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Amine-Based Carbon Capture Technology: CO_2 scrubber prototype fabrication and amine scrubbing efficiency testing

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Abstract

Fossil fuel burning and industrial gaseous emissions are releasing CO_2into the atmosphere which is responsible for at least 55 % of global warming today. Pakistan is one of the most severely hit countries by global climate change and the consequences are evident from the fast receding glaciers, floods, droughts and heat waves. Carbon sequestration technology consists of various methods employed to remove CO_2 from the atmosphere. This paper presents the prototype design of amine-based CO_2 capture technology. It uses two amine solvents: Monoethanolamine (MEA) and diethanolamine(DEA) in varying concentrations to test the efficiency of the system (solvent and scrubber). It was discovered that MEA solution at 30% concentration yielded the highest efficiency. The scrubbing reaction is exothermic. Corrosion of the scrubber vessel was identified as a problem in applying this method of sequestration.

Keywords: CO_2, monoethanolamine, diethanolamine, carbon capture, carbon sequestration, amine solvents, CO_2–scrubbe

Introduction

Global warming and climate change have emerged as two of the most significant issues of the 21st century. Natural calamities such as floods, climate extremes i.e. heat waves and cold spells have disturbed the intricate radiation balance of the earth and resulted in the loss of life and resources worldwide. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) stated that “approximately 50% of a CO_2 increase will be captured naturally from the atmosphere within 30 years and an additional 30% will take another few centuries” [1-2].

It is, however, a point of concern to note that the 50% of the CO_2 resources discussed in the IPCC report is merely for smaller emissions and does not necessarily hold true for future large-scale industrial emissions. In addition, the carbon sinks available to the natural ecosystems may soon be highly saturated rendering them less effective if not completely non-functional, to capture and absorb CO_2 [3-5].

The Kyoto Protocol in 1997 established the concept of carbon credits. Over the years following the Kyoto Protocol, many countries have endeavored to cut down on carbon emissions. Measures such as ISO 14001 certification have been introduced to encourage industries to reduce their carbon emissions.

While Pakistan is not a CO_2 emissions contributor, its geographical location makes it vulnerable to climatic change [6]. Neighbors; India, China and Russia contribute their share of emissions to the regional environment.

Carbon capture and sequestration (CCS) is an emerging science in the environmental domain. It involves techniques to offset CO_2 released from various sources. The IPCC estimates that economic potential for CCS technologies should be between 10% and 55% by 2100 [7]. Amine scrubbing, a type of CCS technology, is being used by industries since the 1930s due to its high efficiency [8]. Researchers [9] calculated maximum CO_2 removal efficiency and loading capacity by Monoethanolamine (MEA), a type of amine absorbent, at 94% and 0.40 Kg CO_2/Kg MEA, respectively.

Many alterations have been made in the conventional MEA scrubber process flow sheet system over the years. Hitachi has developed new technology using 30 different amines for higher efficiencies.

This study aims to compare the efficiency of different concentrations of amine solvents Monoethanolamine (MEA) and Diethanolamine

(DEA) for CO_2 capture; propose cost-effectively, energy efficient and high-performance solution for capturing and sequestering CO_2 in the local industrial environment and propose an amine based CO_2 scrubber design for local industries.

Materials and Methods

The data was acquired from experimentation on the prototype and was recorded and analyzed to draw results. Quantitative analysis was applied to the study to analyze numerical primary data.

Daily experiments for data acquisition were conducted on the prototype manufactured. Experiments were conducted for a period of 75 days. Temperature, time, and CO_2 concentrations at every step were recorded by the researcher. Emissions of the source were recorded separately to make comparisons and calculate efficiencies later. Secondary information comes from published literature and industrial reports acted as supporting evidence for research conclusions.

Phase 1: Fabrication of the Prototype

Phase 1 included preliminary consultations and scoping, baseline studies, conceptual plan and final fabrication and experimentation. The prototype was named as ‘Ultra Magnus’ (UM).

