Sensitivity Analysis of Post Combustion Carbon Capture Using Monoethanolamine (MEA) as a Solvent. A Simulation Study

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Abstract. Carbon capturing and storage (CCS) is new technology to remove CO$_2$ from the processes that involve elimination of CO$_2$ as its effect on the environment and incessant increase in temperature of the Earth, makes it interesting as well as most dangerous issue that should be dealt timely to reduce the greenhouse gas emissions. In the present research, the data obtained from the experimental study of CO$_2$ capture pilot plant at the Laboratory of Engineering Thermodynamic in TU Kaiserslautern, Germany, is used for the rate based model validation for different cases using monoethanolamine (MEA) as a solvent. Process simulation sensitivity analysis performed includes a wide range of CO$_2$ concentrations for flue gas of different sources i.e. natural gas fired power plant, exhaust gas recycle and coal based power plant. Results obtained from sensitivity analysis point out the effects of lean loading, stripper pressure, MEA concentration and CO$_2$ concentration in flue gas on energy requirement of reboiler and degree of regeneration using MEA as a solvent for a pilot-scale study. It was found that the specific reboiler duty is least for coal-fired power plant in comparison to the natural gas –fired and exhaust gas recycled power plant, keeping the flow rate of the flue gas constant.

Keywords: Carbon capture, sensitivity analysis, monoethanolamine

1. Introduction
Carbon capture in industry is widely practiced and dates to decades ago. There are several industrial processes which require carbon capture for the refinement or the quality of the finished product. In natural gas processing, CO$_2$ is removed to reduce the compression and transportation cost. CO$_2$ is removed from H$_2$ as it affects the catalyst which is used for the reaction of H$_2$ and N$_2$ in ammonia process. Above all, CO$_2$ is posing a serious threat to the environment due to its greenhouse gas ability, resulting in climate change and global warming. So, carbon capturing and further storing it is relatively new technology to remove CO$_2$ from the processes that involve elimination of CO$_2$ as its effect the environment and result in incessant increase in temperature of the Earth, making it an interesting as well as most dangerous issue that should be dealt timely to reduce the greenhouse emissions [1].

Prior to industrialization, CO$_2$ concentrations into the atmosphere have been recorded 280 parts per million by volume (ppmv) in 1860 and it has been incessantly growing from now on and reached to a level of 316 ppmv in 1958. Today, it is estimated to a hilarious level of 420 ppmv. Without taking eminent measures to stop CO$_2$ concentration into the atmosphere, it is predicted to escalate as high as 750 ppmv by 2100. Unfortunately, third world countries even great proportion of developed countries are fulfilling their power generation demands from fossil fuel-fired power plants (e.g. coal and natural gas) [2].

Three different routes of technology are available to capture CO$_2$, including pre-combustion CO$_2$ capture, post-combustion CO$_2$ capture (PCC), and oxy-fuel combustion CO$_2$ capture. Oxy-fuel combustion is a general term used for technologies where nitrogen (N$_2$) is excluded from the combustion process. In case of pre-combustion CO$_2$, the CO$_2$ is captured prior to combustion. It is well suited for gas fired combined cycle power plants.

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The fuel is reacted with steam or steam/oxygen mixture to produce a mixture rich in H₂ and CO₂ and then CO₂ is removed before combustion [3]. In case of PCC, the tail end recovery of the CO₂ from the flue gas of the power plant is exploited. The most mature technology from the number of the PCC involves the use of the liquid solvent to capture CO₂ from the flue gas. However, PCC is most viable and promising technology as diversity of solvents are exploited to minimize energy requirements of the process [3].

In power generation sector, generally the most trusted and commercially utilized technology to capture CO₂ is PCC technology as it involves the capturing of CO₂ after the conversion of fuel into energy. The flue gas of natural gas fired power plant typically contain 3-5 % CO₂ and 5-13 % in exhaust gas recycle (EGR), while 13-15 % CO₂ is present in the coal fired power plant [4].

The challenges which are underway in implementation of PCC are: how to mitigate high capital and operating cost and how the process can be scaled up for industrial use. Stripping is energy intensive process as reboiler duty requirements are higher. As a consequence, a lot of work is done to reduce the specific reboiler duty and the operating cost [5]. Aspen Plus software has been used to simulate the absorption/desorption mechanism, highlighting the process and design parameters to validate the base case [6]. Pointing out that the reduction in reboiler can be achieved if absorber height is increased by 20 %. The rate based model examination in terms of film discretization ratio and flow models along with packing type resulting in excellent predictability to scale up the process [7].

