared to MDEA while it represents more CO₂ absorption rate and capacity. It is noticeable that activities of tertiary alkanolamines for CO₂ absorption/desorption depend on the functional groups attached to the nitrogen atom in the amine structure. While the presence of hydroxyl group will help the amine to be dissolved in water and reduces the amine loss by increasing its boiling point, it also increases the absorption heat and regeneration energy. As a result, an amine with less hydroxyl groups in its structure such as DEEA might be preferred to an amine containing higher hydroxyl groups (MDEA) (Xiao et al., 2016). DEEA has also appropriate chemical stability and high resistance against degradation. Accordingly, mixing of DEEA with a physical solvent having proper environmental degradation stability and low regeneration energy such as sulfolane (Shokouhi et al., 2019; Wang et al., 2019) can enhance the absorption capacity at high pressures and surpass the stoichiometric limits (Macgregor and Mather, 1991; Schafer et al., 2002; Wang et al., 2010; Dash and Bandyopadhyay, 2016).

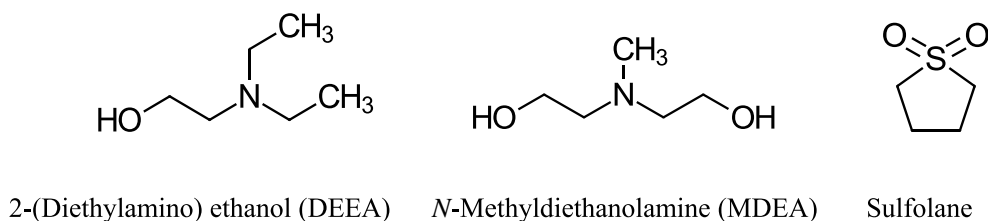
To our knowledge, except for a study by Wang et al. (2019) that measured the solubility of CO₂ in DEEA/DETA/sulfolane solution, no experimental data has been reported concerning CO₂ solubility in the DEEA/sulfolane hybrid solution in literature. In the present work, in addition to the hybrid solution (DEEA/sulfolane/water), all the experiments are also carried out for the aqueous DEEA solution to determine the role of physical solvent in the absorption (Macgregor and Mather, 1991). Furthermore, all the experiments are also performed with MDEA and the results are compared with those by DEEA.

2. Materials

The absorbents used in the experiments were supplied by Merck (Scheme 1). MDEA, DEEA, and sulfolane had minimum purities of 98%, 99%, and 98%, respectively. The CO₂ and N₂ gases were supplied by domestic manufacturers and had purities of 99.9% and 99.99%, respectively.

3. Experimental procedure

A schematic diagram of the setup used in this study to measure the CO₂ absorption capacity is demonstrated in Fig. 1. The core of the setup consists of a 1-Liter stainless steel laboratory pressure reactor (Buchiglas Uster) equipped with a thermocouple, stirrer, pressure transmitter, and a heating/cooling jacket. The reactor is fed initially by an experimental solution. The air above the liquid phase in the reactor is driven out using a flow of nitrogen gas. Then, the top gas phase is evacuated using a vacuum pump (BS 2208, Edwards). A stainless steel gas cylinder with a volume of 0.5 L is used for gas injection. The air inside the cylinder is initially evacuated by the vacuum pump. The cylinder is filled with carbon dioxide, weighed by a scale with ±0.01 g accuracy, and mounted on the reactor. The gas injection from the gas cylinder into the reactor is conducted in order to raise the reactor pressure to the desired setpoint. Stirring the liquid phase inside the reactor by the reactor stirrer is started, and altering in reactor pressure is monitored using a pressure transmitter (PAA-33X, Keller). Sufficient time is considered to assure that the equilibrium conditions have been attained in the reactor. The gas cylinder is then detached from the reactor and weighed by the scale. The vapor pressure of the solution is obtained beforehand using the



Scheme 1. Chemical structures of applied sorbents.

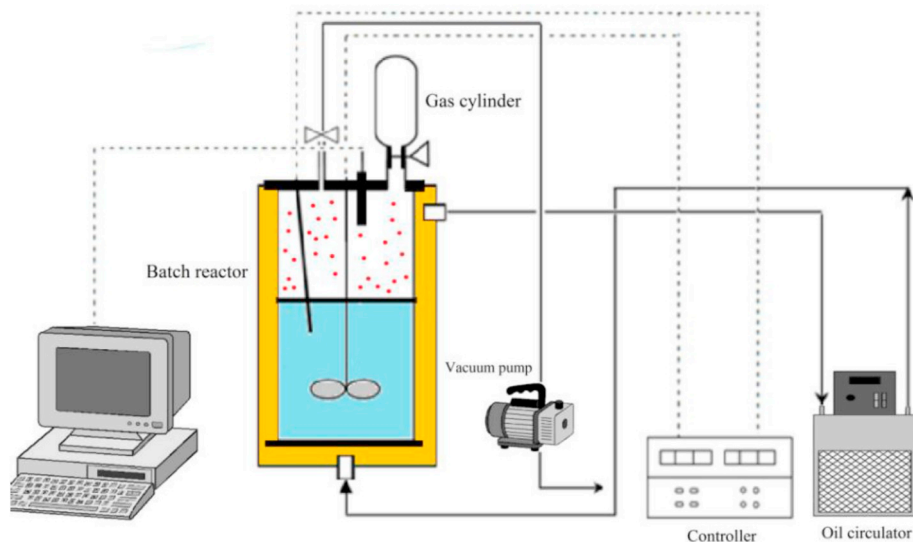


Fig. 1. Schematic diagram of experimental setup.

same experimental procedure. In order to measure the absorption capacity of the recycled solution, the solution is exposed to elevated temperatures (80 °C) where the absorbed carbon dioxide is desorbed gradually. The absorption test is then performed for the regenerated solution to measure its absorption capacity.

