Carbon Capture Based on Chemical Absorption: Process Design and Techno-Economic Assessments

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Abstract. *It is a widely accepted scientific fact that emissions of greenhouse gases, mostly Carbon dioxide (CO2) from fossil fuels, contribute to global warming. However, the world's energy industry continues to rely mostly on fossil fuels, which still provide an 85percent of the world's energy needs. The realization has set in that fossil fuels would remain the main energy source for many years due to the lack of economically viable sources of renewable power and the availability of cheap fuels including coal. Consequently, it is imperative to create technology that allows for the continued use of fossil fuels while reducing the amount of Carbon dioxide released into the environment. To minimize emissions into the atmosphere,* CO_2 *from pollution sources should be captured. The theory behind several methods of* CO_2 *collection will be examined in this study, and their benefits and drawbacks will be considered. After that, a selected separation method will be thoroughly examined by running simulations of the process utilizing the program As-pen Plus with three solvents, including NH3, DEA, and MEA. The effectiveness of the separation process was examined concerning operational circumstances. In contrast with other solvents, DEA stands out because of its increased CO2 removal efficiency and its decreased sensitivity to lean loading.*

Keywords:

Carbon capture, Chemical absorption, MEA, DEA, NH3

1. Introduction

Fossil fuels can provide about 68 percent of the world's production energy requirements, and carbon dioxide (CO_2) releases from fossil fuel combustion have been recognized as a key cause of climate change [1]. At the present level of development, nevertheless, it is difficult to lessen reliance on fuels of fossil and shift to non-fossil, including renewable and hydrogen energy. Furthermore, the non-fossil fuel conversion efficiency is often lower than fossil fuels. As a result, in order to reach mid- to long-term objectives, cost-effective CO_2 emission reduction methods must be found [2].

Fossil fuel power plants seem to be the greatest Carbon dioxide potential sources, accounting for more than 1/3 of global CO_2 releases. As a result, reducing CO_2 emissions from power station flue gas becomes critical [3]. There are numerous efficient ways to reduce carbon dioxide emissions, which will be covered in the sections bellow. The focus will be on the most economical and efficient method to treat power plant emissions, which is absorption using chemical solutions.

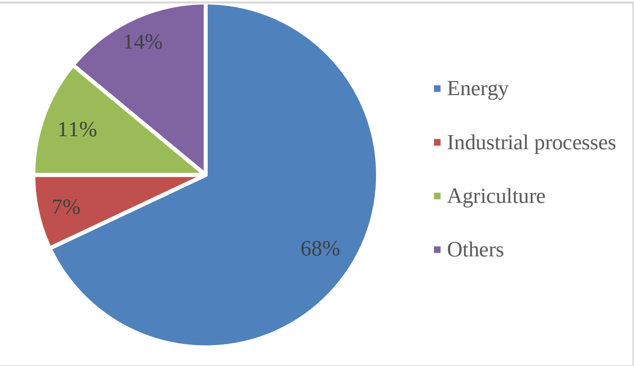

Fig. 1 CO2 emissions percent from fuel combustion usage per field [4].

2. Carbon Capture and Storage (CCS)

Carbon dioxide capture and storage (CCS) is one of the alternatives for lowering CO_2 emissions from human activities in the atmosphere. CO_2 is released primarily through the combustion of fossil fuels, which occurs in big combustion units like those utilized in electric power production and smaller, dispersed sources, including automotive engines and ovens utilized in home and commercial buildings. The releasing of CO_2 is also produced by several industrial and resource extraction activities, and forest fires during land clearing. Significant CO_2 point sources of, including large industrial activities and power stations, would most likely benefit from CCS. Some sources might provide decarbonized fuels like hydrogen to the industrial, transportation, and construction sectors, lowering releases from those spread sources [5].

