

Measurement of CO₂ Absorption in a 4 M Aqueous Solution of 3-Amino-1-Propanol for CO₂ Removal

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Carbon dioxide (CO₂) emission into the atmosphere causes environmental concern. The main sources of CO₂ come from industries such as power generation. The current technology to remove CO₂ effectively is carbon capture and storage or CCS especially absorption with aqueous amine solutions. The commonly used amine solutions are monoethanolamine (MEA) and methyldiethanolamine (MDEA). They have some disadvantages like low capacity and high energy consumption. A new solvent such as 3-amino-1-propanol (AP) has been designed to be used as an alternative solvent for CO₂ removal. This solvent should provide the absorption and cyclic capacities close or higher than the commercial ones. The objective of this research is to measure the CO₂ absorption in a 4 M aqueous solution of AP at the temperature from 303.15 K to 353.15 K and CO₂ partial pressures ranging from 5 to 100 kPa and the absorption results of CO₂ in AP solution are compared with that of aqueous solution of MEA. From the experiment, the results present that AP at 4 M provides the performance relatively close to that of MEA. The cyclic capacities of AP are relatively lower than that of MEA for 26.83 and 2.73 % for CO₂ partial pressure at 15 and 100 kPa. The absorption capacity of AP is higher when CO₂ partial pressure increases and reduces as temperature increases. AP can be considered as an alternative solvent for CO₂ removal at high CO₂ partial pressure. Other properties like kinetics, mass transfer, energy penalty for solvent regeneration as well as other criteria have to be investigated for AP before it can be used for commercial purposes.

1. Introduction

Power plants mainly use fossil fuels such as coal and natural gas to obtain energy. It causes a drastic increase in emission of carbon dioxide (CO₂) in the atmosphere and evokes the more serious climate change problem (Chauhan et al., 2003). Table 1 presents the flue gas characteristic from different sources of energy in the power plants. Carbon capture and storage (CCS) is a technology that has been developed to capture and store CO₂ produced from the use of fossil fuels by using chemical absorbent to reduce CO₂ emissions from power plant flue gas (Rudin et al, 2017). There are many chemical agents, especially derivative of alcohols which are explored for their capability to handle the emitted CO₂ (Leung et al, 2014).

Table 1: Flue gas characteristics emitted from fossil-based power plant (IPCC, 2014)

Characteristic	Natural gas power plant	Coal fired power plant
Concentration (vol%)	5 - 10	12 - 18
Pressure of flue gas (MPa)	0.1	0.1

Over the past several years, researchers have searched for the effective adsorbents for more capable of capturing CO₂ (Mehassouel et al, 2016). The main adsorbents are alkanolamines which have higher capacity and higher reaction rate to absorb CO₂ with less energy required for solvent regeneration (Singh et al., 2011). The commonly used amine solutions nowadays are primary amines as monoethanolamine (MEA) (Shen and Li, 1992), secondary amines like diethanolamine (DEA) (Chauhan et al., 2003) and tertiary amine like methyl-diethanolamine (MDEA) (Aronu et al., 2011). Many researchers invent new solvents that are expected to get better efficiency in CO₂ removal such as 4-diethylamino-2-butanol (DEAB) (Maneeintr, 2009), 2-(methylamino)ethanol (Haider et al., 2011) and single and mixed amines (Puxty et al., 2009). Testing new amine solutions is required to prove the assumption of solutions like absorption capacity, corrosion, heat of regeneration. For CO₂ absorption ability, basically, it is reported in form of CO₂ loading (mol CO₂/mol amine) (Chowdhury et al., 2013). In this work, the new chemical solvent of 3-amino-1-propanol (AP) is investigated and compared the results with that of MEA. This is expected to compensate the defects of commercial solvents and increase the efficiency of CO₂ or it can be used as an alternative for CO₂ absorbing agent in the future. Figure 1 illustrates the molecular structure of MEA and AP. The molecular structures of these amines look similar except that AP has one more carbon in the chain of backbone alcohol. The difference of amine structure may provide different carbon capture performance.



Figure 1: Molecular structures of (a) MEA and (b) AP

The objective of this research is to measure the CO₂ solubility in a 4 M aqueous solution of AP at the temperature from 303.15 K to 353.15 K and CO₂ partial pressures ranging from 5 to 100 kPa. The results of CO₂ in AP solution are compared with that of aqueous solution of MEA. AP can be considered as an alternative solvent for CO₂ capture in the future.