The mole of unabsorbed CO₂ in the gas phase, n_u , is determined by knowing the reactor pressure (P_r), vapor pressure of the solution (P_s), and temperature (T_K) as follows:

$$n_u = \frac{P_C}{Z} \frac{V}{R T_K} \quad (1)$$

where P_C is the CO₂ partial pressure obtained from Eq. (2):

$$P_C = P_r - P_s \quad (2)$$

R is the universal gas constant, and V and Z are the gas volume and compressibility factor at the corresponded temperature, respectively. The mass of unabsorbed carbon dioxide in the gas phase, m_u , is then obtained from the following equation:

$$m_u = n_u \times M \quad (3)$$

where M is the molecular weight of CO₂. The mole of absorbed carbon dioxide, n_a , is then calculated by Eq. (4) (Mortaheb et al., 2012):

$$n_a = (m_t - m_u) / M \quad (4)$$

In which, m_t is the total mass of carbon dioxide injected into the system. The CO₂ absorption capacity (M_A) in the liquid phase is calculated by the following equation, in which W_{sol} is the weight of solution in the reactor:

$$M_A = \frac{n_a}{W_{sol}} \quad (5)$$

The relative absorption capacity, R_A , can also be identified as the absorption capacity per mole of reactant, n_r , as:

$$R_A = \frac{n_a}{n_r} \quad (6)$$

In order to ensure about accuracy of the method and calculations, the experimental data obtained for an aqueous solution of 30 wt% MDEA at 303.15 K and 313.15 K were compared to the corresponding data in literature as seen in Fig. 2 (Maleki et al., 2018; Shen and Li, 1992).

4. Results and discussion

The absorption performances of aqueous and hybrid DEEA solutions are assessed for fresh and regenerated solutions. The absorption performance of conventional alkanolamines (MDEA) are also evaluated for both aqueous and hybrid solutions. For more comprehension about CO₂ capturing performances of aqueous and hybrid solutions, the percentages of regeneration efficiencies of absorption capacity (obtained by dividing absorption capacity of the regenerated solution into that of the fresh one) are also represented.

4.1. Effect of absorbent concentration on absorption capacity

Figs. 3 and 4 show the effects of absorbent concentration on the absorption capacity of aqueous and hybrid DEEA solutions in the specified conditions, respectively. As seen in the figures, the absorption capacity increases by increasing DEEA concentration. This can be interpreted considering the chemical reaction of tertiary alkanolamines with CO₂. Unlike primary and secondary alkanolamines, tertiary alkanolamines such as DEEA do not react directly with CO₂ and they only act as proton acceptors (Donaldson and Nguyen, 1980). The main reactions occurred for absorption of carbon dioxide in the presence of a tertiary

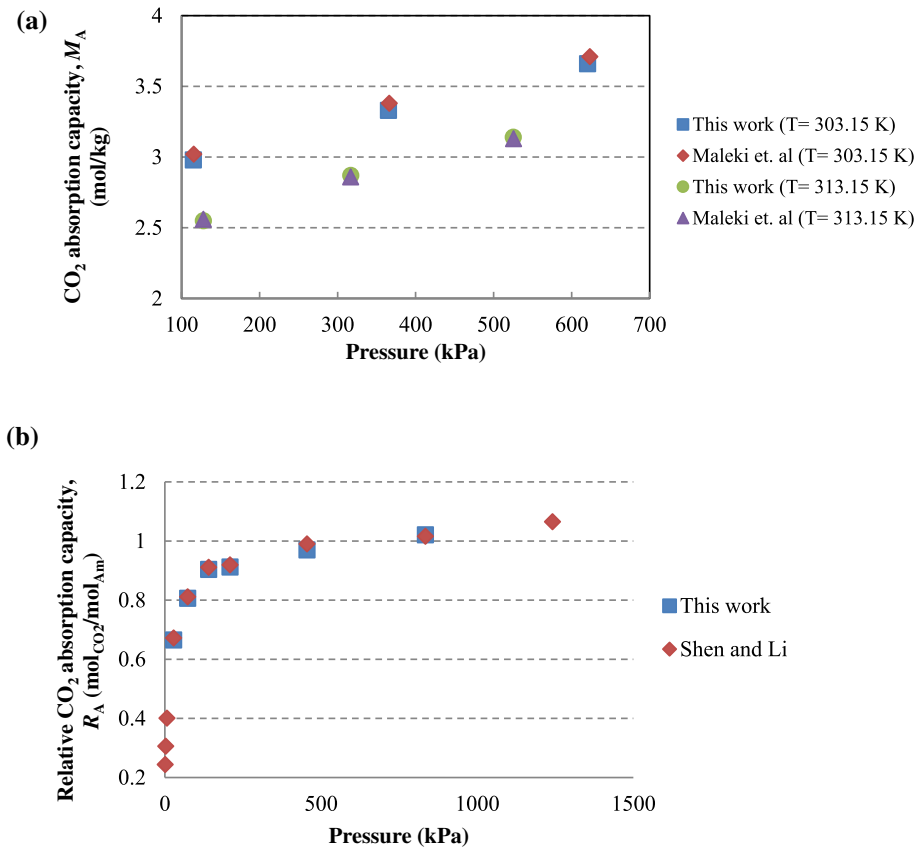


Fig. 2. Validation tests for solubility of CO₂ in a solution of 40 wt% MDEA at (a) 303.15 K and 313.15 K (Maleki et al., 2018), and (b) 30 wt% MDEA at 313.15 K (Shen and Li, 1992).

