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Study of absorber intercooling in solvent-based CO_2 capture based on rotating packed bed technology

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Abstract

Application of process intensification (PI) technologies such as rotating packed beds (RPBs) to replace packed beds (PBs) in solvent-based CO_2 capture could reduce plant footprint. Concentrated monoethanolamine (MEA) solvents are generally expected to be used in RPBs. Under this circumstance, expected temperature rise during CO2 absorption should be estimated to determine whether or not intercooling is necessary for RPBs. In this study, we demonstrated that intercooling is inevitable with RPBs using 40-70 wt% monoethanolamine (MEA) solvent through liquid phase energy balance for a hypothetical scenario. Our analysis showed that liquid phase temperature rise could be as high as 80°C in some cases and this will significantly reduce absorption rate without intercooling.

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Keywords: *Post-combustion CO_2 capture; chemical absorption; packed bed; rotating packed bed; absorber intercooling*

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1. Introduction

1.1. Background

Concerns about rising atmospheric CO_2 levels have paved way for the development of carbon capture and storage (CCS) technologies. Post-combustion CO_2 capture (PCC) is the most matured and commercially ready approach for

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deploying CCS [1,2]. Conventional PBs used as absorbers and strippers in PCC processes are huge in size contributing significantly to plant footprint, capital and operating costs. The huge cost has been a major setback for the technology. PI is considered to have good potential to reduce the column sizes and consequently the cost and footprint of the entire PCC plant [3]. RPBs as typical PI equipment have been investigated in this regard [4,5]. Joel *et al*. [4] reported about 12 times size reduction in size for the absorber when RPBs are used. RPBs have already been successfully demonstrated in the industry for natural gas desulphurization [6].

Nomenclature

$C_{p,soln}$	Specific heat capacity of MEA solution (kJ/kg K)
ΔH	Heat of absorption (kJ/mol CO_2)
p_{CO_2}	Equilibrium partial pressure of CO_2 (kPa)
R	Ideal gas constant (J/K mol)
T	Temperature (K)
$[MEA]$	MEA concentration (mol/L)
$\alpha_{rich}, \alpha_{lean}$	Rich and lean loading (mol CO_2/mol MEA)
ρ_{soln}	Density of solution (kg/L)

1.2. Problem statement

RPB absorber is made up of annular packed bed (rotor) mounted on a rotating shaft with the gas and liquid phases flowing radially across the bed (Fig.1) [7]. The liquid and gas phases are as a result subjected to intense centrifugal acceleration which is many times the gravitational acceleration in PBs [3]. As a result, RPBs allow high flooding rate leading to drastic reduction in packing volume and also permit viscous solvents.

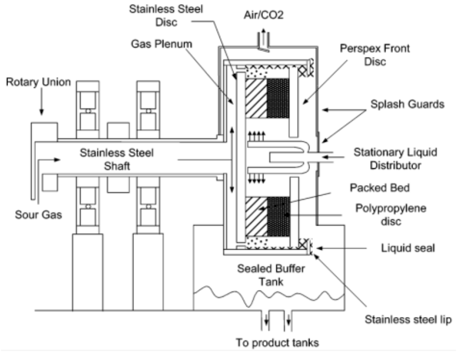

Fig. 1. Sectional view of an RPB [8]

Concentrated monoethanolamine (MEA) solutions (up to 70 wt%) are generally used as solvents in RPBs [4]; concentrated solvents are permitted in RPBs due to centrifugal acceleration of the liquid phases. Also, the solvents have rapid kinetics as required in RPBs due to their short residence time. Under this scenario, heat accumulation in the solvent due to CO_2 heat of absorption will predictably be high. The temperature increase will result in significant reduction of absorption rate. Expected rise in temperature have not been exactly quantified for different concentrations of MEA in RPBs. This could be used to determine if or not intercooling will be necessary in RPBs. Similar analysis for PBs with 30 wt% MEA solvent showed about 35°C rise in the liquid phase temperature and incorporation of absorber intercoolers leads to about 10% improvement in performance [9].

1.3. Aim and objectives

As discussed in Section 1.2, it is likely that temperature rise in RPBs will be excessive with concentrated MEA solvent (up to 70 wt%). This could result in reduction in absorption rate. There are no reported studies addressing this gap in literature. Joel *et al.* [4] and Kang *et al.* [5] analyzed temperature profile for RPBs. However, their analysis based on Jassim *et al.* [8] benchmark involved only a small fraction of CO_2 absorption and did not as a result reveal temperature rise potentials. Another analysis by Kang et al. [5] based on Yu *et al.* [10] benchmark showed temperature rise potentials. However, this was performed using 30 wt% MEA solution as solvent. In this study, the aim is to estimate potential temperature rise for different MEA concentrations (40, 50, 60 & 70 wt%) using a hypothetical scenario (i.e. at different CO_2 loadings). This can be used to demonstrate the necessity of intercooling for RPB absorbers with concentrated MEA solution as solvent.

