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Experimental study of energy requirement of CO_2 desorption from rich solvent

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Abstract

Amine scrubbing has been considered to be the most feasible route for CO_2 capture. However, the main drawback of this technology is high regeneration energy. A better understanding of energy requirement of CO_2 desorption from rich solvent is required. In this study the regeneration energy and its three contributions is examined at various process parameters through experimental work. The regeneration process parameters include rich solvent flow rate, MEA concentration, feeding solvent temperature, rich solvent loading, reboiler temperature and stripper operating pressure. It was found that the regeneration energy was sensitive to those process parameters. The regeneration energy of a mixed MEA/MDEA solvent was also examined. The results show that the regeneration energy can be reduced by using a mixed MEA/MDEA solution.

Keywords: CO_2 capture; regeneration energy; CO_2 desorption; stripper

1. Introduction

Anthropogenic climate change due to excess emissions of CO_2 has become more and more serious. A number of technology options to reduce CO_2 emissions have been developed. Among of these, amine scrubbing has been considered to be the most feasible route for CO_2 capture. However, the main drawback of this technology is high regeneration energy. It's widely known that the energy requirement for solvent regeneration accounts for almost 80% of the operating cost of a CO_2 capture system[1]. A better understanding of energy requirement of CO_2 desorption from rich solvent is required.

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Though the regeneration energy is of both fundamental interest and practical significance, the available literature in this area is relatively scarce as compared to the extensive work done on the absorber. Tobiesen et al[2,3] developed a rigorous desorber model to discuss the effects of system operational parameters on regeneration energy. Recently, several researchers have done experimental research on the energy performance of stripper at regeneration conditions[4,5,6]. However, the three energy contributions of the regeneration energy at various process parameters were uncertain. In this study, an experimental investigation was undertaken to optimize the stripper process parameters with minimum energy requirement.

2. Experimental setup and procedure

2.1. Experimental setup

The schematic diagram of experimental apparatus is shown in Fig. 1. The apparatus fundamentally consist of a stripper (diameter=60mm, packing height=1m), random packed with Dixon ring (2.5mm×2.5mm) and other auxiliary equipments such as a rich solvent reservoir, two metering pumps, a pre-heater, a condenser, a wet gas flowmeter, a cooler and a lean solvent reservoir. Heat for stripper is supplied by electrical heating rods. The reboiler temperature is controlled by temperature controller. The stripper is well insulated to reduce heat loss. The high-precision watt hour meter is connected with the electrical heating rods to record the energy requirement for CO_2 desorption. The CO_2 flow rate from the top of the stripper is measured by wet gas flowmeter. The amine concentration and CO_2 loading of solvent are determined by titration. The experimental conditions are summarized in Table 1.

Each experiment run began by pumping the rich solvent into the reboiler and heating it up to reboiler temperature. When the reboiler and pre-heater reached the desired set point, the rich solvent then was pumped continuously at a given flow rate to the stripper. The liquid level in the reboiler was remained constant by adjusting the flow rate of lean solvent. The lean solvent sample was taken during the steady state.

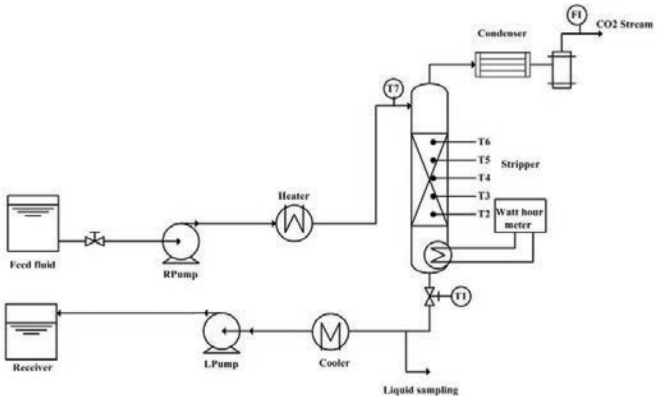

Fig. 1. Schematic diagram of experimental setup

Table 1. Operating parameters

Parameter	Value
MEA concentration (wt%)	20 - 40
MDEA concentration (wt%)	58.4
Solvent flow rate (g/min)	30 - 140
Feeding solvent temperature (°C)	75 - 90
Reboiler temperature (°C)	100 - 120
Operating pressure (kPa)	130-200
Rich solvent loading (mol_{CO2}/mol_{amine})	0.3 – 0.6