CCS includes using techniques to gather and concentrate CO_2 generated by energy- and industrial-related activities, transport it to an appropriate storage place, after storing it for a long time away from the environment. Fossil fuels could be used with less GHG because of CCS. Suppose the biomass is not harvested at an unsustainable rate. In that case, CCS may result in net CO2 removal from the atmosphere (frequently known as "negative releases") by absorbing and storing the ambient CO2 absorbed by biomass. As shown in Figure 2, the three crucial steps in the CCS process are storage, conveyance, and capture. These elements are used in industrial operations but not necessarily for CO2 storage. One step in the capture process includes CO2 extrication from other gaseous products. In fuel-burning operations like those used in power stations, extraction techniques may capture CO2 after decarbonizing or combustion the fuel before combustion. Moving CO2 gathered from the CO2 source to a suitable storage facility located far away may need the transport phase. In order to facilitate both transportation and storing, the captured CO2 gas is frequently subjected to pressure to increase the density at the capturing facility. Possible storing alternatives include industrial fixation in inorganic carbonates, injection into deep ocean sedimentary formations, and injection into subterranean geological formations. Numerous industrial processes may use small amounts of collected CO_2 and store it in manufactured items. Different CCS system components have different levels of technical development. While certain technologies, particularly in the gas and oil industry, are still in the study, production, or demonstration phases, others are now extensively used in established businesses [6].

Oxyfuel combustion capture, pre-combustion capture, and post-combustion capture are the three main techniques of CCS [8]. In the short- to medium-term, post-combustion carbon capture is the best option because, unlike the other two strategies, it could be adapted to current power plants [7]. Post-combustion Carbon dioxide capture may be separated into three categories as the last carbon capturing phase of the entire combustion process: chemical, physical, and biological approaches.

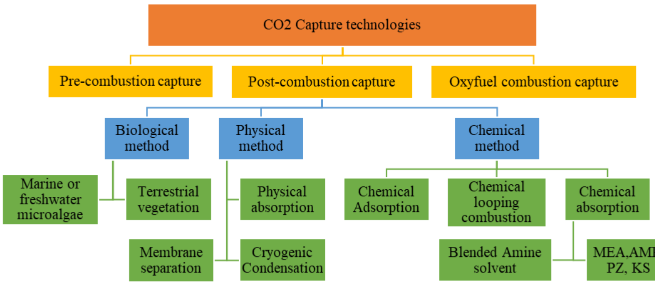

Fig. 2 CO_2 capture Technologies.

A. *Biological method*

Regarding the biological process, CO2 is fixed without needing energy via photosynthesis in photosynthetic bacteria, algae, and plants. Biological fixing by terrestrial ecosystems and freshwater and marine microalgae is one of the biological methods. However, its applicability is hampered by its limited absorption capacity and efficiency [8].

B. *Physical method*

The physical approach involves utilizing organic solutions to absorb and eliminate CO2 from flue gas. The CO2 capture procedure does not include any chemical reactions, and this approach's main goal is to identify absorbents' features. Membrane separation, cryogenic condensation, and physical absorption technology are part of the physical technique. The physical approach has a better CO2 absorption efficiency than the biological method, but the absorbent cost is higher due to certain unique criteria. CO2 was extracted from power station flue gas utilizing a chemical process that involves interacting with chemical absorbents [9].

C. *Chemical method*

Chemical processes involve chemical absorption, chemical adsorption, and chemical looping combustion. On the other hand, chemical absorption offers several obvious advantages, including low cost, proven technology, and great efficiency. The most common chemical absorption method is CO_2 capture by amine solutions. The core concept is the neutralization process, where amine solutions are utilized as an absorbent and combines with CO_2 in the flue gas to produce carbonate and bicarbonate. [10].

3. The Benefits and Drawbacks of CO_2 Capture

Compared to other forms of carbon removal technology, CCS provides several benefits [11]. By transferring heating more rapidly and requiring less energy to compress steam, CO2-based steam cycles, where CO2 subjects to pressure into a supercritical fluid, may improve the efficiency of power generation turbines. Additionally, extracting geothermal heating from the same locations where it is injected utilizing geologically stored CO2 may be possible, producing sustainable geothermal energy. Additionally, it is theoretically probable to change CO2 into fuel. A few techniques to do this are available, but they are all costly and time-consuming. Infrastructure with a longer lifespan might be created by utilizing CO2 absorbed from the atmosphere to strengthen concrete. The production of polymers and chemicals, including polyurethanes, which are utilized to produce soft foams, including those present in mattresses may also be accomplished by utilizing CO2.