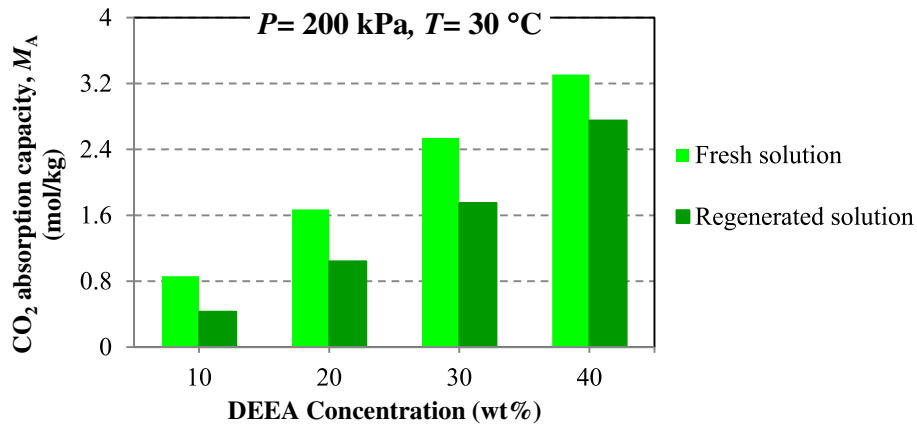


Fig. 3. Effect of DEEA concentration on absorption capacity of aqueous DEEA solution.

alkanolamine is explained by Eqs. (7) and (8), which are summed up as Eq. (9). The reactions represented by Eqs. (10) and (11) are also the side reactions, which may take place in an aqueous solution (Monteiro et al., 2013).

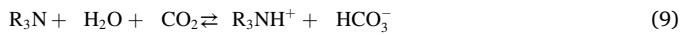


Table 1 represents the absorption capacities of pure sulfolane, sulfolane/water (40/60) solution, and pure water at 30 °C in various pressures. As it can be seen in the table, either sulfolane or sulfolane/water (40/60) solution have higher CO₂ absorption capacities than water. Therefore, it is expected that by replacing water with sulfolane, the hybrid solutions must have higher capacities than that of the aqueous solution. However, comparison of 30\10, 30\20, 30\30, and 30\40 solutions in Fig. 4 shows that the absorption capacity decreases with increasing the concentration of sulfolane that could be related to the deficiency in access to the reactant (Luo et al., 2016) and also to

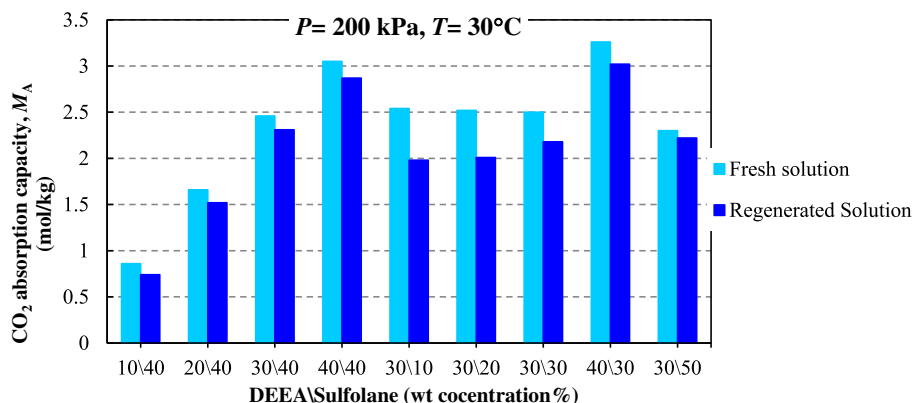


Fig. 4. Effect of DEEA/sulfolane weight concentration on absorption capacity of hybrid DEEA solution.

Table 1

CO₂ absorption capacities (mol.kg⁻¹) in pure sulfolane, sulfolane/water solution, and pure water at 30 °C.

Solution	Pressure (kPa)			
	100	200	400	800
Sulfolane	0.085	0.182	0.351	0.729
Sulfolane + Water (40–60%)	0.041	0.083	0.168	0.335
Water	0.030	0.060	0.120	0.240

decrease in contribution of chemical absorption as the content of water, which is essential for protonation of the tertiary alkanolamine, is reduced (Haghtalab and Shirazizadeh, 2019). It is also seen in Fig. 4 that by decrease in the water content (comparison of 30/50 and 30/40 hybrid solutions, also 40/40 and 40/30), the R_A is decreased (Ghanbarabadi et al., 2019). The solubility of CO₂ in the hybrid solutions is more sensitive to temperature comparing to the aqueous solutions which results in CO₂ desorption to be accomplished at lower temperatures for the hybrid solutions (Zheng et al., 2013). Therefore, as it can be seen in Fig. 5, the absorption capacity of the recovered hybrid solution is expected to be higher than that of the aqueous solution. The effects of concentration on CO₂ absorption capacity in aqueous and hybrid MDEA solutions are represented in Fig. 6. The solubility of CO₂ in an amine is affected by the molecular structure (Li et al., 2007; Xiao et al., 2018). In comparison to MDEA that contains one methyl group and two hydroxyl groups (-CH₂CH₂OH), the strong electron donor ethyl groups in DEEA increase the basic strength of N atom in its structure, which results in increased CO₂ solubility in DEEA. On the other hand, the more hydroxyl groups in MDEA decrease the electron density of the nitrogen atom and thus reduce the CO₂ absorption capacity in MDEA solution compared to that in DEEA solution (Xiao et al., 2016). Therefore, by comparing the

absorption capacities in Figs. 5 and 6, it is observed that the absorption capacities for DEEA solutions at all concentrations are higher than those for MDEA solutions (Xiao et al., 2018).

