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Energy Savings in CO_2 Capture System through Intercooling Mechanism

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Abstract

It has been globally recognized as necessary to reduce greenhouse gas (GHG) emissions for mitigating the adverse effects of global warming on earth. Carbon dioxide (CO_2) capture and storage (CCS) technologies can play a critical role to achieve these reductions. Current CCS technologies use several different approaches including adsorption, membrane separation, physical and chemical absorption to separate CO_2 from flue gases. This study aims to evaluate the performance and energy savings of CO_2 capture system based on chemical absorption by installing an intercooler in the system. Monoethanolamine (MEA) was used as the absorption solvent and Aspen HYSYS (ver. 9) was used to simulate the CO_2 capturing model. The positioning of the intercooler was studied in 10 different cases and compared with the base case 0 without intercooling. It was found that the installation of the intercooler improved the overall efficiency of CO_2 recovery in the designed system for all 1-10 cases. Intercooler case 9 was found to be the best case in providing the highest recovery of CO_2 (92.68%), together with MEA solvent savings of 2.51%. Furthermore, energy savings of 16 GJ/h was estimated from the absorber column alone, that would increase many folds for the entire CO_2 capture plant. The intercooling system, thus showed improved CO_2 recovery performance and potential of significant savings in MEA solvent loading and energy requirements, essential for the development of economical and optimized CO_2 capturing technology.

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Keywords: CO_2 capture; Climate change; Energy savings; Intercooling; Aspen HYSYS; Greenhouse gases (GHG)

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1. Introduction

Greenhouse gases (GHGs) trap and absorb heat radiated by the earth in the upper atmosphere causing greenhouse effect. The IPCC (Intergovernmental Panel on Climate Change) has identified six anthropogenic GHGs with climate change potential: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), chlorofluorocarbons (CFCs), and hydrofluorocarbons (HFCs) [1]. Human industrial activity is adding to the natural greenhouse effect causing the earth temperature to increase. This could have dangerous effects on the planet earth. The CO_2 has the lowest climate change potential, but has the largest impact due to the sheer total volume of its emissions. Essentially, it is a by-product of many industrial processes including the generation of non-renewable electricity production plants. The combustion of fossil fuels, 67% of the world's electricity production source, including coal, oil, and gas in power stations and transportation fuel cause most of the CO_2 emissions [2]. There is an international agreement to limit the emissions of GHG to mitigate the global warming problem, especially the CO_2 as being the most significant GHG [3]. For example, the EU has the target of reducing domestic GHG emissions by at least 40% by 2030, against a 1990 baseline [4]. Although tremendous efforts are made to develop other technologies, including renewable energy generation to reduce fossil fuels consumption, but more efforts in terms of economics and time are required to reduce the CO_2 emissions. In particular, the efficiencies of all energy processes should be improved together with appropriate technologies to capture the remaining CO_2 emissions from going into the atmosphere [5-9].

CO_2 capture and storage (CCS) technologies are extensively studied in recent years to develop more efficient and cheaper technology. Ideally, the CCS technology needs to be adaptable to current CO_2 producing plants and processes. Any captured CO_2 could be stored underground, utilized in the food industry for carbonated soft drinks or in the petroleum industry for enhanced oil recovery [1-3]. Adsorption, membrane separation, physical and chemical absorption are some of the techniques currently being investigated for CO_2 separation from flue gasses. Amine-based CO_2 absorption systems are the current techniques of choice as they can fit to the existing plants, however more research is required to improve their efficiencies [3,4]. This method of absorption utilizes the ability to regenerate most of the amine used for CO_2 absorption, as it is collected through a reversible thermal reaction. Monoethanolamine (MEA) is currently one of the most used amines for CO_2 absorption from a flue gas [10-12]. However, research is being carried out into other amines such as the tertiary amine Methyl Diethanolamine (MDEA) as well. This study aims to optimize a CO_2 capture system by intercooling mechanism. MEA was used as an absorption solvent, and Aspen HYSYS was used to develop the simulation model. The effect of various intercooling positions on CO_2 absorber performance as well as on energy and material savings were studied. The challenges and future perspectives of developing cheaper and optimized CO_2 capturing technology were also examined.

