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Full Length Article

A comparative study of novel activated AMP using 1,5-diamino-2-methylpentane vs MEA solution for CO_2 capture from gas-fired power plant

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ABSTRACT

Bench-scale pilot plant study of AMP and 1,5-diamino-2-methylpentane (DA2MP) blend for CO_2 capture from gas-fired power plant is investigated. The concentration of the amine blend is 2 kmol/m^3 AMP-1.5 kmol/m^3 DA2MP while that of single solvent MEA is 5 kmol/m^3. Comparative analysis was based on CO_2 absorption efficiency (%), absorber mass transfer coefficient ($K_Gav_{(ave)}$, kmol/kPa h m^3), desorber mass transfer coefficient (K_Lav, h^{-1}), rich amine loading (α_{rich}, mol CO_2/mol amine), lean amine loading (α_{lean}, mol CO_2/mol amine), cyclic loading (C_L, mol CO_2/mol amine), cyclic capacity (C_C, mol CO_2/L-amine soln.), CO_2 absorption rate (r_{abs}, g-CO_2/h), and regeneration energy (Q_{reg}, GJ/tonne CO_2). The contribution of sensible energy (Q_{sen}, GJ/tonne CO_2), vaporization energy (Q_{vap}, GJ/tonne CO_2), and desorption heat (ΔH_{des}, GJ/tonne CO_2) towards Q_{reg} was also investigated. Results showed that the AMP-DA2MP blend possess higher $K_Gav_{(ave)}$ (11.66%), K_Lav (7.67% higher), and CO_2 absorption efficiency (4.66% higher) than MEA. Also, the superior cyclic loading (51.5%) and cyclic capacity (6.7%), and lower regeneration energy (13.8% lower) was observed for the AMP-DA2MP blend. The desorption heat (ΔH_{des}) was the major contributor to the Q_{reg} of both amine systems however the ΔH_{des} of AMP-DA2MP was 23% lower than MEA. It was noticed that though the water concentration of the amine blend (60.7 wt%) is lower than MEA (70 wt%), the vaporization energy of the amine blend was 32.9% higher than MEA. Therefore, besides the amount of water concentration, higher desorber temperature profile, amine solvent vapor pressure and boiling point also increases the vaporization energy. The results is a revelation of possible reduction in capital cost and operating costs for the AMP-DA2MP blend compared to the standard MEA.

1. Introduction

The need to reduce carbon emissions from large industrial sources has led to the increased study of carbon dioxide (CO_2) capture, utilization and storage (CCU&S). It has been reported by the International Energy Agency that coal accounts for the most of the 2016 CO_2 emissions in the energy sector [1]. According to the Environment and Climate Change Canada 45% of greenhouse gas (GHG) emissions was contributed by stationary combustion sources in 2016 [2]. This has led to an increase in the switch from coal to natural gas for power generation, and it is solely because natural gas is cleaner than coal. However, natural gas being a fossil fuel release CO_2 into the atmosphere when combusted, hence it is imperative to capture CO_2 from gas-fired power plants is imperative. Typical CO_2 concentration in flue gases from natural gas fired boiler and natural gas combined cycle turbine can vary from 3 vol% to 8 vol% [3–5].

Several technologies for capturing CO_2 include absorption (chemical or physical solvents), adsorption, membrane, cryogenic and biological processes. However, the most matured, most studied, can handle high gas flow rate and capable of 90% CO_2 capture efficiency is the absorption technology using amine solvents [6–9]. There are different classification of amine solvents namely primary amine (MEA, monoethanolamine), secondary amines (DEA, diethanolamine) and tertiary amines (MDEA, methyldiethanolamine). In addition, other specialty amines like sterically hindered amine (AMP, 2-amino-2-methyl-1-propanol) and reactive polyamines like piperazine (PZ) and diethylenetriamine (DETA).

There are various amine-based carbon capture projects at different stages, for example two CO_2 capture plants integrated to coal-fired power plants are currently in operation in Canada and USA [10–12]. However, four projects are currently under construction which includes two in Canada, one in China and one in Australia [12].

The benchmark amine solvent and concentration is the primary amine, monoethanolamine (30 wt% MEA or 5 kmol/m^3 MEA). This is