2.2. Methodology

The regeneration energy is defined as a ratio of energy supplied from the reboiler and the mass rate of CO_2 released from the stripper:

$$Q_{reg} = (H_{reboiler} - H_{loss}) / \dot{m}_{CO_2} \quad (1)$$

Where, Q_{reg} is the regeneration energy, $H_{reboiler}$ is the heat duty of the reboiler, H_{loss} is the system energy loss which was neglected, the mass flow rate of CO_2 can be also calculated by following Equation

$$\dot{m}_{CO_2} = \dot{m}_{solvent} C_{a\min e} \left(\alpha_{CO_2,rich} - \alpha_{CO_2,lean} \right) MW_{CO_2} \quad (2)$$

Where, $\dot{m}_{solvent}$ is the mass flow rate of the rich solvent, $C_{a\min e}$ is the molar concentration of amine, MW_{CO_2} is the molecular weight of CO_2, $\alpha_{CO_2,rich}$ and $\alpha_{CO_2,lean}$ are the CO_2 loading of rich and lean solvent.

The regeneration energy is a sum of three terms:

$$Q_{reg} = Q_{des,CO_2} + Q_{sens} + Q_{vap,H_2O}$$
$$= \Delta H_{abs,CO_2} + \rho_{solvent} \dot{V} C_p \left(T_{reb} - T_{feed} \right) / \dot{m}_{CO_2} + \dot{m}_{H_2O} \Delta H^{vap}_{H_2O} / \dot{m}_{CO_2} \quad (3)$$

Where, $\Delta H_{abs,CO_2}$ is heat of reaction, the value was used based on literature data of Kim[7], C_p is the heat capacity of the rich solvent, the values of MEA, MDEA and MEA/MDEA solvent are from the work by Weiland et al[8] T_{reb} and T_{feed} are reboiler temperature and feed solvent temperature, respectively. $\dot{m}_{H_2O}$ is the mass flow rate of water vaporized from stripper and $\Delta H^{vap}_{H_20}$ is the heat of vaporization.

3. Results and discussion

3.1. Effect of solvent flow rate and MEA concentration

In this set of experiments, the solvent flow rate is varied at three different MEA concentrations (20 wt%, 30 wt%, 40 wt%). The rich solvent loading was 0.5 mol_{CO2}/mol_{MEA}, the feeding solvent temperature was 85 ℃, the reboiler temperature was 110 ℃ and the stripper operating pressure was 150 kPa. The results are shown in Fig. 2. It can be seen in Fig. 2(a) – (c), the regeneration energy decreases with increasing solvent flow rate until a minimum is attained.

For 20 wt% MEA, the optimum solvent flow rate is around 80 g/min, with minimum regeneration energy of 7.3GJ/ton CO_2. The regeneration energy is determined by three contributions: the energy for (1) desorption of CO_2, (2) generating stripping stream, (3) heating up of the solvent. These contributions are also shown in Fig. 2(a). The heat of reaction and sensible heat remain almost constant, while heat of water vaporization change greatly as the solvent flow rate. For 30 wt% MEA, the optimum solvent flow rate is around 60 g/min, with minimum regeneration energy of 4.26 GJ/ton CO_2. As Fig 2(b) shown, the heat of reaction and sensible heat are the main contributions to the regeneration energy. As Fig 2(c) shown, For 40 wt% MEA, the optimum solvent flow rate is around 70 g/min, with minimum regeneration energy of 5.09 GJ/ton CO_2. The heat of reaction and sensible heat are also the main contributions to the regeneration energy. For the three MEA concentrations, the mass flow of CO_2 from the top of the stripper increases as the solvent flow rate increases. From Fig. 2(d), the regeneration energy was found to decrease with increasing MEA concentration. The minimum regeneration energy of 30 – 40 wt% MEA solution is lower than 20 wt% MEA solution.