Fig. 7 shows the regeneration efficiencies of absorption capacities for aqueous and hybrid solutions. As seen in the figure, the regeneration efficiencies of absorption capacities for hybrid solutions are higher than those of the aqueous solutions. It is noticeable that the total regeneration energy (E_{regen}) is comprised of three parts: The heat of reaction (Q_{rxn}), the sensible heat (Q_{sens}), and the latent heat (Q_{latent}). Applying sulfolane as a replacement for a part of water in the aqueous solution decreases Q_{sens} and Q_{latent} and thus reduces E_{regen} . Since the regeneration temperatures for both aqueous and hybrid solutions are the same, the remained CO₂ after desorption in the hybrid solution is lower than that in the aqueous solution, and thus the absorption capacity of the regenerated hybrid solution is higher than that of the regenerated aqueous solution (Wang et al., 2019). As shown in Fig. 7, under the same temperature and pressure conditions, the regeneration efficiency of absorption capacity in the (DEEA and MDEA) aqueous solutions increased with increasing concentration indicating that the loss of solvent at high concentrations had less effect on the absorption. According to Fig. 7, while a negligible change in the regeneration efficiency of absorption capacity in the hybrid MDEA solution is observed by adding sulfolane, the change in the regeneration efficiency of absorption capacity is significant for the hybrid DEEA solution.

Since increasing CO₂ absorption capacity by increasing the regeneration efficiency of absorption capacity is preferred to that by increasing the reactant concentration (Xu et al., 2019), and based on the obtained results, the hybrid solution of 30/40% (DEEA/sulfolane) was chosen to investigate the other parametric effects.

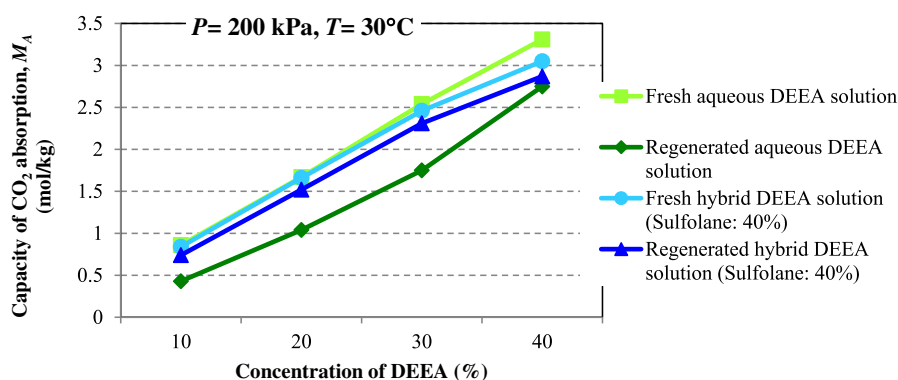


Fig. 5. Effect of DEEA concentration on absorption capacity of aqueous and hybrid DEEA solutions.

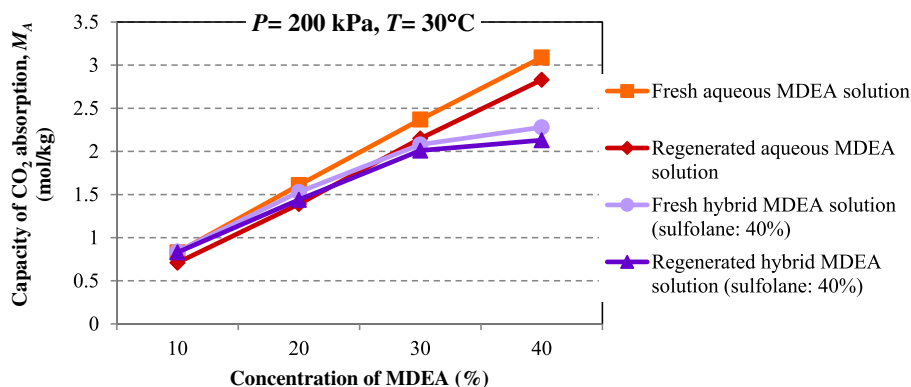


Fig. 6. Effect of MDEA concentration on absorption capacity of MDEA aqueous and hybrid solutions.

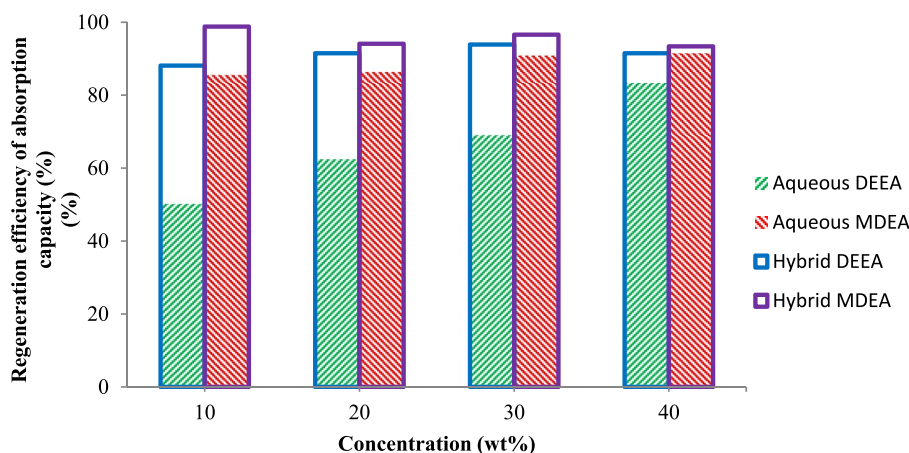


Fig. 7. Regeneration efficiency of absorption capacity in different concentrations.