2. Methodology

The temperature rise for CO_2 absorption in a given concentration of MEA solution is estimated as follows:

$$\Delta T = \frac{\Delta H(\alpha_{rich} - \alpha_{lean})[MEA]}{\rho_{soln} C_{p,soln}} \tag{1}$$

The ΔH is obtained by applying the Gibbs-Helmholtz equation to solubility data as existing experimental data of ΔH in literature is mainly for 30 wt% MEA solution [11]. The Gibbs-Helmholtz equation is given as follows:

$$\left[\frac{\partial \ln p}{\partial \left(\frac{1}{T}\right)}\right]_P = \frac{\Delta H}{R} \tag{2}$$

The solubility data is obtained using eNRTL model in Aspen Plus®. The default eNRTL model parameters have been fine tuned for high concentration MEA solution using the Aspen Plus Data Regression System and vapour-liquid equilibrium (VLE) data from literature [12,13]. Comparison between the model predictions and the experimental data showed good agreement for different concentrations (as presented in Fig. 2), although there is a slight deviation at high concentration.

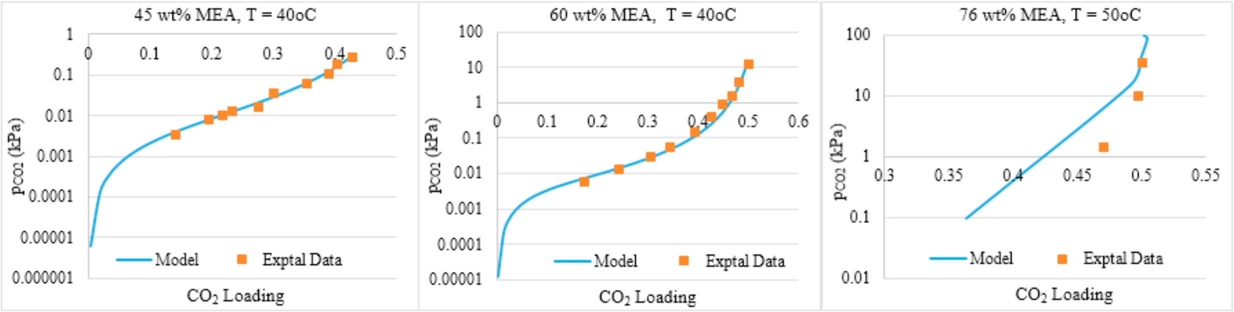

Fig. 2. VLE model predictions vs experimental data

There is a bit of inherent inaccuracy with this approach for estimating ΔH due to the accompanying numerical differentiation [14] and prediction error is expected to be as high as ±20% [15]. That noted, the results given in Fig. 3 showed that ΔH increases slightly with concentration. The ΔH for any given concentration is also relatively constant up to about loading of 0.45 mol CO_2/mol MEA. The decline in ΔH beyond loading of about 0.45 reflects onset of saturation as less CO_2 is absorbed. The trend of ΔH is similar to the reported trends for 30 wt% MEA [16]. The upper limit loading range in the RPB is expected to be about 0.45 mol CO_2/mol MEA. On this basis, it is therefore safe to assume that ΔH is fixed over the operating loading range for the RPB regardless of the MEA concentration.

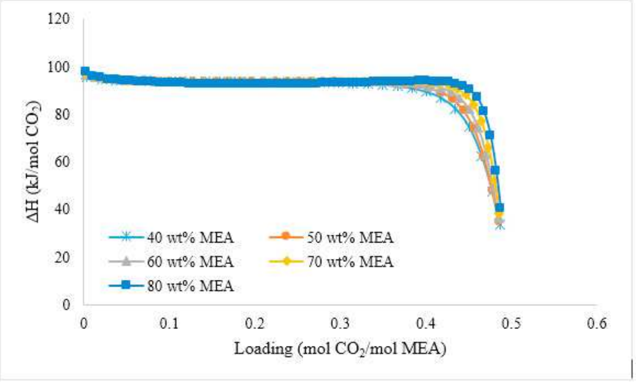

Fig. 3. Heat of solution for different MEA concentrations T = 40ºC

3. Results and discussions

The temperature rise (ΔT) has been estimated for different MEA concentrations using Eqn. 1, summary of different inputs are given in Table 1. Three hypothetic scenarios involving differential loadings ($i.e.\ \alpha_{rich} - \alpha_{lean}$) of 0.15, 0.2 and 0.25 have been assumed. These differential loadings are generally achievable based on experience from PBs using 30 wt% MEA solution as solvent with initial loading of about 0.2. Other physical properties namely density and specific heat capacity have been obtained from Aspen Plus® database.