The pyramid shape with a square base of 7 inches’ length, in the absorber unit, helped provide the necessary contact time for the reaction to occur between CO_2 and solvent. Flue gas with minimal CO_2 is converged and recovered from the top.

The pyramid shape with a square base of 6 inches’ length, in the Desorber unit, aided in achieving and maintaining a temperature of 120 °C in the Desorber. The solvent is converged at the outlet in the bottom and passes through the recycle line before being sprayed again at the absorber unit.

Showerhead in the absorber unit allowed a flow rate of 0.2 liter/second to be maintained. Heating rod in the Desorber unit is suspended by means of metal rods. Fabrication of UM Absorber and Desorber units was done at the Manufacturing Resource Center (MRC) at NUST. Final design is shown in fig 1.

Phase 2: Experimentation and Result Analysis

Experimentation and solution preparation started at the IESE laboratory at NUST.

Monoethanolamine (MEA)

MEA is an alkanol amine, which absorbs $CO_2$with a high efficiency at temperatures above 250˚F. Chelating agents are used to prolonging the life of MEA, which can operate for over 1000 hours before degradation begins [10]. Besides scrubbing, MEA is used as an emulsifier, textile finisher, detergent and adhesive [11].

Diethanolamine (DEA)

Diethanolamine (DEA) is a weak base and it is not as corrosive as MEA. It is weaker than MEA, therefore, its efficiency is lower and is not recommended for commercial sequestration of CO_2 .DEA also finds usage in metalworking and photographic chemicals [11].

A Honda CD70 2005 model motorcycle model was used as fuel emission source.[1] The five Gas Emission Analyzer (GEA) supplied by Taylor (US) was used to analyze the gases. CO_2 concentration (%) was recorded for the fuel source. The emission analyzer showed the following major gases as constituents of the exhaust gases (given with their average concentrations):Carbon dioxide (6%); Nitrogen dioxide (1000 ppm); Nitrous oxide (700 ppm); Ozone (0.1%); Oxygen (0.1%); and Water vapors (7%).

Four absorbers were designed: one for each scenario.Flue gases were then allowed to enter the Absorber through the inlet. The Solvent solution was showered from the top of the unit. A reaction time of five to ten minutes was allowed to absorb the flue gas CO_2 into the amine solvent. The Temperature in the Absorber was noted to increase due to the chemical reaction and complex formation in the Absorber.

Readings were taken for CO_2 concentration at the one-minute interval. After an average of 12 minutes, CO_2 concentration in the Absorber became almost constant.

The length of the unit provided adequate contact time for the reaction. CO_2 initiated degradation begins with the formation of 2-oxazolidone. 2-oxazolidone reacts with another MEA molecule to form N-(2-hydroxyethyl) - ethylenediamine via intermediates of N, N′-di(hydroxyethyl)urea and 1-(2-hydroxyethyl)-2-imidazolidone [12-13].

The complex formed, travelled through the pumping line and was pumped to the Desorber Unit where a temperature of 120˚C was pre-set. At this temperature, the solvent-CO_2 complex is thermally degraded to yield the amine and capturedCO_2. The clean flue gases were released into the atmosphere [14]. The amine solvent was recycled back through the recycling line into the Absorber.

Results and Discussion

Two parameters (temperature and CO_2 concentrations) were analyzed when MEA

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[1] Motorcycle emissions for the manufactured prototype were suitable because the prototype is approximately 1/500 times less in size compared to an actual industrial unit. A large fuel source was therefore, not recommended for this study.

concentration was 30% (MEA30) and 20% (MEA20) and when DEA concentration was 30% (DEA30) and 20% (DEA20). The temperature was used to measure the change in heat content of the system and temperature increase in each scenario shows that the reaction is exothermic in nature. Based on the amine concentrations used for testing efficiency of solvents, four scenarios were developed, each with different solvent concentration. These scenarios and results obtained after running them are discussed in detail as under:

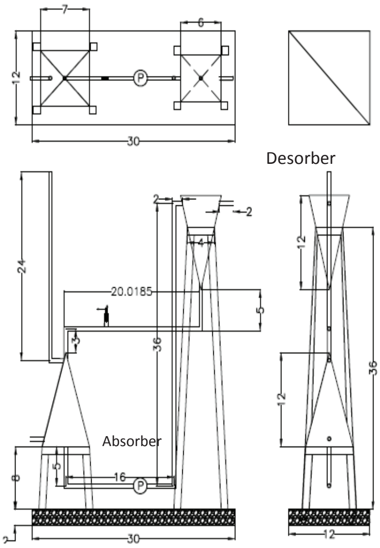

Fig-1: Design for Ultra Magnus

Scenario *A:* MEA30

Here 30% by weight concentration of MEA solution was prepared as a solvent. Initial CO_2 concentration was noted at 6.5% which decreased to a value of 0.3% in first four minutes and stabilized at around 0.2% within 17 minutes. This showed approximately 97% removal efficiency. The Temperature increased from 25°C to approximately 28°C in first six minutes and then stabilized. The increase in temperature is due to chemical absorption of flue gases into MEA solvent and the incoming heated gases from motorbike's exhaust (Fig 2).

Scenario B: MEA20

Using 20% MEA in the Absorber unit this time; a decline from an initial 1.8% CO_2 concentration to a mere 0.2% concentration was noted in 10 minutes. This shows a removal efficiency of approximately 90%. A negligible temperature change of approximately 0.3°C was noted in this scenario. (Fig 3).

Scenario C: DEA30

For DEA solvent at 30% concentration, the decrease in CO_2 concentration from an initial reading of 1.2% to final 0.19% in 10 minutes was noted (Fig 4). A relatively fast temperature increase of 2°C was observed in the first four minutes which then stabilized at around 31.5°C. The efficiency of solvent was 84% approximately.

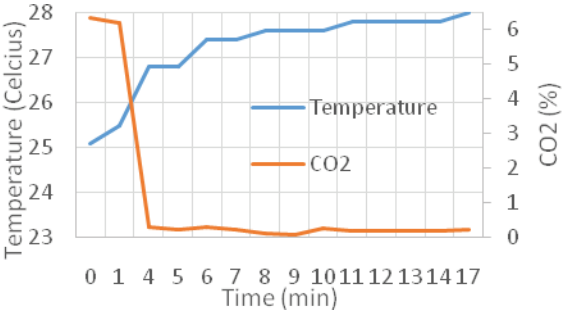

Fig-2: CO_2 and Temperature variations in Scenario A (MEA30)

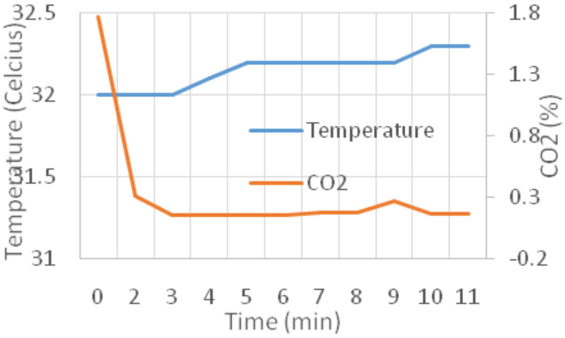

Fig-3: CO_2 and Temperature variations in Scenario B (MEA20)

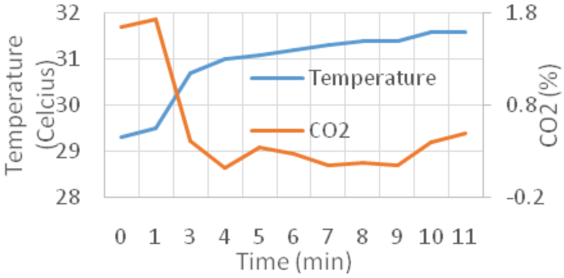

Fig-4: CO_2 and Temperature variations in Scenario C (DEA30)

Scenario D: DEA20

CO_2 concentration level in the absorber unit decreased from 1.2% initial level to 0.19% in 16 minutes, with the introduction of 20 % DEA. A slow temperature increase of approximately 1.5°C was recorded over the 16 minutes' time (Fig 5).