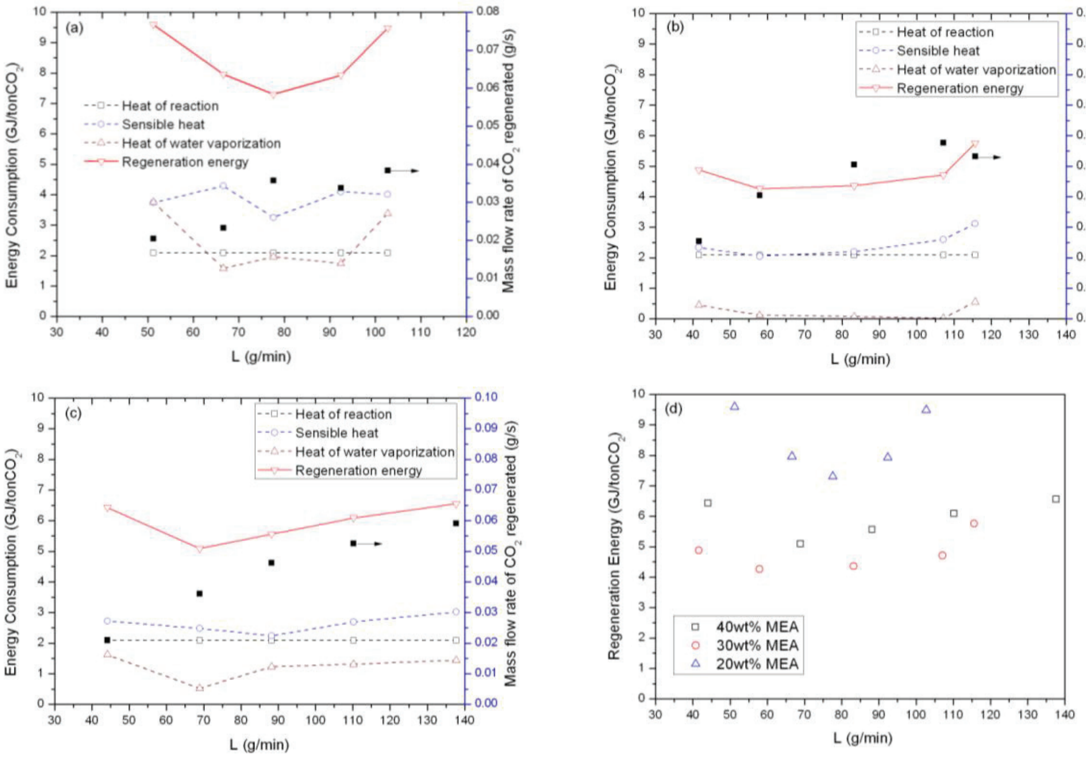

Fig. 2. Effect of solvent flow rate and MEA concentration: (a) 20 wt% MEA; (b) 30 wt% MEA; (c) 40 wt% MEA

3.2. Effect of feeding solvent temperature

The effect of feeding solvent temperature was also investigated. In this experiment, the MEA concentration was 30 wt%, the rich solvent loading was 0.5 mol_{CO2}/mol_{MEA}, the reboiler temperature was 110 ℃ and the stripper operating pressure was 150 kPa. As Fig. 3 shown, the regeneration energy decreases as the feeding solvent temperature increases. The results can be explained that the lower temperature difference between feeding solvent and reboiler leads to a lower sensible heat. In the four temperature cases, we also found that the same desorption ratio was achieved.