Table 1. Input conditions used for ΔT estimation

wt%	ρ_{soln}	$[MEA]$	$C_{p,soln}$	$\alpha_{rich} - \alpha_{lean}$
40	1.144	6.6	3.069	0.15,0.2,0.25
50	1.186	8.2	2.874	
60	1.228	9.8	2.685	
70	1.273	11.5	2.477	

The results in Fig. 4 show a significant increase in temperature rise as concentration increases. This is attributed to the following:

- Heat of absorption: CO_2 absorption in MEA solution is an exothermic process giving out an amount of heat equivalent to the heat of absorption. Increase in temperature rise as concentration increased was because the heat of absorption for more concentrated solutions are slightly higher as demonstrated in Fig.3.

- Specific heat capacity: Specific heat capacity generally quantifies the amount of heat to raise the temperature of a unit mass (kg) of the solvent by 1 K. The specific heat capacity of the solution decreased as concentration increases (Table 1). This signified that any given amount of heat in the solution, which is in the form of heat of absorption, will potentially result in higher temperature rise in more concentrated solutions than in less concentrated solution.

It is also observed in Fig. 4 that the expected temperature rise is higher as differential loading of the solvent increases. For a fixed initial loading of the solvent, in our analysis fixed initial loading of 0.2 mol CO_2/mol MEA was assumed for all the cases, increasing differential loading means that more CO_2 absorbed and invariably more heat is released during CO_2-MEA reaction. This is so before the solvent begins to saturate wherein the heat of absorption for any CO_2 absorbed begins to decreases as shown in Fig. 3. Our analysis in Fig. 3 indicated that loading up to 0.45 is achievable before saturation begins to set in. Consequently, the analysis of differential loading scenario in Fig. 4 reflects increase in heat of absorption as more CO_2 is absorbed. Generally, water vaporisation and the packing are expected to have some cooling effect on the solution [5]. However, in RPBs the smaller packing volume and higher concentration of the solvent mean that their cooling effect will be less than expected for 30 wt% MEA solution in PBs.

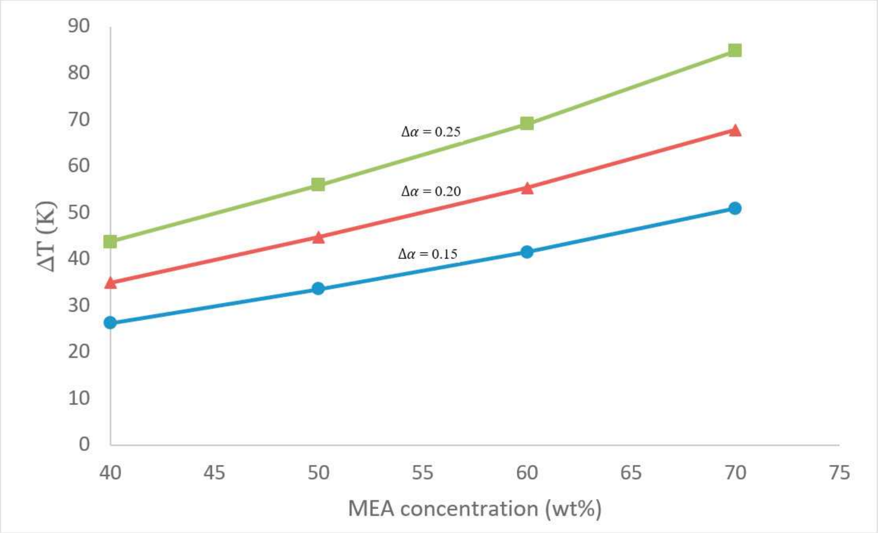

Fig. 4. Estimated temperature rise for different scenario

4. Conclusions and recommendations for future research

RPBs as a typical PI equipment are considered to have the potential to replace PBs in solvent-based CO_2 capture processes. This will result in lower plant footprint and capital and operating costs. There is a potential for excessive rise in the liquid phase temperature in RPBs due to the higher solvent concentration and smaller volume of the packing. Expected temperature rise is investigated in this study for different MEA concentrations (40, 50, 60 & 70 wt%) using a hypothetical scenario. Our findings show that RPBs with up to 70 wt% MEA solution as solvent commonly presented in literature should inevitably be operated with intercooling as temperature rise could reach 80^{o}C in some cases. In the future, this analysis should be further demonstrated through experiments.

Acknowledgements

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