Simultaneous removal of CO₂ and H₂S using MEA solution in a packed column absorber for biogas upgrading

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Abstract

Biogas production and utilization is an emerging alternative energy technology that has gained importance since the price of oil and gas has increased steadily over the last two decades. Biogas primarily consists of methane (CH₄) and carbon dioxide (CO₂) with smaller amounts of hydrogen sulfide (H₂S) and ammonia (NH₃). For many applications the quality of biogas has to be improved. The main parameters that may require removal in upgrading systems are CO₂ and H₂S. This work presents the study of simultaneous absorption of CO₂ and H₂S by Monoethanolamine (MEA) solution in a packed column. Simulated biogas containing 40% CO₂ and 60% N₂ and biogas generated from an anaerobic digestion plant were used as feed gas streams. The effects of gas flow rate, L/G ratio and absorbent concentration were investigated. The performance of the system was found to vary with process parameters. Increasing L/G ratio and MEA concentration causes the system efficiency to increase whereas increasing gas flow rate results in lower efficiency. An operating condition of L/G ratio of 83.3 ml/L, gas flow rate of 3 L/min and MEA concentration of 3 mol/L was found to remove more than 99.5% of CO₂ and H₂S from biogas. The volumetric overall mass-transfer coefficient (K̇ₐᵥ) for CO₂ removal initially increases with increasing gas flow rate up to a certain value beyond which the coefficient becomes essentially constant. The K̇ₐᵥ also increases with increasing L/G ratio throughout the range tested in this study.

Keywords: biogas, carbon dioxide, monoethanolamine, chemical absorption, packed column

1. Introduction

Biogas is a renewable fuel and an energy source that can be applied in many different settings. It is defined as a combustible gas mixture produced by the anaerobic digestion of biomass by bacteria and takes only a relatively short time to form. Biogas produced in anaerobic digestion plants is primarily composed of 55 to 65% of methane (CH₄) and 35-45% of carbon dioxide (CO₂) with smaller amounts of hydrogen sulfide (H₂S) and ammonia (NH₃) (Appels et al., 2008).

Methane (CH₄) combats quite cleanly with hardly any soot particles or other pollutants, making it an almost clean fuel. Generally, biogas can be used directly to generate power, but the large volume of CO₂ reduces the heating value of the gas. For example, biogas containing 60% CH₄ has a calorific value of 21.5 MJ/Nm³ while pure CH₄ has a calorific value of 35.8 MJ/Nm³. The high CO₂ content in the biogas also increases compression and transportation costs and limits the economic feasibility for further use at the point of production. H₂S which is always present in biogas corrodes mechanical components in engine generator sets and vehicle engines. Moreover, sulfur dioxide (SO₂) produced from the combustion of H₂S can react with water in the atmosphere leading to acid rain problem. It is possible to upgrade or improve the quality...
of biogas by removing CO₂ and H₂S in order to enrich its CH₄ content up to the natural gas level, which is 75-98% (Vijay et al., 2006). In Thailand, biogas resources are from industrial wastewater and live stock manure, which have a potential of 459 and 363 kilo tons of oil equivalent per year, respectively (DEDE, 2009). Therefore, upgrading the biogas allows for a wider variety of uses, either for heat and electricity production, or as a vehicle fuel.

Currently, technologies that could be used for CO₂ removal from gas include physical and chemical absorption, pressure swing adsorption (PSA), membrane separation, cryogenic separation and biological methane enrichment (Ryckebosch et al., 2011). However, among these, CO₂ absorption using alkanolamines as chemical solvents appears to offer an interesting and practical alternative. In this technique, CO₂ is separated from a gas stream by passing the gas stream through a continuous scrubbing system consisting of an absorber and a desorber. After absorbing CO₂ in an absorber, the solvent is then sent to a desorber where the temperature is raised, resulting in CO₂ stripping from the solvent (solvent regeneration). The regenerated solvent is then returned to the absorber thereby creating a continuous recycling process. With the advantage of high efficiency and stability, packed column is widely used as the absorber and desorber in the CO₂ capture system (Yu et al., 2010).