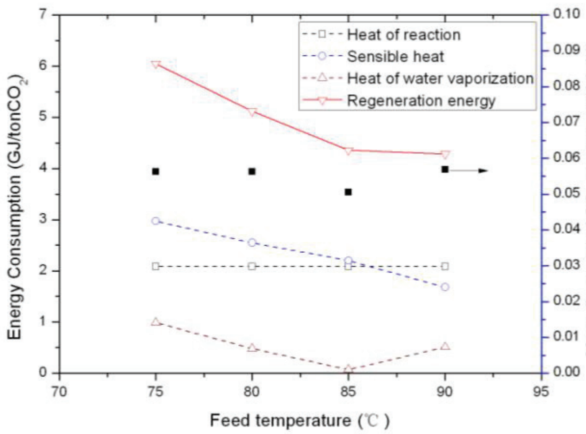

Fig. 3. Effect of feeding solvent temperature

3.3. Effect of rich solvent loading

The effect of rich solvent loading has also been investigated. In this experiment, the MEA concentration was 30 wt%, the feeding solvent temperature is 85 ℃, the reboiler temperature was 110 ℃ and the stripper operating pressure was 150 kPa. As Fig. 4 shown, the regeneration energy decreases as the rich solvent loading increases. It can be found that the mass flow rate of CO_2 increases significantly as the rich solvent loading increases, so the sensible heat decreases accordingly. Meanwhile, the heat of water vaporization decreases as rich solvent loading increases. This effect is mainly attributed to the differences in magnitude of equilibrium CO_2 partial pressure at different rich solvent loading. From the McCabe-Thiele diagrams in Fig. 5, the equilibrium CO_2 partial pressures for $0.3mol_{CO2}/mol_{MEA}$ rich solvent loading are much lower than those of $0.5mol_{CO2}/mol_{MEA}$ rich solvent loading. This indicates that stripping CO_2 from 0.5 mol_{CO2}/mol_{MEA} rich solvent to 0.3 mol_{CO2}/mol_{MEA} rich solvent requires less amount of water vapor, causing the heat of water vaporization decreases significantly.