High oxygen concentrations are employed during oxyfuel burning, which significantly reduces emissions of sulfur dioxide and nitrogen oxide (NOx) [12]. When oxyfuel combustion is assessed to combustion with traditional air, one study conducted for the Argonne National Lab detected a 50 percent decrease in NOx releases [13]. An electrostatic precipitator could be utilized to eliminate the particles left behind after consuming oxyfuel. CCS The financial impact of carbon appears to be a financial evaluation of the benefits and costs to society from the effects of climate change brought on by one more metric tonne of CO2 released into the atmosphere every year. Instances of societal consequences of rising CO2 emission include hurricane damage and detrimental effects on human health. The increase in agriculture's overall productivity may be advantageous. Removing CO2 directly from the source may decrease net societal losses.

Regardless of the benefits of utilizing CCS to aid decrease CO2 emissions into the environment, several implementation issues still require to be handled. Product costs would increase when subsidies are not provided to upgrade existing electric manufacturing plants and industries with CCS technique. To compensate for the deployment of CCS technology, specialists at the University of Utah estimated that energy costs would increase by 50 to 80percent [14]. The cost of materials and equipment required to extract CO2, construct infrastructure to transport it, and then store it could be prohibitively costly since there are currently no governmental drivers in most spaces to promote or mandate the utilization of CCS.

A fatal leak is always possible despite the rarity of CO2 delivery errors. CO2 leaks from a pipeline, a concentration of 7 to 10% in the surrounding air might immediately endanger human life. Another possibility at the subsurface storage facility is leaking. If a CO2 leak happens unexpectedly at an injection site, the health of nearby humans and animals may be in danger. A slow leak from injection wells or rock stratum cracks might harm the soil and groundwater in the vicinity of the storage location. CO2 injection-induced earthquakes may create havoc in the vicinity of the storage facility [15]. The public is hesitant about carbon storage through CCS due to several perceived risks. A CO2 storage facility would require large-scale CCS installation [16].

The MEA-based CO2 capture method has received much attention in the literature [17], where various operating strategies and control parameters designed to cut down on energy use throughout solvent regeneration have been detailed. The most significant factor in the system's response time has been proven to be the liquid residence time in the boiler. A linear relationship has been found between the optimum solvent rate, the energy flow to the boiler, and the boiler load [18]. Numerous operating scenarios for the process were identified, and the input flue gas flow rate impacts the degree of unrestricted freedom.

In certain studies, technical advancements to the conventional approach are being made to utilize less energy. For instance, [19] reduced the high duty demand of the stripper by utilizing a CO2 ab-sorption-desorption system that relies on MEA with capacitive deionization (CDI). The carbon-rich MEA solution was concentrated in a CDI cell before being sent to the stripper for regeneration; throughout the charging cycle, ionic species were adsorbed at oppositely charged electrodes, and an ion-free solution was sent back to the absorber. The results suggest that 10-45percent of the total energy supplied to the stripper might well be conserved due to the high Carbon dioxide loading of the solution. It was also illustrated that utilizing ultrasounds accelerates physical desorption, which is possible at temperatures lower than 80-degree centigrade [20].

In [21] suggested two options for the desorption process, contemporaneous amine deprotonation and removing a reaction product, namely the bicarbonate ion. These methods greatly lowered the energy needed to regenerate the assessed tertiary amines (TIPA, triisopropanolamine, triethanolamine, me-thyldiethanolamine, and pyrrolidine) (for instance, the carbon dioxide-rich amine treated with calcium hydroxide or utilizing an anionic exchange resin).

Another example is the combination of amine-based chemical absorption with solar-assisted post-combustion CO2 capture for CO2 collecting in a power station [22]. Solar thermal energy may meet the thermal need for CO2 collection, and the recommended integration tends to outperform the conventional method while maintaining a low investment cost. Solar thermal energy is still a potential technology due to the global size of CO2 collection; however, its capacity is currently inadequate to supply all energy needs.

In order to reduce the amount of Carbon dioxide released into the atmosphere, a study is now being done. The collected Carbon dioxide may subsequently be used for improved oil recovery, ocean or subsurface storage, or both. Carrying out simulation studies on a chosen technique (Carbon capture based on chemical absorption) utilizing Aspen Plus software. As well as exploring the influence of MEA solvent on the chemical absorption of CO2 capture.