In the existing industrial absorption processes, alkanolamines such as Monoethanolamine (MEA), Diethanolamine (DEA), Di-2-propanolamine (DIPA) and Methyl diethanolamine (MDEA) are commonly used (Mandal et al., 2003). MEA is the most widely employed solvent for CO₂ absorption (Krumdieck et al., 2008). Although new alkanolamines and alkanolamine mixes have been developed, MEA is still the preferred absorbent for CO₂ absorption. This is because MEA has a high reactivity, low solvent cost, low molecular weight (giving a high absorption capacity on a weight basis) and reasonable thermal stability (Ma’mn et al., 2007). There are also several techniques to remove H₂S. Examples are absorption in water, chemical absorption in aqueous solutions and adsorption on solid absorbents (Petersson and Wellinger, 2009). Over the years, a large amount of data on the CO₂ removal from flue gas and natural gas by using MEA has been published (e.g. deMontigny et al., 2005, Godini and Mowla, 2008 and Lv et al., 2012). However, there have been a few research papers applying such technology to biogas, which contains much higher CO₂ concentration than flue and natural gas. Moreover, a few works have focused on using MEA for simultaneous absorption of CO₂ and H₂S from biogas.

The objective of this work was, therefore, to evaluate the performance of a packed column for CO₂ removal from simulated biogas and for simultaneous removal of CO₂ and H₂S from biogas by using MEA solution as an absorbent. Effects of process parameters including gas flow rate, liquid to gas ratio (L/G) and concentration of MEA were investigated through a series of absorption experiments. The system performance was evaluated in terms of removal efficiency (%) and mass transfer coefficient.

2. Theory

2.1 Reaction schemes of CO₂ and H₂S with MEA

The chemistry of CO₂ reactions in amine solution is remarkably complex and cannot be said to be entirely understood. However, according to Choi et al. (2009), it has been generally accepted that the overall reaction of CO₂ with primary (RNH₂) such as MEA can be represented as in Reaction 1.

$$\text{CO}_2 + 2\text{RNH}_2 \leftrightarrow \text{RNHCOO}^- + \text{RNH}_4^+ \quad (1)$$

This mechanism comprises two steps, namely, formation of the CO₂-amine zwitterions as shown in Reaction 2, followed by base catalyzed deprotonation of this zwitterions as shown in Reaction 3:

$$\text{CO}_2 + \text{RNH}_2 \leftrightarrow \text{RNH}_3^+ \text{COO}^- \quad (2)$$

$$\text{RNH}_3^+ \text{COO}^- + B \leftrightarrow \text{RNHCOO}^- + B^- \quad (3)$$

where B is a base which could be amine, OH⁻ or H₂O.

The reaction of H₂S and MEA is reversible and instantaneous. H₂S reacts with MEA by proton transfer. The reaction (Al-Baghli et al., 2001) is shown in Reaction 4.

$$\text{RNH}_3^+ + \text{H}_2\text{S} \leftrightarrow \text{RNH}_4^+ + \text{HS}^- \quad (4)$$

2.2 Mass transfer coefficient

The absorption performance of a packed column can commonly be presented as the volumetric overall mass-transfer coefficient (K_gα). The determination of K_gα is based on both the mass flux and material balance of the transferred CO₂ across the gas-liquid interface where the absorption takes place. The common equation used for calculating the K_gα is Equation 5 (Aroowilas and Veawab, 2004):

$$K_g\alpha = \left( \frac{G_i}{P(\text{y}_\text{CO}_2 - \text{y}_{\text{CO}_2}^*)} \right) \frac{dY_{\text{CO}_2}}{dZ} \quad (5)$$

where G_i is the inert gas velocity in kmol/(m²·h), P is the total pressure of the system in kPa, Z is the column height in m, y_\text{CO}_2 and \text{y}_{\text{CO}_2}^* are the mole fraction of CO₂ in the gas stream and equilibrium mole fraction of CO₂, respectively, and y_{\text{CO}_2} is the mole ratio of CO₂ in the gas stream. The \text{y}_{\text{CO}_2}^* term can be evaluated using solubility data. However, for CO₂ absorption into MEA solution, the \text{y}_{\text{CO}_2}^* term can be assumed to be zero since the chemical reaction is fast (deMontigny et al., 2005).