2. Methodology

2.1 CO_2 absorption process

The principle for this process is an exothermic reversible reaction where a weak acid (CO_2) reacts with a weak base (MEA) to produce salt. The inlet (flue) gas makes contact with the solvent flowing counter-currently in an absorber. The flue gases are absorbed by the solvent. The CO_2 rich solution then leaves the absorber and is heated to reverse the initial reaction before it enters the stripper. The CO_2 capturing process by MEA solvent takes places in four stages; 1) cooling and compression of flue gas, 2) CO_2 absorption by solvent, 3) solvent regeneration, and 4) compression of CO_2. This study was focused on mainly the CO_2 absorption stage. The intercooler will be attached to the absorber once a conventional CO_2 capturing plant has been simulated and used as a base case to compare and contrast the changes. Therefore, an optimization of the plant must be carried out to analyze the optimum number of trays required for absorber and stripper columns based on the flue gas specifications given in literature [11-14]. The absorber column is usually a packed column, and offers enough surface area for the absorption of CO_2. The amine enters the column at a loading of 0.2 to 0.3 and leaves with a loading of around 0.5.

Loading is defined on a mole basis as given by:

$$Loading = \frac{Moles\ of\ all\ CO_2\ carrying\ species}{Moles\ of\ all\ MEA\ carrying\ Species} = \frac{[CO_2]+[HCO_3^-]+[CO_3^{2-}]+[MEACOO^-]}{[MEA]+[MEA^+]+\{MEACOO^-]} \qquad [1]$$

The low amine concentration stream is known as the lean amine and enters on top of the absorber usually at second stage. Make-up water is added to the tower at the first stage to act as water wash and to cool the vent gas. The amine leaves the bottom of the column once it has absorbed CO_2 and is known as a rich amine. The rich amine then enters a heat exchanger, in which the heat is transferred from the lean amine stream from stripper to this rich amine stream.

2.2 CO_2 absorption process modelling

2.2.1 Package selection

Aspen HYSYS was used for process simulation using acid gas property package for thermodynamics. This package simulates the detailed required aqueous-phase equilibrium and kinetics reactions based on Electrolyte NRTL model [13]. The vapor phase can cause a deviation from an ideal solution. Therefore, Peng-Robinson Equation of State was used for vapor phase properties to take care of this deviation [13,14]. The model is to assess the excessive Gibbs free energy in an electrolyte solution and assumes that this is due to two following contributing factors:

- Short-range forces between all species include the local ion-ion, molecule-molecule, ion-molecule interactions.
- The long-range electrostatic ion-ion interactions.

This model is also based on two following fundamental assumptions:

- Like-ion repulsion assumption; due to the large repulsive forces between ions of the same charge, it is assumed that the local composition of cations around cations and anions around anions is zero [11].
- Local electro-neutrality assumption; the distribution of cations and anions around the solvent molecule is such that the net local ionic charge is zero.

Therefore, the Electrolyte NRTL model calculates the excess Gibbs free energy using the following expression;

$$g^{ex*} = g^{ex*,LR} + g^{ex*,local} \quad [2]$$

Where:
g^{ex*} is the molar excess Gibbs free energy
$g^{ex*,LR}$ is the molar excess Gibbs free energy contribution from long range forces
$g^{ex*,local}$ is the molar excess Gibbs free energy contribution from local forces
The long-range contributions are calculated using a combination of the Pitzer-Debye-Hucel contribution and the Born expression. Whereas, the local interaction contribution is derived as per NRTL mode [10-14].