4. Materials and Methods

Figure 3 depicts the traditional CO2 collecting procedure utilizing MEA scrubbing. An absorber, a heat exchanger, and a stripper are the main components of the MEA process. The CO2 in flue gas (Flue Gas) reaches the absorber at the bottom, while the MEA solvents (Cold Lean MEA) enter the absorber at the top. The CO2 is preferentially absorbed by the MEA solvent thru an exothermic process [23].

The CO2-rich solution (Cold Rich MEA) drains from the bottom of the absorbers and is preheated by passing thru the heating exchanger. The stripper's top is filled with a preheated rich solvent (Hot Rich MEA) and desorbs CO2 at a high temperature. The CO2 is caught at the stripper's top, and the CO2 lean solvent (Hot Lean MEA) drains out the stripper's bottom. The cool leaner solvent (Cold Lean MEA) has been recycled and entered the top of the absorber after the lean solvent has been cooled by passing via a heating exchanger and a cooler.

The present emphasis of CO2 absorption research utilizing MEA is on reducing energy usage during solvent regeneration [24][25] compiled a comprehensive evaluation of CO2 absorption process enhancement depending on patents and study materials. Three main study classifications have been recognized, along with their sub-groups:

- Absorption improvement: inter-heated absorber, double loop absorber, rich solvent recycles, expansion and flue gas compression;
- Heating integration: rich solvents (splitting, preheating, and flashing), inter-heated stripper, heat integrated stripper, multi-effect stripper, and vacuum operated stripper;
- Heat pump: integrated heating pump, lean vapor compression, and rich vapor compression. Because most research was performed through process modeling, this investigation illustrates a detectable dearth of pilot plant size estimation. Moreover, the capture processing energy performance is enhanced, which affects complexity and cost and diminishes its operability.

Table 1 Flue gas feeding amount and input factors

Factors	Value
The rate of flow	2861 tones/hr
Temperature	40ºC
Pressure	1.1 bar
Feeding gas composition	Value (mol%)
H2O	8
sN2	76
CO2	4
O2	12
H2S	0