4.2. Effect of temperature on absorption capacity

The absorption capacities of 30% aqueous DEEA solution and 30% \ 40% hybrid DEEA solutions at 20, 30, and 40 °C are shown in Figs. 8 and 9. The figures indicate that the capacity of CO₂ absorption decreases as the temperature increases for all the solutions due to decrease in the physical solubility of gases in the liquids with increasing temperature (Yih and Sun, 1987). Comparison of the values in the two figures also reveals that the absorption capacity of the aqueous solution at each temperature is slightly higher than that of the hybrid solution.

According to Fig. 10, CO₂ absorption capacity in regenerated hybrid DEEA solution is higher than that of the recovered aqueous DEEA solution owing to the larger amount of CO₂ removed from the hybrid solution in all the temperatures. It also should be noted that the regeneration efficiency of absorption capacity for the hybrid DEEA solution at 40 °C is higher whereas the desorption conditions are the same for all temperatures. Therefore, the amount of CO₂ remaining in the regenerated hybrid solution at 40 °C is lower than those of 20 and 30 °C. Fig. 11 represents the effect of temperature on capacities of CO₂ absorption in aqueous and hybrid MDEA solutions. The figure shows that

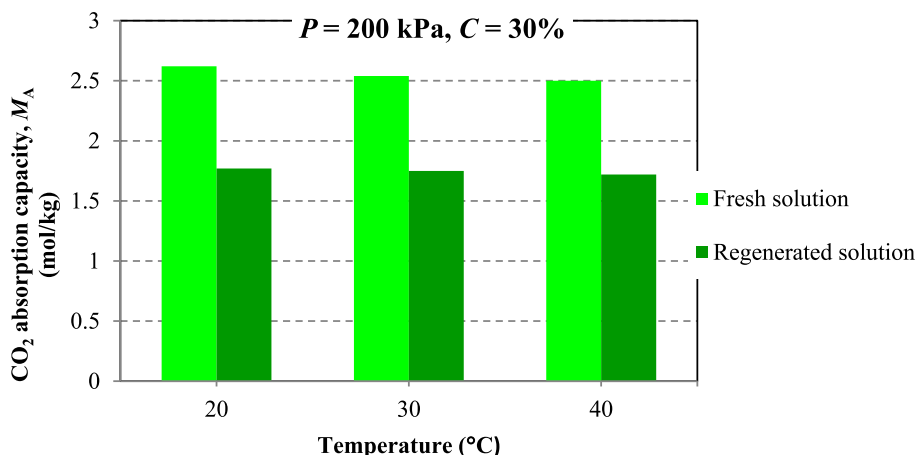


Fig. 8. Effect of temperature on absorption capacity of aqueous DEEA solution.

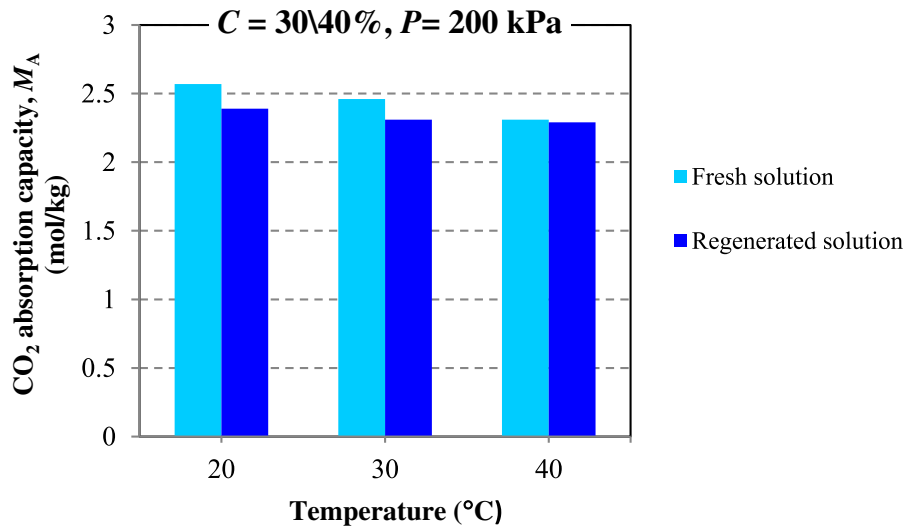


Fig. 9. Effect of temperature on absorption capacity of hybrid DEEA solution.