2.2.2 CO_2 absorption in base case

The absorber column from the model palette was used as the absorber for the process, with a Lean MEA and flue gas stream as inputs and sweet gas as the overhead vapor outlet and the rich MEA as the liquid bottom outlet. The column was set up with an 8 meter packing height and 0.3 meter diameter using 25 mm IMTP random packing, operating at atmospheric pressure. The correlations for both mass transfer, interfacial area and pressure drop exist in Aspen HYSYS. The Bravo-Fair correlation was used for both the mass transfer and interfacial area estimation [14,15]. The pressure drop was calculated with the built in vendor for the packing type used. The stripping column was set up using 14 trays along with a reboiler and condenser. The dimensions of the column were calculated by the software and also used 25 mm IMTP random packing. The stripper was set up with the condenser operating in full reflux, with the overhead product being labelled as acid gas. The reboiler is operating at 122 kPa with the liquid outlet being labelled Bottoms. The inlet stream temperature to the stripper was set to 99°C as it is generally an accepted maximum temperature to avoid acid gas breakout and corrosion problems in the equipment [15]. The separating column and cooler were added to obtain a relatively pure CO_2 stream that can be compressed for storage. The water stream can be used as the water make-up stream. The flue gas specifications used in Aspen modelling include; temperature (40°C), flowrate (600 kg/s), pressure (300 mbar), mole fractions of 0.067, 0.737, 0.196 for CO_2, N_2. O_2, respectively.

2.2.3 CO_2 absorption with Intercooling System

An intercooler is a mechanical device used to cool the fluid between the stages. When the intercooler is installed to the column, a side stream is drawn from the absorber column, cooled down then reintroduced to the column just

below where it was taken from. Intercooling can be carried out in any tray or height of the column, and the location has a significant effect on intercooling efficiency and energy required [12]. The flowsheet appears the same when an intercooler is applied to the absorber. It is added to the simulation by adding a side draw to the absorption column. For this, the intercooling draw rate was set to 50,000 kg/hr and temperature of the stream reduced by 10°C before returning the stream to the stage above, where it was taken from. The intercooler was moved down the column at different stages to find out the optimum position. It was then compared with the base case to find the effect it has on CO_2 absorption, amine recirculation rates and the resulting impact in the form of process energy savings.

3. Results and Discussion

3.1 CO_2 absorption base case

The Aspen HYSYS base case model is shown in figure 1and the results of the simulation are shown in table 1. The CO_2 loading from the Lean MEA entering the column was increased as expected from 0.124 to 0.381 after collection of CO_2 from the gas. Most importantly, the CO_2 recovery is indicated by the total amount of CO_2 remaining in the sweet gas stream that is only 7.39%. This means at these operating parameters, 92.610% of the CO_2 from the flue gas stream was absorbed and captured by the MEA solvent. The CO_2 compositions in the product streams of CO_2 showed a very high molar % of 0.948, and the H_2O stream had molar % of 0.052, which can be used in the water make-up stream. The loading of the MEA is within a viable range and is comparable to that found in another recent study [14].