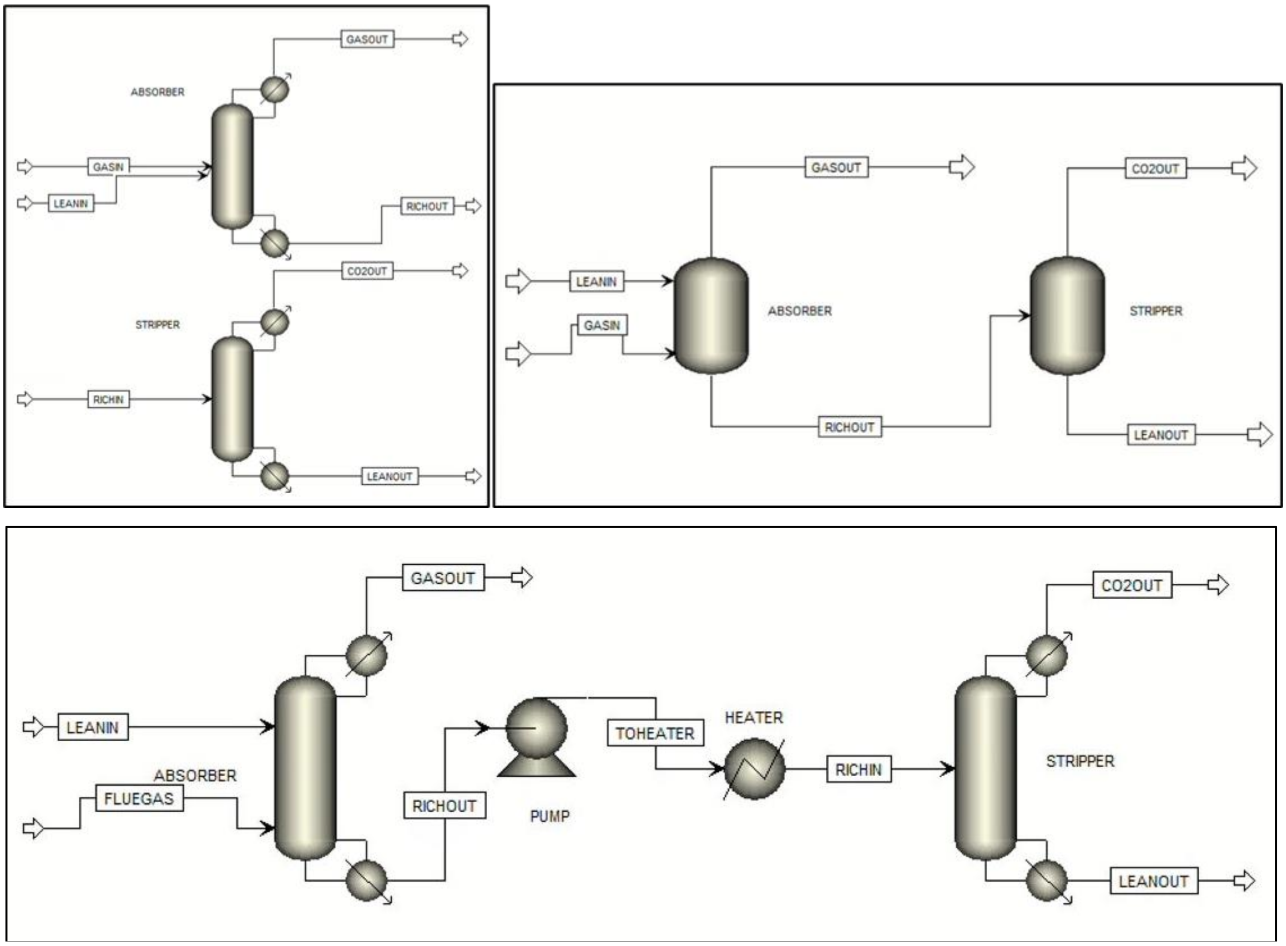

Fig. 3 The PFD of the CO2 capture process utilizing aqueous NH3, DEA, and MEA scrubbing.

5. Results

A. *For NH3 solvent*

Figure 4 illustrates the CO2 removal efficacy under various amounts of aqueous ammonia solution. Figure 4 detected that the CO2 removing efficiency improved with increasing the amount of NH3, where the best NH3 amount that obtained the highest removal was 0.25, and increasing the amount of NH3 higher than this ratio made the removal constant. As the ammonia amount rises, the mole fraction of ammonia to carbon dioxide also rises. This means that as the ammonia amount rises, more active ammonia would be accessible to diffuse towards the gas-liquid interaction and interface with Carbon dioxide, which will boost the development parameter and increase the absorption rate [26].

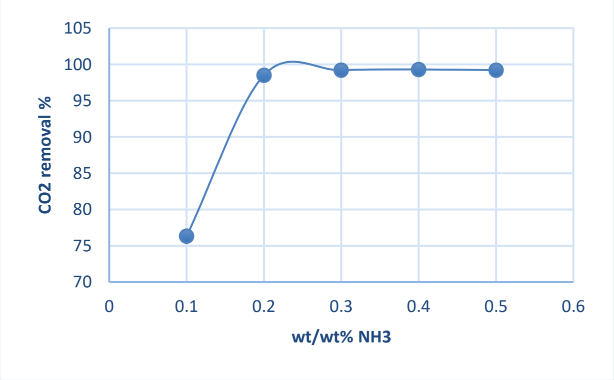

Fig. 4 CO2 removal variation by NH3 different concentration

Figure 5 studies the impact of NH3 solvent temp on the CO2 removing efficacy. Although increasing the solvent temperature increases the efficiency of CO2 removal, the findings illustrated that the higher CO2 removal of about 80% could be reached when the solvent temperature is around 20-30 C, which industrially is considered acceptable and economical. However, as shown in figure 6, the CO2 removal efficacy is impacted by the lean loading %. It has been demonstrated beyond any reasonable doubt that elevating the lean loading will reduce CO2 removal efficiency.