In this work, Equation 5 was rewritten according to Setameteekul et al. (2008) to represent the CO₂ concentrations in the gas entering and leaving the absorber (Y_{\text{CO}_2,\text{in}} and Y_{\text{CO}_2,\text{out}}). The local mass-transfer driving force P(\text{y}_{\text{CO}_2} - \text{y}_{\text{CO}_2}^*) was replaced by a logarithmic mean, ΔP_{\alpha}. The mass-transfer equation was then written as in Equation 6:
\[ K_G a_v = \frac{G_s (Y_{CO_2, in} - Y_{CO_2, out})}{\Delta P_{LM} Z} \]  

where \( \Delta P_{LM} = P \left( \frac{(y_{CO_2} - y'_{CO_2})_{in} - (y_{CO_2} - y'_{CO_2})_{out}}{\ln((y_{CO_2} - y'_{CO_2})_{in} / (y_{CO_2} - y'_{CO_2})_{out})} \right) \)

3. Materials and Method

3.1 Materials

Aqueous solutions of monoethanolamine (MEA) used for CO\(_2\) absorption were prepared by diluting the concentrated MEA (97% MEA), obtained from Fisher, with deionized water. N\(_2\) and CO\(_2\) gases with a purity of 99.99% and 99.97%, respectively, were used to produce simulated biogas at a concentration of 40% CO\(_2\) and 60% N\(_2\). Biogas used as feed gas stream in this work was obtained from the wastewater treatment plant of a local swine farm.

3.2 Experimental procedure

3.2.1 CO\(_2\) absorption from simulated biogas

CO\(_2\) absorption experiments were conducted in a laboratory-scale absorption unit of which a simplified flow diagram is given in Figure 1. The unit consisted of an acrylic absorption column (0.05 m in diameter and 1.00 m in height), CO\(_2\) and N\(_2\) gas cylinders, flow meters, mixing chamber and solvent tanks. The absorption column was packed with 6-mm raschig rings to a height of 0.70 m. The void fraction of the packing layer was 0.76 m\(^3\)/m\(^3\) and the specific area was 625 m\(^2\)/m\(^3\).

Each experimental run began by introducing N\(_2\) and CO\(_2\) gases from cylinders through flow meters at desired flow rates to produce simulated biogas at a concentration of 40% CO\(_2\), which was fed to the bottom of the column. The concentration of CO\(_2\) in the feed gas was checked and adjusted until the desired value was obtained. An aqueous MEA solution was pumped at a given flow rate to the top of the column and sprayed through the nozzle. After absorbing CO\(_2\) and traveling through the column, the CO\(_2\)-rich solution was collected continuously in the liquid receiving tank. This operation was continued for at least 15 minutes to allow the system to reach steady state. At this point, CO\(_2\) concentration of the treated gas stream was measured. The process parameters and the experimental conditions are listed in Table 1.

3.2.2 H\(_2\)S absorption from biogas

The H\(_2\)S absorption procedure was the same as described for the CO\(_2\) absorption. Biogas from a local swine farm was used as feed gas instead of the simulated biogas. MEA solution at a concentration 3.0 mol/L was used as absorbent in the absorption unit. At steady state, the feed and treated gas streams were sampled and analyzed for CO\(_2\) and H\(_2\)S concentrations in order to calculate system efficiencies.

All measurements were done in triplicate and the results were plotted and analyzed using ANOVA (analysis of variance) at 5% level.

3.3 Gas sample analysis and calculation

The concentrations of CO\(_2\) and CH\(_4\) in the feed and treated gas stream were analyzed by a gas chromatograph equipped with a TCD detector and Porapak Q packed column. The analysis of H\(_2\)S concentration in the gas stream was performed using the standard method given by AOAC (1990). The volumetric overall mass-transfer coefficient \( (K_G a_v) \) was calculated by Equation 6. For the simulated biogas treatment, the CO\(_2\) removal efficiency \( (\eta_{CO_2}) \) of the system was determined by Equation 7 (Aroowilas and Veawab, 2004), and for the biogas treatment, the CO\(_2\) removal efficiency \( (\eta_{CO_2}) \) and H\(_2\)S removal efficiency \( (\eta_{H_2S}) \) of the system were determined by Equation 8 and 9 (Lu et al., 2006), respectively:

![Figure 1. Schematic diagram of the gas absorption unit.](image)

Table 1. Experimental operating conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow rate (L/min)</td>
<td>1.0-10.0</td>
</tr>
<tr>
<td>Liquid to gas ratio; L/G (ml/L)</td>
<td>16.7-83.3</td>
</tr>
<tr>
<td>MEA concentration (mol/L)</td>
<td>1.0-7.0</td>
</tr>
<tr>
<td>Liquid feed temperature (°C)</td>
<td>25</td>
</tr>
<tr>
<td>Absorption column pressure (kPa)</td>
<td>102.3</td>
</tr>
</tbody>
</table>
Effect of simulated biogas flow rate on CO$_2$ and H$_2$S entering and leaving the absorption column, respectively.

\[
\eta_{CO_2} = \left[1 - \frac{y_{CO_2,\text{out}}}{y_{CO_2,\text{in}}} \left(\frac{1 - y_{CO_2,\text{in}}}{1 - y_{CO_2,\text{out}}}\right)\right] \times 100
\]

\[
\eta_{CO_2} = \left[1 - \frac{y_{CO_2,\text{out}}}{y_{CO_2,\text{in}}} \left(\frac{1 - y_{CO_2,\text{in}} - y_{H_2S,\text{in}}}{1 - y_{CO_2,\text{out}} - y_{H_2S,\text{out}}}\right)\right] \times 100
\]

\[
\eta_{H_2S} = \left[1 - \frac{y_{H_2S,\text{out}}}{y_{H_2S,\text{in}}} \left(\frac{1 - y_{H_2S,\text{in}}}{1 - y_{H_2S,\text{out}}}\right)\right] \times 100
\]

where $y_{CO_2,\text{in}}$ and $y_{CO_2,\text{out}}$ denote mole fractions of gas phase CO$_2$ entering and leaving the absorption column, respectively, and $y_{H_2S,\text{in}}$ and $y_{H_2S,\text{out}}$ denote mole fractions of gas phase H$_2$S entering and leaving the absorption column, respectively.

4. Results and Discussion

4.1 CO$_2$ absorption from simulated biogas

4.1.1 Effect of gas flow rate

The effect of gas flow rate on CO$_2$ removal efficiency at three different MEA concentrations is shown in Figure 2. The CO$_2$ removal efficiencies of all MEA concentrations decrease as the gas flow rates increase. For example, when 3.0 mol/L MEA solution is used, the efficiency drops from about 100 to 81% as the gas flow rate increases from 1.0 to 10.0 L/min.

4.1.2 Effect of liquid to gas ratio

Figure 3 shows the CO$_2$ removal efficiency as a function of L/G ratio at a gas flow rate of 3.0 L/min. The L/G ratio affects the CO$_2$ removal efficiency in the same pattern for all MEA concentrations used in this study. An increase in the L/G ratio results in an increase in efficiency. In the case of using 5.0 mol/L MEA solution, 96.2% of CO$_2$ in the gas stream is removed when an L/G ratio of only 16.7 ml/L is applied. Increasing the L/G ratio to 33.3 ml/L is enough causing the efficiency to reach a maximum of around 100%. Therefore, in practice, using L/G ratio greater than 33.3 ml/L may not be economical for this MEA concentration. For 3.0 mol/L MEA solution, removal efficiencies higher than 95% are obtained when the L/G ratios are in the range of 33.3-83.3 ml/L. However, for 1 mol/L MEA solution, an increase of L/G ratio from 16.7 to 33.3 ml/L cannot result in an efficiency of 95%, indicating insufficient amount of MEA to absorb CO$_2$ in the gas stream.

4.1.3 Effect of MEA concentration

The effect of MEA concentration was tested in this study to compare the performance of various absorbent concentrations at a gas flow rate of 6.0 L/min. The curve of CO$_2$ removal efficiencies of aqueous MEA solutions is shown in Figure 4. As can be seen that with an increase of absorbent concentrations from 1.0 to 7.0 mol/L, the CO$_2$ removal efficiency increases from 72.8 to 99.7%. This is due to the fact that increasing MEA concentration raises the molar ratio of MEA/CO$_2$, resulting in better CO$_2$ absorption and thus greater efficiency. This trend agrees well with the results obtained by Choi et al. (2009). However, it should be noted that the increasing rate of CO$_2$ removal efficiency decreases when MEA concentration is greater than 5.0 mol/L. This indicates...
that increasing concentration from 5.0 to 7.0 mol/L causes a slight increase in efficiency.