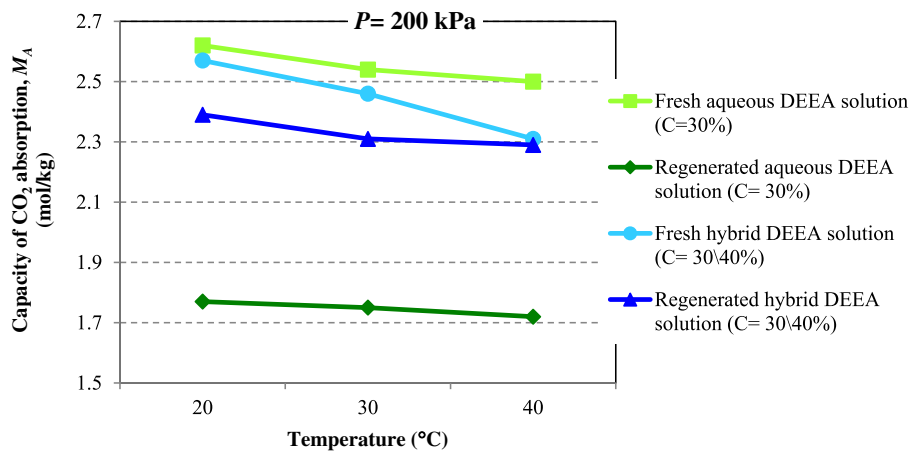


Fig. 10. Effect of temperature on absorption capacity of aqueous and hybrid DEEA solutions.

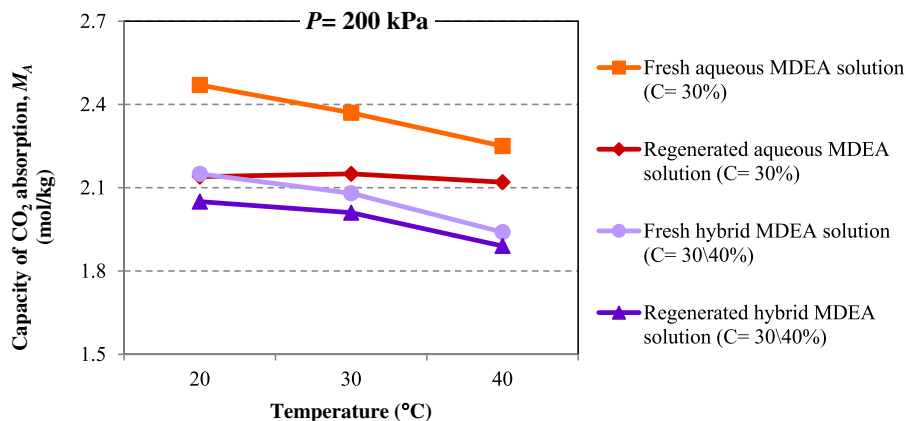


Fig. 11. Effect of temperature on absorption capacity of aqueous and hybrid MDEA solutions.

the absorption capacity is decreased by increasing temperature while the regeneration efficiency of absorption capacity of hybrid solution is slightly higher than that of the aqueous solution (Fig. 12). Furthermore, it can be found that the solutions containing DEEA illustrate better performances in the presence of sulfolane.

4.3. Effect of pressure on capacity of CO₂ absorption

Increase in pressure results in higher CO₂ concentration at the gas-liquid interface and thus a stronger driving force and more CO₂ molecules being dissolved in the liquid phase (Li et al., 2012). However, since

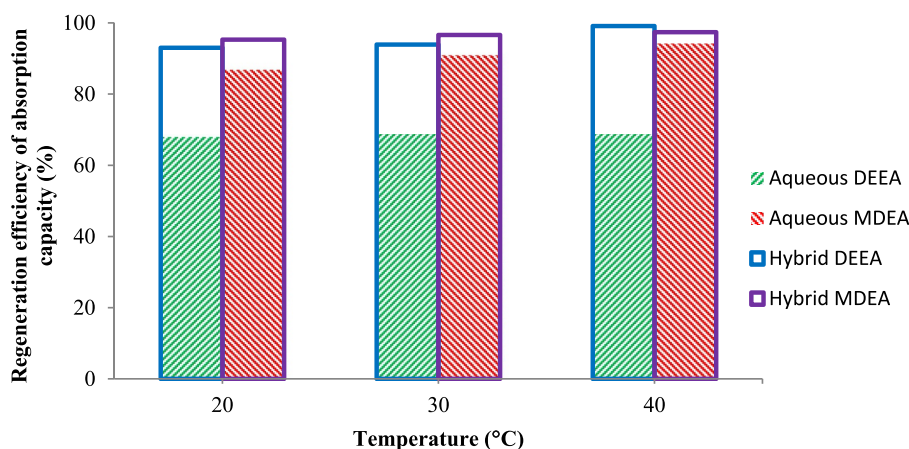


Fig. 12. Regeneration efficiency of absorption capacity at 20, 30, and 40 °C.

the chemical absorption of acidic gases has stoichiometric limitations, the corresponding increments in the aqueous and hybrid absorption capacities are not proportional to increase in the pressure (McKetta, 1978). Comparison of absorption capacities in Figs. 13 and 14 reveals that steady increasing in the absorption capacity of hybrid solutions is more predictive than that of the aqueous solution with increasing the pressure. This is due to the presence of sulfolane as a physical solvent that has a higher tendency to CO_2 absorption than water (Wang et al., 2019). Fig. 15 shows that with increasing pressure, the CO_2 absorption capacity in the hybrid solution is closer to that of the aqueous solution and surpasses it at higher pressures. According to Fig. 15, the differences in absorption capacities by increasing pressure from 100 kPa to 800 kPa in the aqueous and the hybrid solutions are 0.1 and 0.39 mol kg^{-1} , respectively. The difference of 0.29 between these two values is attributed to the physical absorption of CO_2 in sulfolane (based on the values in Table 1, the physical absorption capacity of pure sulfolane at 800 kPa is 0.729 mol kg^{-1} , which corresponds to 0.292 mol kg^{-1} in a 40%-solution). It also confirms that unlike sulfolane, water as a physical absorbent merely provides a media for the chemical absorption in the alkanolamine (Shokouhi et al., 2019). The effects of pressure on absorption capacity of aqueous and hybrid MDEA solutions are represented in Fig. 16. Similar to the aqueous DEEA solutions, the aqueous MDEA solution performs well at low pressures while the absorption behavior of hybrid MDEA solution is better at high pressures. Fig. 17 confirms that the regeneration efficiencies of absorption capacity in the hybrid solutions do not alter by changing the pressure whereas the