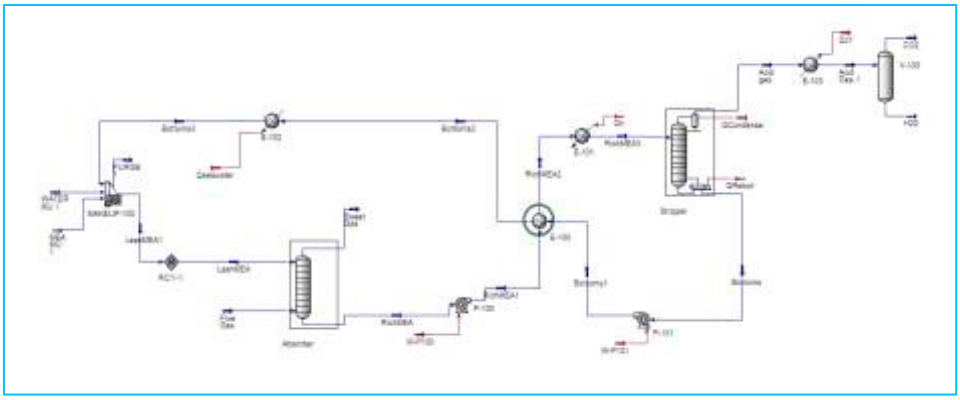

Figure 1. Aspen HYSYS Base case Model

3.2 Effect of intercooling mechanism on CO_2 absorption efficiency

The impact of intercooler installation at various positions on absorber column of the CO_2 capturing through MEA solvent has been studied. Table 2 shows the positions of the intercooler installed at within the absorber in each given case and its impact on the CO_2 capturing efficiency and the lean MEA flow rates. Case 0 is without intercooling system and is shown to represent the base case for data comparison purposes. It can be seen from the data that the installation of the intercooler improved the overall efficiency of CO_2 recovery in this system for all 1-10 cases (Table 2). The increment in CO_2 absorption by the MEA solvent fluctuates from case to case. For instance, CO_2 recovery of 92.638, 92.636 and 92.664% were achieved for the cases 1, 5 and 10 respectively. Intercooler case 9 was found to be the best case to give the highest recovery of 92.679% of CO_2. At this position, the intercooler had its draw stage on tray 11. This makes the best position for intercooling to be about a quarter of the column from the bottom. These findings are in agreement with another published study [12,14].

Table 1. Base case absorber results

Streams	Molar flow rate (MMSCFD)	CO_2 (Mol %)	$CO_2/CO_{2\,total}$ (%)	CO_2 loading
Flue gas	1473	4.500	-	-
Sweet gas	1576	0.445	7.39	-
Lean MEA	2018	1.424	-	0.124
Rich MEA	1915	4.595	92.61	0.381

The data in table 2 also illustrates the effect the intercooler placement has on the lean MEA flow rates required to maintain the highest CO_2 absorption rate of 92.610%. It is obvious from the obtained data that the installation of the intercooler system results in lower lean MEA flow rates required to achieve the maximum CO_2 recovery of 92.610% in all 1-9 cases as compared to the base case (Table 2). The increment in flow savings vary from case to case. For example, flow savings of 1.15, 1.47 and 1.79% were achieved for the cases 1, 5 and 10 respectively. Case 9 was found to be the best case to save the maximum 2.51% of MEA flow, which means it required 59,000 kg/h less solvent to achieve the maximum CO_2 recovery as compared to the base case without intercooling system installed. The reduced flow rate was achieved due to the increased CO_2 loading with the use of the intercooling, as the cooler solvent can carry more CO_2 gas (Table 2). The increased efficiency of the solvent is attributed to the lower temperature in the absorber aiding the absorption reaction of CO_2 onto the solvent. The intercooling system thus showed potential of significant savings in amounts of solvent loading and energy requirement, leading to cheaper and optimized CO_2 capturing technology development.

Table 2. Intercooler case results

Intercooler case no	Draw stage position	Return stage position	CO_2 Capture (%) @ Lean MEA flow rate 2,344,000 kg/h	Rich MEA loading	Lean MEA flow rate (kg/h) @ fixed 92.610% CO_2 capture	Flow Rate differential (kg/h)	Flow Saving (%)
0	-	-	92.610	0.3822	2,344,000	-	-
1	3	4	92.638	0.3841	2,317,000	27,000	1.15
2	4	5	92.630	0.3848	2,312,200	31,800	1.35
3	5	6	92.647	0.3846	2,31,1500	32,500	1.38
4	6	7	92.635	0.3850	2,310,000	34,000	1.45
5	7	8	92.636	0.3849	2,309,500	34,500	1.47
6	8	9	92.653	0.3852	2,306,000	38,000	1.62
7	9	10	92.658	0.3853	2,305,000	39,000	1.66
8	10	11	92.665	0.3851	2,302,000	42,000	1.79
9	11	12	92.679	0.3876	2,285,000	59,000	2.51
10	12	13	92.664	0.3862	2,302,000	42,000	1.79