It is important to note that an increase in L/G ratio or solution flow rate leads to higher circulation and regeneration costs, while an increase in solution concentration is expensive and accelerate corrosion rates in steel vessels. Thus, maximizing these two operating parameters may not necessarily improve the overall system performance.

4.2 CO₂ and H₂S absorption from biogas

4.2.1 CO₂ absorption

From the analysis, the untreated biogas from the chosen swine farm consists of 61.5% of CH₄, 38.4% of CO₂ and 1,760 ppm of H₂S. These values are in the range of the typical biogas compositions found in literature (Appels et al., 2008). The biogas was used as feed gas stream in this work. Plots of CO₂ removal efficiency and CH₄ outlet concentration against gas flow rate at 3.0 mol/L MEA solution are shown in Figure 5. It can be observed that the CO₂ removal efficiency decreases as the gas flow rate increases. Removal of CO₂ from the biogas results in a higher outlet CH₄ concentration. When gas flow rates in the range of 1.0-4.0 L/min are applied, the CO₂ removal efficiencies of 97.3-99.7% and the outlet CH₄ concentrations of 98.3-99.9% are obtained, corresponding to the outlet CO₂ concentrations of 0.1-1.7%. The system efficiency then drops as the gas flow rate is higher than 4.0 L/min. This indicates that increasing gas flow rate reduces contact time and increases the amount of CO₂ in the gas phase, thus resulting in lower efficiencies. Although the CH₄ content in the treated gas drops as the gas flow rate increases, using gas flow rates not higher than 6.0 L/min still maintains the outlet CH₄ concentrations at higher than 96.0% (less than 4.0% CO₂). In the application that uses biogas as vehicle fuel or NGV (natural gas for vehicle), the CO₂ and H₂S concentra-

tions of the gas must be lower than 4% and 15 ppm, respectively (Deublein and Steinhauser, 2008).

The effect of L/G ratio on CO₂ removal efficiency was investigated by fixing the gas flow rate at 3.0 L/min and varying the L/G ratio in the range of 16.7-83.3 ml/L. Figure 6 shows that, at the lowest L/G ratio of 16.7 ml/L, the outlet CH₄ concentration is 90.8%. An increase in L/G ratio from 16.7 to 50.0 ml/L increases the efficiency to 99.1%. As the L/G ratio increases, the outlet CH₄ concentration increases. When L/G ratios of 50.0-83.3 ml/L are used, the efficiencies are almost as high as 100%.

4.2.2 H₂S absorption

Figure 7 shows the effect of gas flow rate on outlet H₂S concentration and removal efficiency. When a gas flow rate of 1.0 L/min is used, the H₂S concentration decreases from 1,760 ppm at the inlet to lower than 10 ppm at the outlet,
corresponding to 99.7% of removal efficiency. Increasing gas flow rate from 1.0 to 10.0 L/min causes the outlet H\textsubscript{2}S concentration to rise gradually, resulting in a decrease in efficiency. Despite the fact that the H\textsubscript{2}S removal efficiency decreases as the gas flow rate increases, the efficiency is still higher than 95% as long as the gas flow rate is not higher than 8.0 L/min. However, as it was mentioned earlier, the requirement for using biogas as vehicle fuel is that the H\textsubscript{2}S concentration of the gas must be lower than 15 ppm. Therefore, from Figure 6, the suitable gas flow rate should not be higher than 2.0 L/min.

Figure 8 shows outlet H\textsubscript{2}S concentrations and H\textsubscript{2}S removal efficiencies at different L/G ratios. At an L/G ratio of only 16.7 ml/L, the H\textsubscript{2}S concentration is reduced from 1,760 to 76 ppm, corresponding to 97.1% of removal efficiency. Increasing L/G ratio decreases H\textsubscript{2}S concentration. When an L/G ratio of 83.3 ml/L is used, a H\textsubscript{2}S concentration as low as 10 ppm (99.7% efficiency) is obtained.