The efficiency of DEA solvents is relatively less than MEA solvents due to lower degradability of DEA. The efficiency of DEA20 was calculated to be 81.3%.

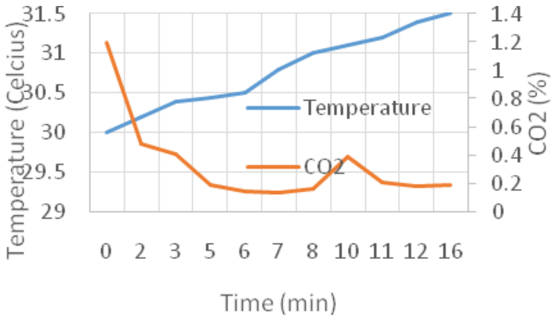

Fig-5: CO$_2$ and Temperature variations in Scenario D (DEA20)

The results in Fig 2,3,4 and 5 show that CO$_2$ concentration in flue gas decreases on reaction with amine solvent while the temperature in the absorber unit increases. It is noted that for higher concentrations of solvents, (MEA30 and DEA30) temperature increase is more rapid, compared to lower concentrations. The efficiency of amine solution is greater for MEA compared to DEA and efficiency increased as the concentration is increased. Corrosion of the absorber vessel was noted after one month of experimentation on absorber, for each solvent. It was visually observed that corrosion of vessel was higher when the solvent concentration was greater (MEA30 and DEA30). Efficiencies of all four solvents tested are given in Fig 6.[2]

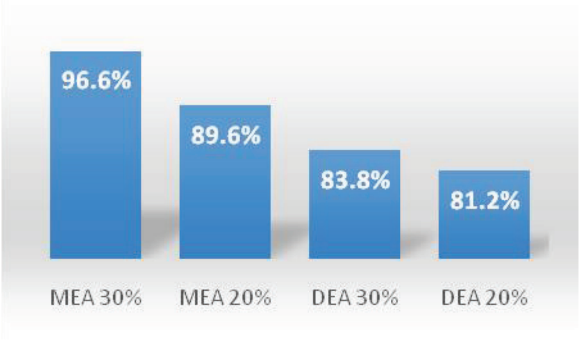

Fig-6: Comparison of Efficiencies of Amine Solvents

Conclusions

Results show that highest scrubbing efficiency for CO$_2$ is achieved with the MEA30 scenario. Efficiency is a function of concentration and decreases with solvent concentration. Overall, DEA solvent is less efficient scrubber than MEA even at same the concentration. The amine-CO$_2$ reaction in the absorber is exothermic and may generate large quantities of heat at larger scales. This has important implications for scrubber design which should be able to sustain the heat generated. The heat can also serve as an energy source for industrial processes.

Corrosion was visually observed in the absorber for each scenario but was highest for MEA30 followed by DEA30, MEA20 and DEA20 solutions. Corrosion may increase with solvent concentration [15]. However, quantitative measurement of corrosion was out of the scope of this research. Study of corrosion's correlation with concentration, as well as corrosion inhibitors in amine technology are proposed as future research topics. Overall, MEA30 solution had the highest CO$_2$-removal efficiency of 97% and is recommended for industrial scrubbing.

Acknowledgements

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[2] The efficiencies may vary on industrial scale due to role of external factors such as flue gas characteristics, scrubber design and contact time.

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