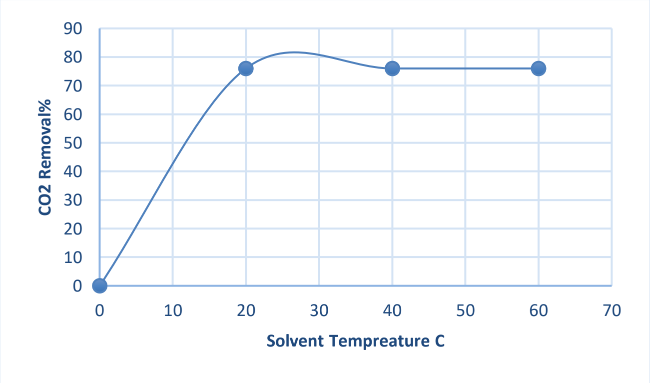

Fig. 5 CO2 removal with NH3 solvent temperature.

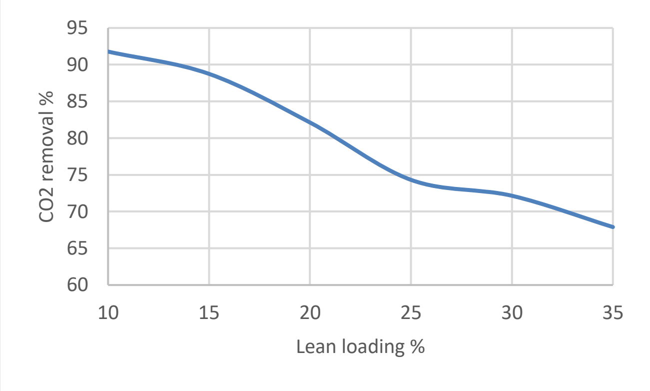

Fig. 6 CO2 removal with lean loading of NH3

B. MEA

MEA is one of the popular amine solvents used in the CO2 capture field. This study focuses on the efficiency of CO2 removal. Several factors affect how well CO2 is removed, but the two most important are amine concentration and solvent temperature. As shown in figure 7, increasing the MEA amount will increase the removal efficiency. The higher efficiency could be obtained at 50 wt% o MEA, about 93%. However, MEA solvents of about 25wt% would deliver an efficiency of about 90%, considered the most economically acceptable in the industrial field.

Figure 8 shows that increasing the temperature, but to a certain value, increases the CO2 removal efficacy. Nevertheless, if the temperature is raised above that value, the effect will be reversed. The higher efficiency could be reached when the solvent temperature is around 40 C.

As demonstrated in the previous case with NH3, increasing the lean loading negatively impacts the efficiency of CO2 removal, as shown in figure 9.