### 4.3 Mass transfer coefficient for CO\textsubscript{2} absorption

Beside the percent removal efficiency, the absorption performance of a packed column can be presented as the volumetric overall mass-transfer coefficient (K\textsubscript{o,a}). The K\textsubscript{o,a} coefficient is a combination of three contributions associated with mass transfer, i.e. thermodynamics, kinetics of the CO\textsubscript{2} absorption system and the hydrodynamic nature of the absorption equipment. Figure 9a shows the variation of the K\textsubscript{o,a} as a function of simulated biogas flow rate for three different MEA concentrations. It is apparent that the gas flow rate affects the K\textsubscript{o,a} but only to a certain point. The K\textsubscript{o,a} increases initially with increasing gas flow rate up to around 6.0 L/min (183 m\textsuperscript{3}/m\textsuperscript{2}/h) beyond which the K\textsubscript{o,a} tends to remain constant. This behavior illustrates the gas-phase controlled mass transfer taking place within the low range of the gas flow rate (less than 6.0 L/min). As the gas flow rate increases the K\textsubscript{o,a} increases simultaneously to a point where the liquid-phase mass transfer takes over and becomes the main controlling factor for CO\textsubscript{2} absorption. A similar trend has been reported by Javed et al. (2010) and Kunz and Aroonwilas (2009).

The effect of biogas flow rate on the K\textsubscript{o,a} is shown in Figure 9b. The K\textsubscript{o,a} increases significantly from 0.10 to 0.23 kmol/m\textsuperscript{3}.h.kPa when the gas flow rate increases from 1.0 to 4.0 L/min beyond which the K\textsubscript{o,a} becomes almost constant. This trend is similar to that of the 3.0 mol/L MEA solution in Figure 9a. Moreover, the values of the K\textsubscript{o,a} for the simulated gas (Figure 9a) and for the biogas (Figure 9b) are almost the same. This indicates that, with the relatively very low concentration (less than 0.2%) compared to the CO\textsubscript{2} concentration in the feed gas stream, the H\textsubscript{2}S does not affect the CO\textsubscript{2} absorption performance of the system.

The effect of L/G ratio on the K\textsubscript{o,a} for the simulated biogas treatment is shown in Figure 10a. It is obvious that the K\textsubscript{o,a} increases with increasing L/G ratio and this holds true for the entire range of L/G ratio tested. This is because the increase in L/G ratio or liquid flow rate results in the spread of liquid on the packing surface and more effective interfacial area between liquid and gas in the packing is formed producing a higher overall mass transfer to take place. Figure 10a also shows that the increase in K\textsubscript{o,a} is observed for the entire range of MEA concentration tested. Previous study on the absorption of CO\textsubscript{2} into potassium carbonate (K\textsubscript{2}CO\textsubscript{3}) solutions (Zhao et al., 2011) in a packed column has also revealed a similar trend of increasing K\textsubscript{o,a} with increasing liquid flow rate. Figure 10b shows the effect of L/G ratio on the K\textsubscript{o,a} for the biogas treatment. It can be seen that as L/G ratio increases, the K\textsubscript{o,a} increases. This trend is similar to that in Figure 10a and the K\textsubscript{o,a} values in the two figures at the same condition are almost the same.

The K\textsubscript{o,a} values obtained from this study and from various references using a packed column technology for CO\textsubscript{2} absorption are compared in Table 2. It can be seen that most studies were carried out at relatively low CO\textsubscript{2} concent-
Table 2. Comparison of $K_{GA}$ values reported in literature.