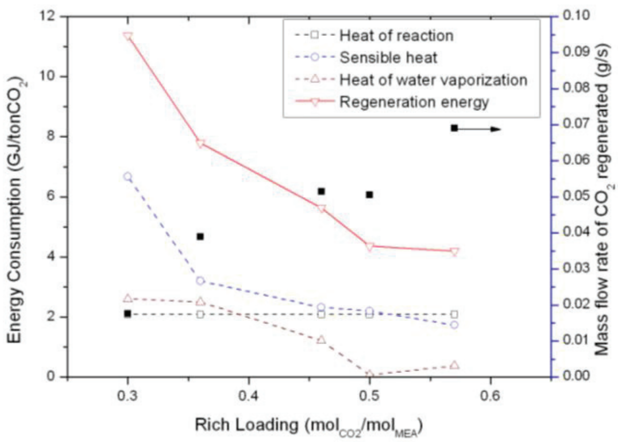

Fig. 4. Effect of rich solvent loading

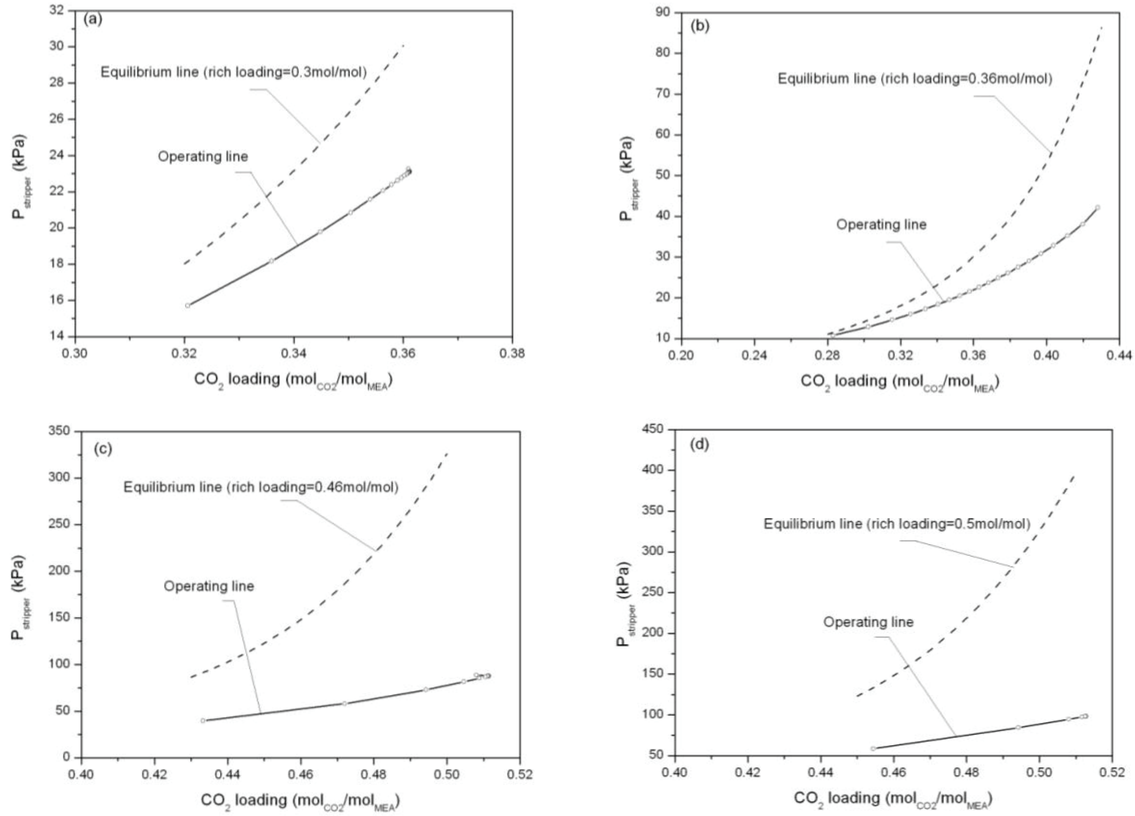

Fig. 5. McCabe-Thiele diagrams for CO2 stripping at different rich loading

3.4. Effect of reboiler temperature

Reboiler temperature is another important parameter that influences the regeneration energy. In this experiment, the MEA concentration was 30 wt%, the feeding solvent temperature is 85 ℃, the rich solvent loading is 0.5 mol_{CO2}/mol_{MEA} and the stripper operating pressure was 150 kPa. As Fig. 6 shown, the regeneration energy increases as the reboiler temperature increases from 110 ℃ to 118 ℃. It is possible that under the pressure of 150kPa, the boiling point of water is around 111.4 ℃, most of reboiler temperatures in this study is beyond the boiling point of water, so more and more water was evaporated. It can be seen that the mass flow rate of CO_2 increases significantly as the reboiler temperature increases. From the Fig. 6, the heat of reaction and sensible heat kept constant and the heat of water vaporization increases significantly as the reboiler temperature increases. That result in an increase of the regeneration energy.