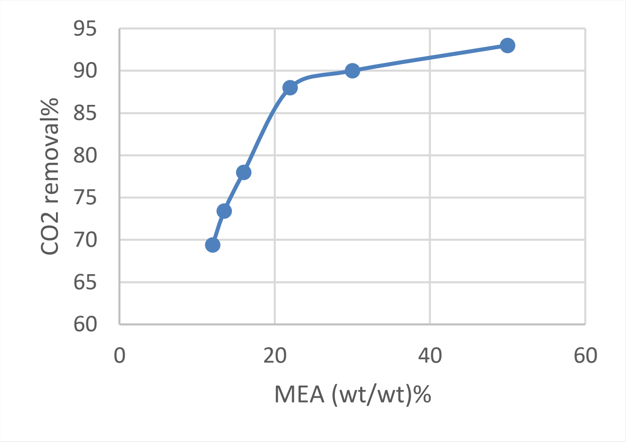

Fig. 7 Removal variation by MEA different concentration

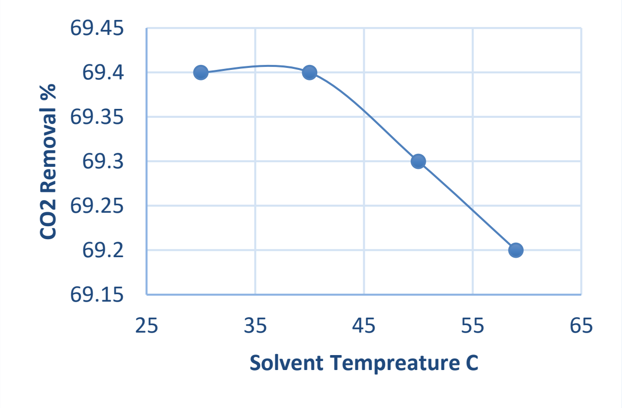

Fig. 8 CO2 removal with MEA solvent temperature

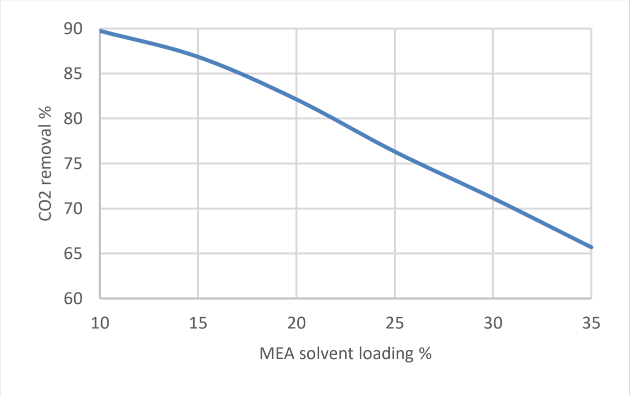

Fig. 9 CO2 removal with lean loading of MEA

C. DEA

DEA is a developed amine version of the last one considered in this work. Solvent Concentration and temperature were considered the key elements are influencing CO2 removal efficiency. As shown in figures 10 & 11, increasing the DEA concentration or the solvent temperature will increase the CO2 removal efficiency. The maximum efficient concentration is around 30wt%, as illustrated in figure 8, where increasing the amount more than that may not have a significant effect but may cause problems such as corrosion. Regarding the solvent temperature, a higher removal efficiency could be obtained at about 45C.

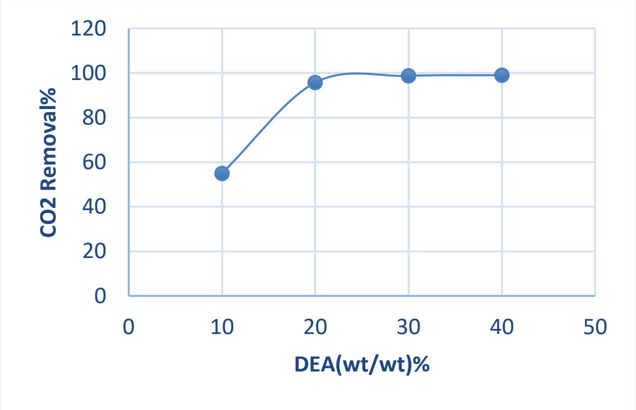

Fig. 10 CO2 removal variation by DEA different concentration

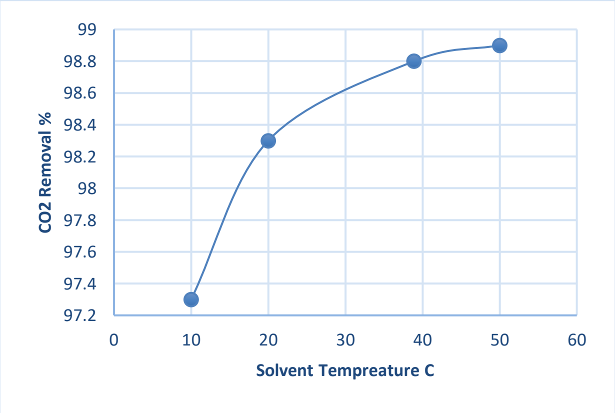

Fig. 11 CO2 removal with DEA solvent temperature

As established in the previous cases with NH3 and MEA, increasing the lean loading negatively impacts the efficiency of CO2 removal. However, in this case, the effect was slightly less than the other solvents as shown in figure 12.