<table>
<thead>
<tr>
<th>References</th>
<th>Gas composition</th>
<th>absorbents</th>
<th>$K_{GA}$ (kmol/m$^3$.h.kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>40% CO$_2$, 60% N$_2$</td>
<td>1-5 mol/L MEA</td>
<td>0.1-0.4</td>
</tr>
<tr>
<td></td>
<td>38% CO$_2$, 62% N$_2$</td>
<td>3 mol/L MEA</td>
<td>0.1-0.3</td>
</tr>
<tr>
<td>Kuntz and Aroonwilas (2009)</td>
<td>15% CO$_2$, 85% air</td>
<td>5 mol/L MEA</td>
<td>0.4-0.5</td>
</tr>
<tr>
<td>deMontigny et al. (2005)</td>
<td>8.4% CO$_2$, 91.6% air</td>
<td>2 mol/L MEA</td>
<td>1.1-1.3</td>
</tr>
<tr>
<td>Dey and Aroonwilas (2009)</td>
<td>5% CO$_2$, 95% N$_2$</td>
<td>5 mol/L MEA</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>15% CO$_2$, 85% N$_2$</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Aroonwilas and Tontiwachwuthikul (1998)</td>
<td>3-10% CO$_2$, 90-97% air</td>
<td>1.1 mol/L LAMP</td>
<td>0.6-0.7</td>
</tr>
<tr>
<td></td>
<td>15% CO$_2$, 85% air</td>
<td>3 mol/L LAMP</td>
<td>1.0</td>
</tr>
<tr>
<td>Zeng et al. (2012)</td>
<td>5-15% CO$_2$, 85-95% N$_2$</td>
<td>1.2-4.5 mol/L Ammonia</td>
<td>0.1-0.4</td>
</tr>
<tr>
<td>Aroonwilas et al. (1999)</td>
<td>15% CO$_2$, 85% air</td>
<td>1.5 mol/L MEA</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5 mol/L NaOH</td>
<td>0.7</td>
</tr>
</tbody>
</table>
trations of about 15% or less, compared to that found in typical biogas (higher than 35%). Various chemicals used as absorbents include MEA, AMP (2-amino-2-methyl-1-propanol), Ammonia and NaOH (Sodium Hydroxide). The results from this study appear to be slightly different from those in the literature. With respect to MEA, the $K_a \cdot \alpha$ values obtained from this study are observed to be lower than those from deMontigny et al. (2005) and Aroonwilas et al. (1999). This is probably due to the fact that they used lower CO$_2$ concentrations. Dey and Aroonwilas (2009) have found that $K_a \cdot \alpha$ decreases with the increasing CO$_2$ concentration. This can be seen in Table 2, because when the CO$_2$ concentration is raised from 5 to 15%, the $K_a \cdot \alpha$ drops from 1.3 to 0.4 kmol/m$^3$.h.kPa at the MEA concentration of 5.0 mol/L.

Compared to other techniques (Petersson and Wellinger, 2009; Scholz et al., 2013), results obtained in this study show high efficiencies of simultaneous removal of CO$_2$ and H$_2$S from simulated biogas and biogas using MEA solution in a packed column. At suitable conditions, the system can effectively reduce CO$_2$ and H$_2$S concentration in the feed gas streams to lower than 1% and 10 ppm, respectively, with outlet CH$_4$ content higher than 99%. However, as mentioned earlier, gas absorption using alkanolamines as chemical solvents usually consists of two units, one for absorption and the other for solvent regeneration. Energy consumption for solvent regeneration is an important parameter that must be known for design and operation and economic analysis. Thus, further work dealing with CO$_2$ and H$_2$S absorption with the system equipped with a regenerating unit may be required.

5. Conclusions

Chemical absorption by MEA solution for simultaneously removing CO$_2$ and H$_2$S from biogas in a laboratory-scale packed column has been studied. Gas flow rate, liquid to gas ratio and MEA concentration are very important parameters affecting the process performance. Increasing L/G ratio and MEA concentration results in higher system efficiency whereas increasing gas flow rate cause the efficiency to decrease. For the simulated biogas treatment, the CO$_2$ removal efficiencies higher than 95% are obtained when using gas flow rates not higher than 6 L/min and L/G ratios of 33.3-50.0 ml/L. Results from the study also show that the CO$_2$ removal efficiency obtained from the biogas treatment is the same as that of the simulated biogas treatment at the same condition. The suitable condition that provides more than 99.5% of efficiency for CO$_2$ and H$_2$S removal from biogas is a gas flow rate of 3.0 L/min and an L/G ratio of 83.3 ml/L, at 3.0 mol/L of MEA solution. The volumetric overall mass-transfer coefficient ($K_a \cdot \alpha$) for CO$_2$ removal initially increases with increasing gas flow rate, but at higher flow rates it is essentially constant. The $K_a \cdot \alpha$ also increases with L/G ratio and MEA concentration.

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