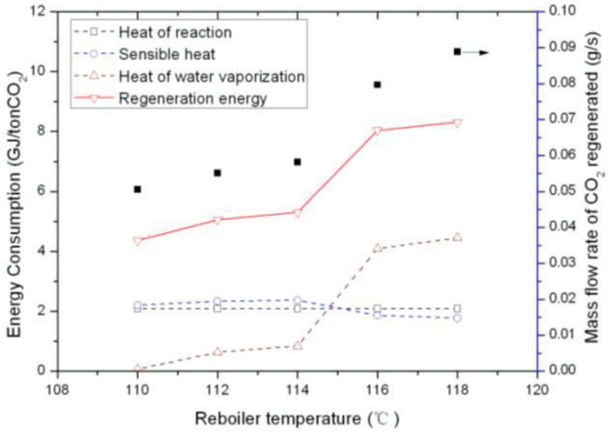

Fig. 6. Effect of reboiler temperature

3.5. Effect of alkanolamine type

MEA solution is economical with high capture efficiency and absorption rate. However, it requires high regeneration energy with severe problems such as corrosion and degradation. MDEA requires low regeneration energy while the reaction rate is slow. Mixed amine of MEA/MDEA was investigated. The heat of reaction of mixed amine was estimated by using following equation [4]

$$\Delta H_{abs,mixed} = \sum_{i}^{n} \frac{C_i}{C_T} \Delta H_{abs,i} \tag{4}$$

Where, $\Delta H_{abs,i}$, C_i and C_T denote the heat of reaction, molar concentration of ith alkanolamine in the mixed solution, and the total molar concentration of alkanolamine, respectively.

In this case, a 30 wt% MEA solution and a 58.4 wt% MDEA solution were used. Both solutions have an amine concentration of 4.8 mol/l. Hence, both solutions can theoretically be loaded with the same amount of CO_2. As Fig. 7 shown, two single alkanolamines (MEA, MDEA) at 0.5 mol_{CO2}/mol_{amine} rich loading were studied. The feeding solvent temperature is 85 ℃, the reboiler temperature was 110 ℃ and the stripper operating pressure was 150 kPa. It can be seen that the regeneration energy of MDEA solution is much lower than that of MEA solution. This mainly attributed to the low sensible heat and heat of reaction of MDEA solution. In this experiment, we also found that the lean loading of MEA solution was about 0.33 mol_{CO2}/mol_{amine}, while the lean loading of MDEA solution was only 0.035 mol_{CO2}/mol_{amine}. That means the regeneration ratio of MDEA solution is much higher than that of MEA solution.

The mixed amine of MEA/MDEA was studied at 4.8mol/l total amine concentration, 0.5 mol_{CO2}/mol_{amine} rich loading and various mixing ratios (2:1, 1:1, 1:2 mol/mol). As Fig. 7 shown, the regeneration energy of MEA/MDEA solution is lower than MEA solution, but larger than the MDEA solution. It is also found that the direct measurements of regeneration energy of the different MEA/MDEA solution agreed with the values by summing of three energy contributions. It appears that heat of reaction is sensitive to the mixing ratio, while the heat of water vaporization increases a little as the mixing ratio decreases.

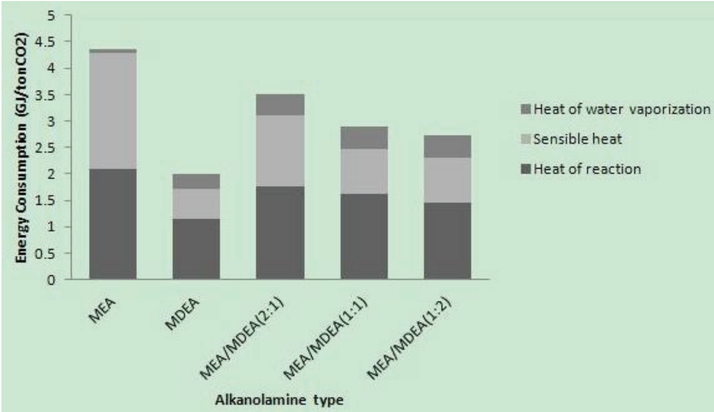

Fig. 7. Effect of alkanolamine type

4. Conclusions

This paper has conducted an experimental study of energy requirement of CO_2 desorption from rich solvent under different regeneration process parameters. The rich loading and feeding temperature of solvent is positive to the regeneration energy, while the reboiler temperature has a negative effect. The results also show that regeneration energy can be reduced by using a mixed MEA/MDEA solution.

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