3.3 Energy savings of CO_2 absorption with intercooling system

The major challenge for post-combustion CO_2 capture is its large parasitic load [10]. Many research studies have focussed on reducing the energy requirement of CO_2 capturing systems to achieve maximum economic and environmental benefits [5-8]. The effect of using intercooling on the energy requirement of a post-combustion CO_2 capture plant has been investigated using MEA solvent in this study. Based on the Aspen simulation results, it has been found that the intercooling system installation reduces the overall energy requirement of the CO_2 capturing system. The energy requirement of CO_2 absorber column has been estimated and compared for the base case and case 9. It has been found that the absorber column required around 6394 GJ/h of energy to work at the maximum MEA solvent flow rate of 2,344,000 kg/h in the base case. This requirement has been reduced to 6378 GJ/h of energy in case 9 to achieve 92.610% of CO_2 absorption. Whereas the energy savings is only around 0.25% compared to base case, this equates to 16 GJ/h that is a significant amount of energy savings. Notably, this is only the energy saving in absorber column of the overall system. The energy requirements for the pumps and the heat operations would also be significantly reduced as there is 59,000 kg/h of less solvent being pumped around the system, with a potential of further significant amounts of energy savings. This study confirms that the installation of intercooling system at absorber column improves the CO_2 capturing efficiency as well as reduces the MEA solvent and energy requirements.

The most energy intense part of the process is the reboiler in the stripper, as this is where the most energy is required to undo the absorption reaction. By reducing the total MEA solvent required with intercooling installation, the strain on the reboiler is reduced, and thus considerable amounts of energy is further saved. The reduced solvent volume also results in lower operating costs for the plant as less solvent is being used on a daily basis. For the conditions used in this study, it can be concluded that based on the simulation model and results, intercooling appears to be a viable option for improving the efficiency of the MEA solvent in the absorber for CO_2 capturing and so a potential energy saver. However, this process still requires a lot of energy to remove CO_2, and more research needs to be done to further

reduce the energy tax for CO_2 capture. Future possibilities involving the use of an intercooling for amine absorption include observing the effect of intercooling on other amine solvents such as MDEA and DIPA. The new data can then be compared with this study to find out the most suitable solvent for optimum CO_2 recovery. Flue gas from other sources could also be investigated; coal-fired power plants produce a flue gas with a very different specification to that of gas-fired plant. The change in composition may have an impact on the intercoolers overall performance and would be worth investigating. Many solvents other than MEA have been studied with little success to find the best solvent that will; achieve high CO_2 capturing performance, require lower energy, be easily regenerated for multiple uses, be cheap and have lower environmental impacts. One of the most challenging and desired features is to develop a closed system in which solvent is reused with little economic and environmental costs. Therefore, an ideal scenario would be to have closed carbon loop, where the CO_2 recovered can be used to produce value-added products, leading to multiple economic and environmental benefits.

4. Conclusions

The installation of intercooler in CO_2 capturing system was found to improve the CO_2 recovery performance and resulted in energy and MEA solvent savings in all 10 cases studied. The ideal location for the intercooler was found to be near the bottom of the absorber, where the loading of the amine was the highest. The highest recovery of CO_2 (92.68%) was observed for the intercooler case 9. It also showed savings of around 2.51% of MEA flow, which means it required 59,000 kg/h less solvent to achieve the maximum CO_2 recovery as compared to the base case without intercooling. Furthermore, energy savings of 16 GJ/h was estimated only from the absorber column that would increase many folds for the entire CO_2 capture plant. For the conditions used, it can be concluded that based on the simulation model, intercooling appears to be a viable option for improving the efficiency of the CO_2 capture system and result in potential savings of energy and MEA solvent. These findings are useful for designing and developing CO_2 capturing systems at global scale. However, the overall energy required for CO_2 capture system is still very high and more research is critical to further reduce the energy tax for CO_2 recovery.

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