alterations in efficiencies by changing either in temperature or in concentration are significant. This might be attributed to this fact that by increasing pressure, the increase in the capacity is further driven by the physical solvent. Therefore, due to complete desorption of sulfolane for all the hybrid solutions at different pressures, the residual CO_2 content is approximately the same. On the other hand, since CO_2 absorption by aqueous solutions is carried out under the same temperature and concentration conditions while the absorption is not proportional to the pressure (McKetta, 1978), the regeneration efficiencies of absorption capacity after desorption are almost identical in all the aqueous solutions.

5. Conclusion

An experimental investigation was carried out to measure the capacity of CO_2 absorption in the aqueous solutions of DEEA and MDEA, as well as in the hybrid solutions of DEEA/sulfolane/water and MDEA/sulfolane/water in different conditions. The absorption capacities of the recycled solutions were also measured. The results showed that the absorption capacities in the solutions containing DEEA were higher than the corresponded values in the solutions containing MDEA mainly due to characteristics of DEEA's molecular structure. The absorption capacities in the aqueous solutions were found to be higher than those of hybrid solutions in all conditions except in high pressures. The regeneration efficiencies of absorption capacity for both DEEA and MDEA absorbents were improved in the presence of sulfolane as a physical solvent.

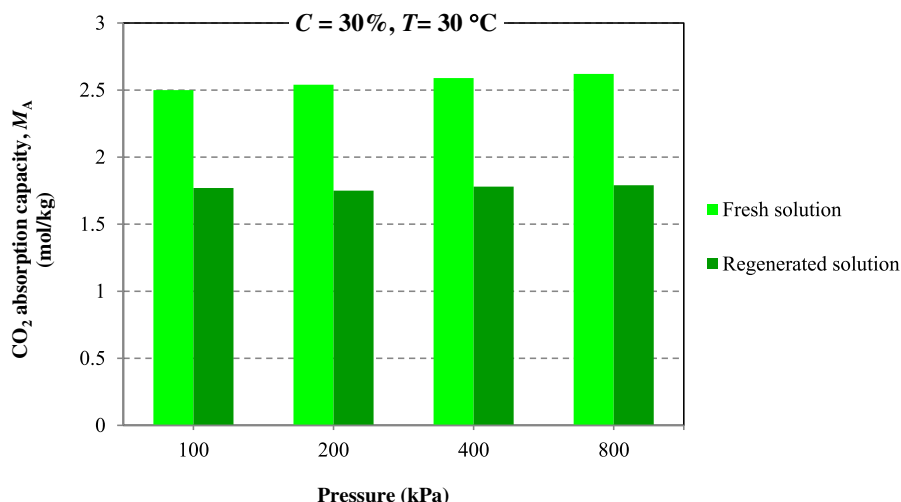


Fig. 13. Effect of pressure on absorption capacity of aqueous DEEA solution.

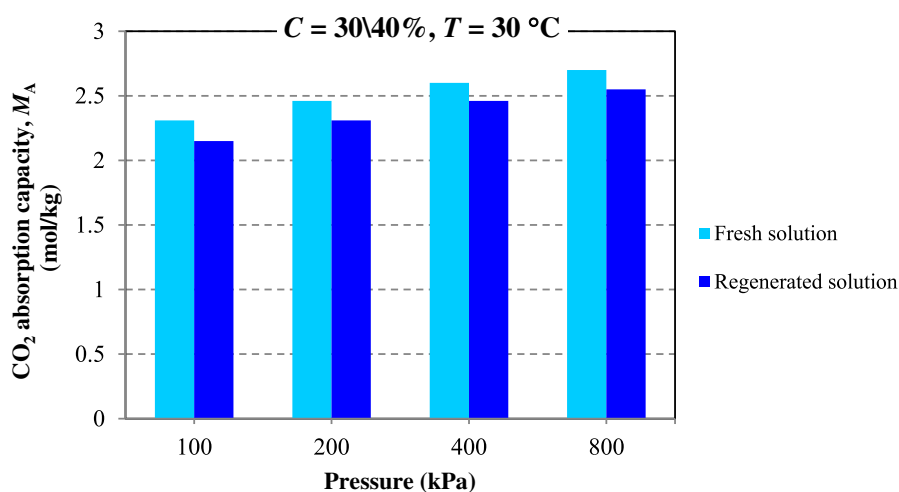


Fig. 14. Effect of pressure on absorption capacity of hybrid DEEA solution.