2. Experiment

2.1 Materials

CO₂ (purity 99.9 %) and nitrogen or (N₂) (purity 99.5 %) were purchased from Praxair (Thailand) Co., Ltd. MEA (purity 99 %) used in this experiment was purchased from Sigma-Aldrich Co., Ltd. AP (purity 99 %) was purchased from Merck Millipore Co., Ltd. Hydrochloric acid (HCl) with purity of 99 % was obtained from Fisher Scientific. De-ionised water from Pure Lab Classic was used for preparing aqueous solution of amines.

2.2 Experimental procedure

This experimental set-up device was operated by a bubble reactor which was used for the absorption studies by placing in temperature controlled water-bath to maintain isothermal condition in a range from 303.15 K to 353.15 K as shown in Figure 2. After that, 4 M of AP solution was filled in the reactor cell. CO₂ and N₂ were mixed together until the mixed gas reached the desired partial pressure in a range of 5 to 100 kPa. In the saturation cell, the gas mixture was saturated with moisture content and passed to reactor cell. The solvent and gas mixture were bubbled together until it reached the equilibrium condition. The whole process took around 10 - 14 hours. Then the samples were taken for 3 times to analyse for CO₂ loading.

3. Results and Discussion

3.1 Equipment verification

The reliability of the experimental apparatus and procedure was performed by comparing the solubility of CO₂ in 5 M aqueous MEA solution at 313.15 K and partial pressure ranging from 5 - 100 kPa with that of Shen and Li (1992). The results from Yamada et al. (2013) is compared as well. Also, the work from Luemunkong (2013) is presented and compared as shown in Figure 3. The percent average absolute deviation (% AAD) was used to calculate for percentage average deviation from the previous work. It was shown that % AAD from 313.15 K to 353.15 K for this experiment was 1.50 % and maximum percentage error was 4.14 %. From this verification, it could be concluded that this apparatus and procedure were reliable enough for further study.

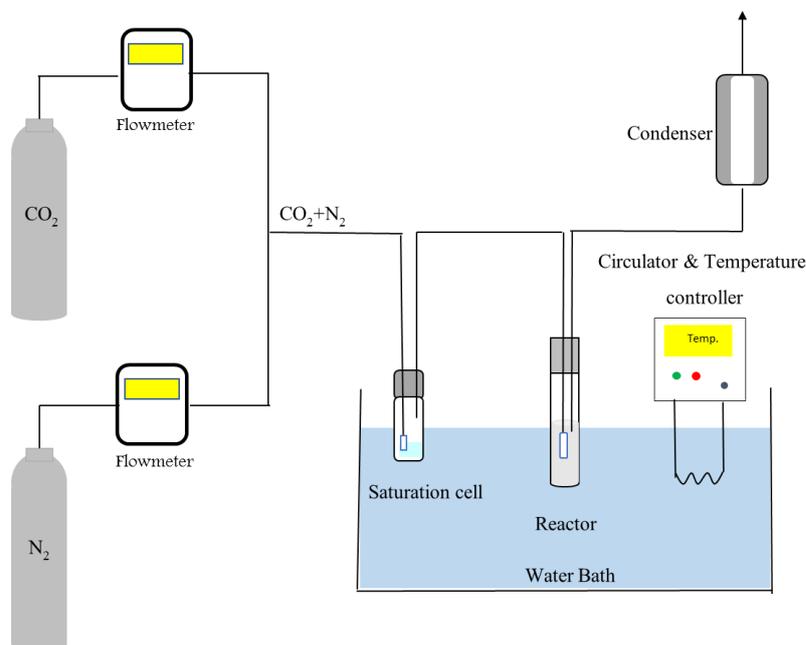


Figure 2: Schematic diagram of the experimental setup

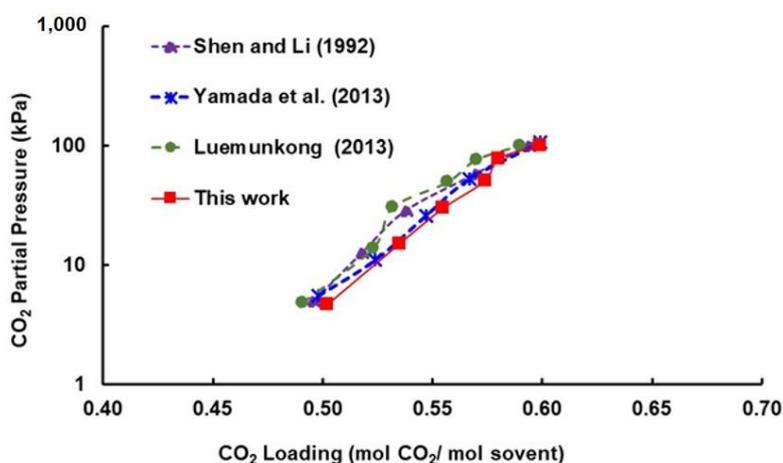


Figure 3: Solubility of CO₂ in MEA solution in comparison with the results from literature at 5 M concentration and 313.15 K

3.2 Types of solvents

The results of different amine solutions were shown in Figure 4 presenting the CO₂ loading, the ratio in mole of CO₂ per mole of amine. The experimental results were compared with that of MEA from the literature (Luemunkong, 2013). From the results, it was clear that AP can capture more CO₂ than MEA solutions. CO₂ loading data were higher in both 313.15 K and 353.15 K. From the result, in term of absorption capacity, AP has a better absorption performance than MEA. AP solution could have a potential as an alternative absorbent. There were also other criteria to consider in many aspects to conclude the performance of this new solvent.