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Nomenclature

AMP	2-amino-2-methyl-1-propanol
DA2MP	1,5-diamino-2-methylpentane
MEA	monoethanolamine
DEA	diethanolamine
MDEA	methyldiethanolamine
PZ	piperazine
DETA	diethylenetriamine
DEAB	diethylamino-2-butanol
$C_{(amine)}$	amine concentration (kmol/m^3 or M)
$F_{(amine)}$	amine flow rate (mL/min)
$T_{(REB)}$	reboiler temperature (°C)
$F_{(GAS)}$	flue gas flow rate (SLPM)
r_{abs}	CO_2 absorption rate (g-CO_2/h)
$K_Gav_{(ave)}$	overall average volumetric mass transfer coefficient (kmol/m^3 h kPa)
P	total pressure of the system (kPa)
P^{sat}	saturation pressure of water at the temperature of the stream exiting the desorber top (kPa)
P_{CO2}	the partial pressure of CO_2 (kPa)
P_{H2O}	the partial pressure of H_2O (kPa)
x_{H2O_lean}	the mole fraction of water in the lean amine
$y_{A,G}$	mole fraction of component A in gas bulk
$y_{A,i}$	mole fraction of component A in interface
y_A^*	mole fraction of component A in the gas phase in equilibrium with the concentration of A in the bulk liquid
$Y_{A,G}$	mole ratio of component A in the bulk gas
av	Gas-liquid interfacial area per unit volume (m^{-1} or m^2/m^3)
dZ	differential height of packed column (m)
G_i	molar flux of total gas without component A or inert gas (kmol/h m^2)
MW_{CO2}	molecular weight of CO_2 (44 g/mol)
N_A	molar flux of component A (kmol/m^2 h)
K_Lav	desorber mass transfer coefficient (h^{-1})
L	molar flux of the aqueous liquid solution (kmol/m^2 h)
L_i	molar flux of the liquid without component A (kmol/m^2 h)
x_{AL}	mole ratio of component A in the liquid bulk
x_{AL_T}	mole fraction of component A in the liquid bulk of the liquid side entering the top of the desorber
x_{AL_B}	mole fraction of component A in the liquid bulk leaving the desorber bottom
ΔT_{des}	temperature difference between the amine solution entering the desorber column and reboiler temperature (°C)
ΔT_{reb}	temperature difference of the silicone oil entering and exiting the reboiler (°C)
$T_{max\text{-}abs}$	maximum temperature profile in the absorber (°C)
$\Delta H_{vap,H2O}$	latent heat of water vaporization at regeneration temperature (kJ/mol H_2O)
$Cp_{\text{-}oil}$	specific heat capacity of the silicone oil at reboiler temperature (kJ/kg °C)
Cp	specific heat capacity of the CO_2 rich amine solution entering the desorber (kJ/kg °C)
m	mass flow rate of the CO_2 loaded amine solution entering the desorber (kg/h)
m_{oil}	mass flow rate of the silicone oil entering the reboiler (kg/h)
Q_{sen}	sensible energy (GJ/tonne CO_2)
Q_{loss}	heat loss of the reboiler (kJ/h)
Q_{vap}	energy of vaporization (GJ/tonne CO_2)
ΔH_{des}	desorption energy (GJ/tonne CO_2)
Q_{reg}	regeneration energy (GJ/tonne CO_2)

because it possesses high mass transfer, low cost and high absorption rate, but it is plagued by high solvent regeneration energy, corrosion and high amine losses via degradation and vaporization [13–18]. According to previous studies, the regeneration energy of MEA-based CO_2 capture adds up to 70–80% of the plant operating cost [19,20]. The regeneration energy is made up of the desorption heat (ΔH_{des}, GJ/tonne CO_2), sensible energy (Q_{sen}, GJ/tonne CO_2) and vaporization energy (Q_{vap}, GJ/tonne CO_2) (Eq. (1)).

$$Q_{reg} = \Delta H_{des} + Q_{sen} + Q_{vap} \quad (1)$$

Sensible energy is the heat is required to raise the temperature of the CO_2 rich amine solution to the regeneration temperature. On the other hand, the vaporization energy is the amount of heat required to vaporize volatile components (mostly water) in the amine solution to strip the CO_2 in the amine solution flowing downwards. Most studies have reported heat of vaporization considering only the amount of water, which is because the amount of water in the CO_2 loaded amine solution is by far higher than specie [21–24]. According to Chakma, a concentrated aqueous amine solution (contains smaller water concentration) will only require less latent heat of water vaporization [25]. Hence, 30 wt% MEA will possess higher heat of vaporization than 50 wt % TEA [25]. This was also confirmed by Nwaoha et al. in AMP-MDEA-DETA and AMP-PZ-MEA tri-amine solvent blends [26,27].

The high energy penalty of single solvent MEA (5 kmol/m^3 MEA) is the reason for blending amine solvents to utilize their specific potentials while minimizing their individual problems [28]. To achieve this, bicarbonate (HCO_3^-) forming amine solvents like tertiary amines (e.g. like methyldiethanolamine, MDEA) and/or sterically hindered amines (e.g. 2-amino-2-methyl-1-propanol, AMP) are blended with reactive monoamines and/or polyamines (e.g. MEA, PZ, DETA etc.) [20,29–34]. This is because amine desorption process is enhanced by the presence of HCO_3^- which in turn reduces the energy of regeneration. The higher kinetics and lower regeneration energy of sterically hindered amine (like AMP) compared to commonly studied tertiary amines is the reason why it is favored [31,35]. Laboratory, pilot plant and process simulation studies have shown that AMP-based blended amine solution exhibit lower capital expenditure and operating cost, lower regeneration energy, increased absorption rates, cyclic loading, cyclic capacity and higher rich amine loading compared to MEA [36–38,32,31,30,39]. Several pilot plant studies have investigated AMP-PZ bi-amine solvent blends [30,40]. However, there are underlying challenges accompanying this blend such as AMP precipitation and PZ crystallization due to limited solubility in water [36,17,41]. In addition, being a secondary amine, PZ has the tendency to produce more nitrosamines when compared to tertiary and primary amines respectively [42,43]. Therefore, it is important to investigate new AMP-based blends that possess superior CO_2 capture capability than MEA, without any operational problems like precipitation and crystallization of AMP-PZ blend. Reduction of nitrosamine formation due to secondary amine reaction with NOx needs to be taken into account.

The aim of this study is pilot plant investigation of CO_2 capture from gas-fired power plant using novel bi-amine solvent blend containing AMP activated by 1,5-diamino-2-methylpentane (AMP-DA2MP) compared to the standard MEA solvent. Considering that AMP at high concentration can precipitate when it absorbs CO_2 [17,36], the AMP concentration in this study was kept at 2 kmol/m^3 (19 wt%). In order not to exceed 40 wt% of amine so that there will be sufficient amount of water in the aqueous amine solution, the concentration of DA2MP was fixed at 1.5 kmol/m^3 (20.3 wt% of water). This is the rational why the concentration of the amine blend was set at 2 kmol/m^3 AMP-1.5 kmol/m^3 DA2MP which is a total amine concentration of 3.5 kmol/m^3 (39.3 wt%). The investigated parameters for comparative assessment