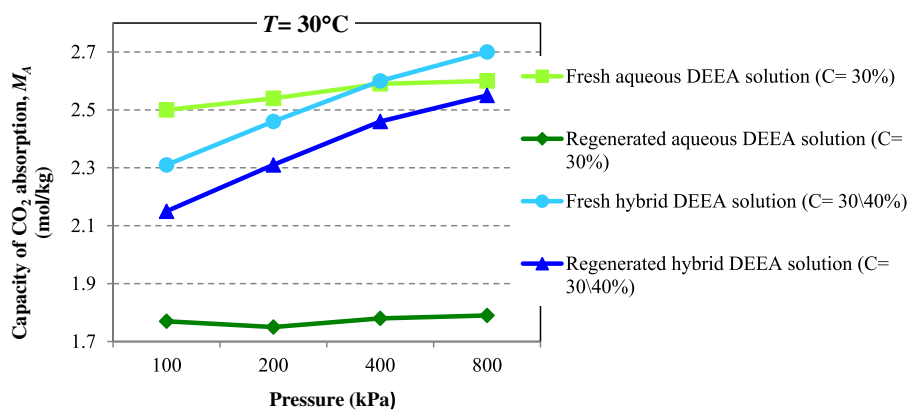


Fig. 15. Effect of pressure on absorption capacity of aqueous and hybrid DEEA solutions.

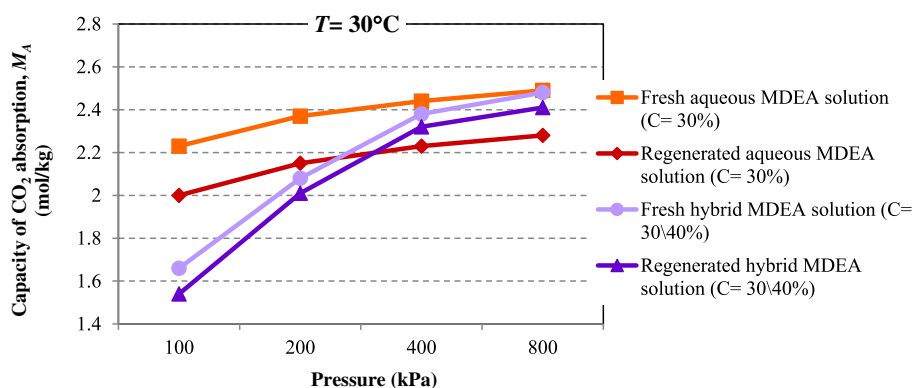


Fig. 16. Effect of pressure on absorption capacity of MDEA aqueous and hybrid solution.

However, the corresponding improvement for the DEEA solution was much higher than that of the MDEA solution.

interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of competing interests

The authors declare that they have no known competing financial

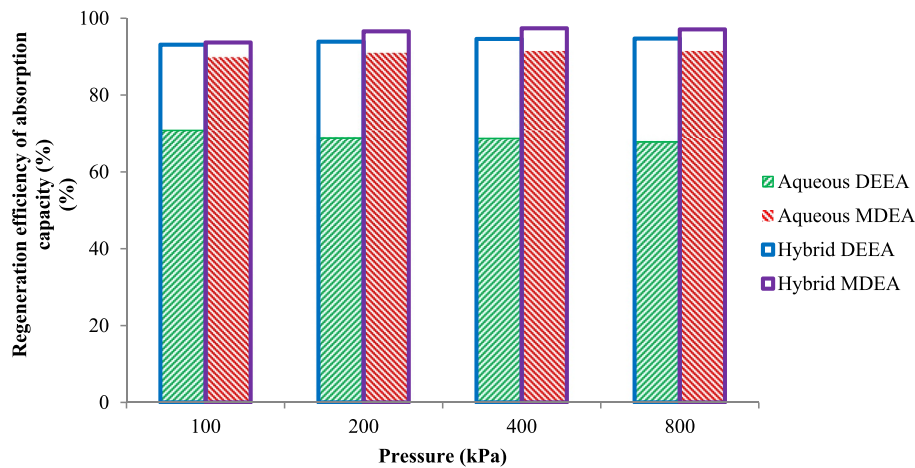


Fig. 17. Regeneration efficiency of absorption capacity in 100, 200, 400, and 800 kPa.

Nomenclatures and abbreviations

DEEA	2-(Diethylamino) ethanol
MDEA	N-Methyldiethanolamine
R ₃ N	Tertiary alkanolamine
C	Concentration (wt%)
E _{regen}	Total regeneration energy
m _a	Mass of absorbed carbon dioxide (g)
m _u	Mass of unabsorbed carbon dioxide (g)
m _t	Total mass of injected carbon dioxide (g)
M _A	CO ₂ absorption capacity (mol.kg ⁻¹)
M	Molecular weight of carbon dioxide (g.mol ⁻¹)
n	Mole of carbon dioxide (mol)
n _a	Mole of absorbed carbon dioxide (mol)
n _r	Mole of reactant (mol)
n _u	mole of unabsorbed CO ₂ (mol)
P _c	Partial pressure of carbon dioxide (kPa)
P _s	Vapor pressure of solution (kPa)
P _T	Total pressure of reactor (kPa)
Q _{latent}	Latent heat
Q _{rxn}	Reaction heat
Q _{sens}	Sensible heat
R	Universal gas constant (mol K L ⁻¹ kPa ⁻¹)
R _A	Relative absorption capacity (mol.mol ⁻¹)
T	Temperature (°C)
T _K	Temperature (K)
V	Volume of gas (lit)
W _{sol}	Weight of solution (kg)
Z	Compressibility factor (—)

Credit author statement

Ali Asghar Nozaeim: Doing Experiment, Formal analysis, Writing: Original draft preparation. Ahmad Tavasoli: Supervision, Project administration. Hamid Reza Mortaheb: Supervision, Conceptualization, Methodology, Writing: Review & Editing, Validation. Morteza Mafi: Resources, Writing - review & editing.

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