3.3 Effects of temperature and pressure

Figure 5 showed the solubility result of CO₂ in aqueous 4 M AP solution at 303.15 K to 353.15 K and partial pressure ranging from 5 to 100 kPa. The results could be explained in term of the reaction that the reaction

between CO₂ and amines was reversible and exothermic. When the temperature increased, it resulted in the lower CO₂ loading capacity.

At low temperature like 313.15 K, CO₂ could be absorbed as absorption condition. At high temperature, it was considered as a regeneration condition since the gas was removed out of the solvent more than dissolved resulting in the low solubility. For pressure, the increase in CO₂ partial pressure from 5 to 100 kPa could enhance the capacity to capture more CO₂ in both MEA and AP solutions, due to the increase of CO₂ driving force. In other words, CO₂ transported more from gas phase to liquid amine phase at higher partial pressure.

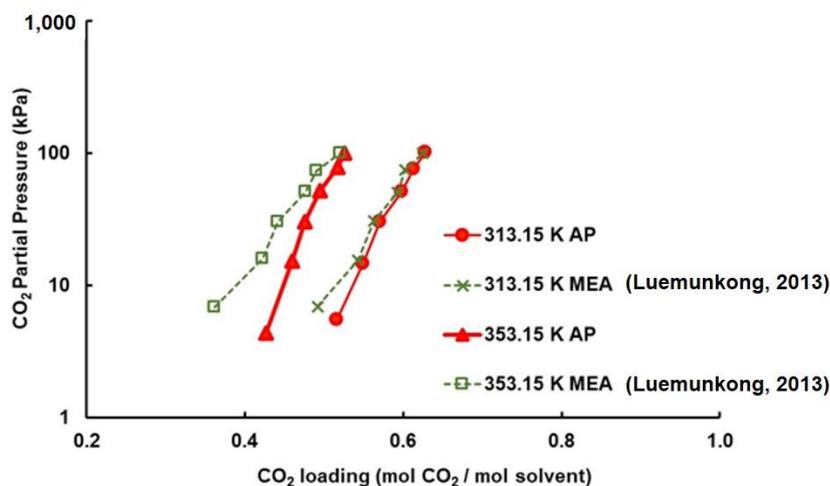


Figure 4: Equilibrium CO₂ loading on CO₂ partial pressure of amine solutions 4 M of MEA and AP at temperature 313.15 K and 353.15 K

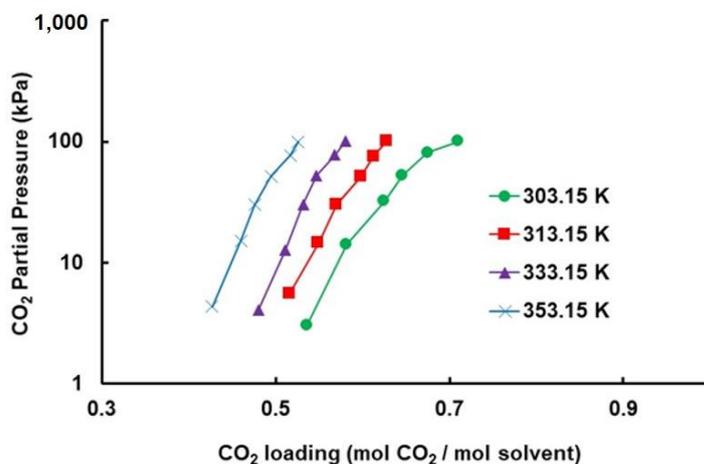


Figure 5: The solubility of CO₂ in AP solution at 303.15 K to 353.15 K

3.4 Cyclic capacity of AP

The cyclic capacity was defined as the difference between the CO₂ solubility in the liquid solvent at absorption condition and that of at regeneration condition. In this study, 313.15 K and 353.15 K were set as absorption and regeneration conditions, respectively.