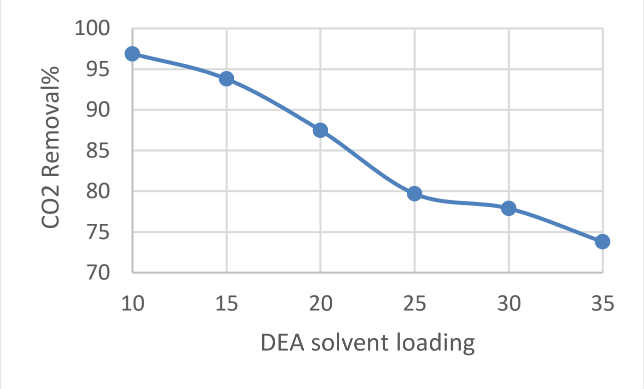

Fig. 12 CO2 removal with lean loading of DEA

From reviewing all the above factors of the three solvents, we can conclude that the best removal efficiency obtained is for the DEA amine at a temperature of 45 C and an amount of 30 wt.%.

D. The reboiler duty

The most significant factor that usually is considered in the study of CO2 capture is the required amount of energy in the amine regeneration plant [27], which is affected by many parameters, including amine concentration, solvent temperature, circulation rate, CO2 content, and size and pressure of the regeneration tower. After reviewing the previous factors and reaching a conclusion of the most efficient amine and operating conditions, the absorber's packing height and pressure will be investigated to study their effect on the reboiler duty. As shown in figures 13 and 14, increasing either one of them will decrease the reboiler duty, which means a more economical process.

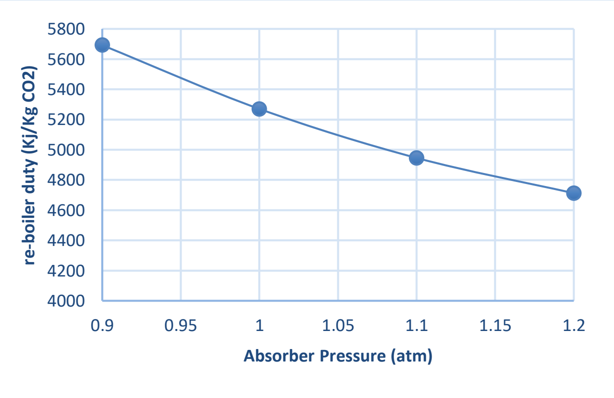

Fig. 13 Re-boiler duty variation with absorber pressure

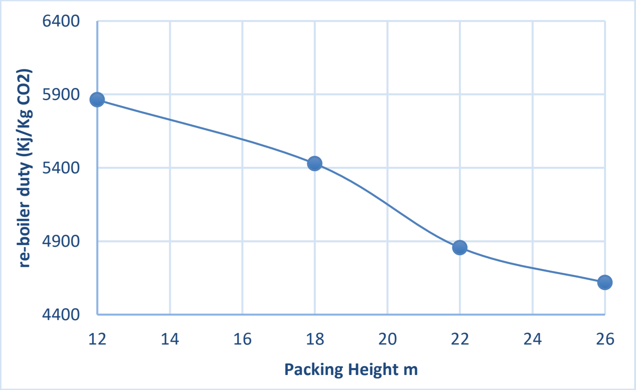

Fig. 14 Re-boiler duty with absorber packing height

Briefly, the most important factor in the studies of CO2 capture is the economic side, which should be precisely investigated when deciding the amine type to maintain the minimum possible operational cost.

6. Conclusions

CO2 Removal efficiency is very sensitive to solvent characteristics such as solvent concentration, temperature, and lean solvent loading. Lean solvent loading has an inverse relationship with removal efficiency, increasing solvent concentration, and temperature. Because the solvent's CO2 reduces, the CO2 removal efficiency drops. However, increasing solvent concentration will increase CO2 absorption capacity. Similarly, increasing the lean solvent temperature will decrease the absorption capacity's driving force, which will increase the reaction rate, resulting in higher CO2 capture.

Compared to other solvents, DEA distinguishes out due to its higher CO2 removal efficiency and its reduced sensitivity to lean loading. However, other factors need to be revised and considered for further understanding.

Studying CO2 removal efficiency is the target of this study; however, the most important target is the economic side of the process, which is mainly affected by the reboiler duty of the regeneration plant. Therefore, the most driving factors of the reboiler duty are the tower pressure and the packing height, which increased either factor resulting in a lower duty.

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