Figure 6 showed the cyclic capacity of CO₂ (mole CO₂/mole solvent) in both MEA and AP solutions. The cyclic capacities of AP were relatively lower than that of MEA for 26.83 and 2.73 % for CO₂ partial pressure at 15 and 100 kPa, respectively. This implied that in term of cyclic capacity, MEA was slightly better performance than AP. Other solvent properties such as kinetics and mass transfer should be studied in the future.

3.5 Rate of CO₂ loading change

Figure 7 and Figure 8 showed the change on the rate of CO₂ loading in 4 M AP solution at 15 kPa and 100 kPa, respectively. Rates of CO₂ loading change versus time were very high at the beginning of the reaction. At higher temperature, the rate of loading change was higher because the higher energy could enhance the rate of reaction; thus, increasing the rate of CO₂ change. For higher partial pressure, the rate of loading change could increase because of higher driving force leading to higher rate of reaction. Later, the rate was relatively stable until it reached equilibrium. It was the same for both temperature and partial pressure.

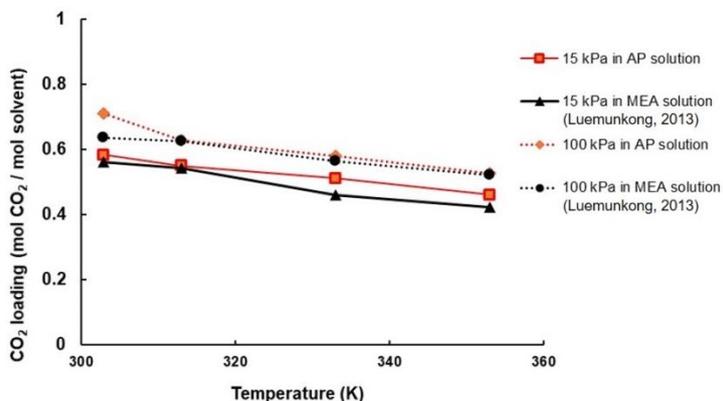


Figure 6: The solubility of CO₂ in 4 M amine solutions versus temperature

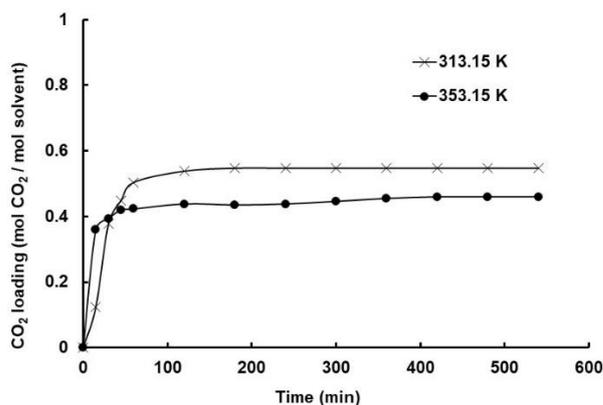


Figure 7: Rate of CO₂ loading change in 4 M AP solution at 15 kPa

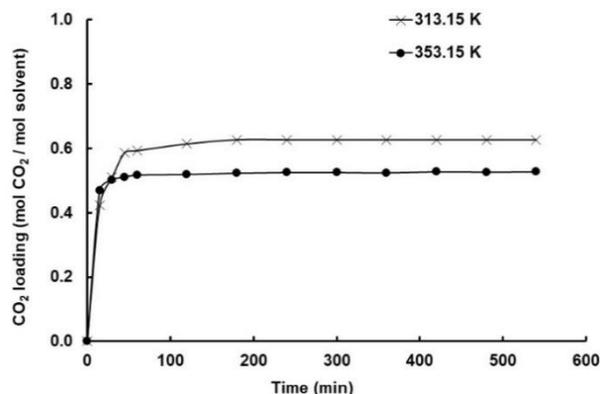


Figure 8: Rate of CO₂ loading change in 4 M AP solution at 100 kPa

4. Conclusions

Solubility measurement is performed in a 4 M aqueous solutions of AP and compared the result with that of commercial MEA solutions. The results present that 4 M AP provides the performance comparatively close to that of MEA. The cyclic capacities of AP are relatively lower than that of MEA for 26.83 and 2.73 % at 15 and 100 kPa CO₂ partial pressure. The absorption capacity of AP is higher when CO₂ partial pressure increases and reduces as temperature increases. The rates of CO₂ loading change versus time are very high at the beginning of the reaction especially at higher temperature because the higher energy can enhance the rate of reaction. The rate was relatively stable until it reached equilibrium. It was the same for both temperature and partial pressure. From the result, in term of capacities and rate of loading change, AP can be considered as an alternative solvent for CO₂ removal. Other solvent properties such as kinetics, mass transfer, heat of regeneration, and so on should also be studied in the future to prove that AP is the promising solvent for CO₂ capture.

Acknowledgments

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