Due to the ever-increasing demand of energy, the dependence on fossil fuels based energy generation will remain higher. So, there is a need to make CO₂ capture process more economical and less energy intensive. The process improvements regarding absorption enhancement, heat integration and heat pumps in order to optimize the energy demands has been proposed in the literature [8]. In addition, the process schematics with tentative changes are recomposed [8]. The sensitivity study of all input parameters related to the thermodynamic properties of the process are performed in the literature [9, 10] and concluded that the high sensitivities are related for the Henry’s law constant, the interfacial area and the enthalpy of absorption as well as for the factors which describe the equilibrium in order to develop the rate based model which need improved interfacial area correlation factors. Thus, the thermodynamic parameters and equations are widely agreed in the literature to predict the optimum or near to optimum results.

A rate based model is presented using 2-amino-2-methyl-1-propanol (AMP) as a solvent and validated by providing sensitivity analysis [11]. The blend of MDEA and MEA is studied with the appropriate ratio for CO₂ capture and a significant reduction is found in energy consumption that is required for CO₂ regeneration [9]. The new solvents are also being discussed to reduce the specific reboiler duty such as two new solvents CASTOR1 and CASTOR2 with MEA were reported [12]. These new solvents showed excellent performance in absorption and reducing energy penalties. CASTOR 2 showed lower required flow rate and for higher columns these solvents need less reboiler duty to strip out CO₂. However, still in the literature MEA is being discussed as a bench-scale solvent to show fundamental findings. Therefore, this study mainly focuses on the absorption of CO₂ using MEA as solvent which is widely studied for this purpose due to its high loading capacity.

Different process alterations are also being discussed in the literature, such as natural gas exhaust gas recycles (EGR) to increase CO₂ concentration in flue gas and calculated optimum liquid to gas ratio which could result in lower energy consumption forfeits [13]. More the concentration of CO₂ is absorbed, the lower will be specific reboiler duty [13]. The process is further improved by reducing the required MEA recycle stream [5]. Important perceptions have been attained on the functioning of washing sections on the top of both absorber and desorption columns by analyzing the factors that limit the flowrates of recycle water and make-up water around the absorber washing section. The desorption model is validated through literature [9]. The heat loss is not dependent on flow rates and reboiler duty, however, it depend truly on level of insulation [4, 14]. Notz et al. [14]. executed a detailed experimental study of absorption/desorption at pilot-scale level. MEA was used as a solvent and influence of all important parameters, such as CO₂ partial pressure, lean loading, desorber pressure, dynamic loading,
CO₂ removal rate and MEA weight percentage checked. Further, the trends were presented by varying operational parameters which give a deep insight how energy requirement can be reduced.

In the nutshell, it is agreed that the main environmental concern is CO₂ emissions by the combustion of fossil-fuel fired power plants to fulfill the increasing energy requirements worldwide. However, the massive emissions of CO₂ are attracting the researcher’s attentions to reduce it by using different existing or innovative technologies to make them practically feasible. Sensitivity analysis is one type of study by which the performance of the post combustion CO₂ capture unit using liquid as a reactive solvent can be assessed by changing the number of parameters for an operable region to be assessed.

Therefore, in the present study, the pilot-scale plant model is developed and simulated using Aspen Plus® (v.10). Rate based distillation model (RDFRAC) simulate the packed as well as tray column keeping into account the mass and energy balance with carefully observing the flooding limit into the absorption/desorption column, hence it is selected for the present analysis. Appropriate kinetic expressions are included for the reaction that don’t reach equilibrium [15]. The rate based model developed in Aspen Plus uses the dimensions from the literature [14]. Further, validation of the developed model is done by comparing the experimental results with simulated results. Finally, the sensitivity analysis is performed to check the effects of process variables on performance of the CO₂ capture process.

2. Materials and methods

2.1. Model development

The rate-based model of CO₂ absorption/desorption model was established within the Aspen Plus® RADFRAC modelling framework. Figure 1 shows the developed Aspen plus flowsheet of the presented model. The model was developed by properly applying a thermodynamic framework that represent the CO₂-H₂O-MEA system, including kinetics of CO₂ reaction with the MEA solution, and appropriate transport properties which affect mass and the heat transfer [3]. Two packed columns acting as absorber and stripper are used for absorption and desorption reaction for MEA+H₂O+CO₂, respectively. The internal specification and dimensions of columns along with process variables are shown in Table 1.

The flue gas containing CO₂ enters the bottom of the absorber while the lean solvent with a 0.1-0.3 CO₂ loading comes in contact counter-currently as flue gas rises the column and solvent falls down under the effect of the gravity. The CO₂ is absorbed in the solvent and absorption increases the temperature.
inside the column and reaches up to 60°C and the scrubbed gas from the absorber is vented to the atmosphere. The rich solvent exists the absorber with higher CO₂ loading in range of 0.3-0.5. The rich stream is further needed to escalate its temperature before entering the stripper so a cross-heat exchanger exchanges the heat from the regenerated stream coming out of the stripper. Finally, the rich solvent enters the stripper at a temperature range of 100-120°C and is operated at higher pressure (1.5-2 bar) than atmospheric pressure. The stripped CO₂ is collected from the top of the stripper and is further transported to storage. Reboiler at the bottom of the stripper provides the heat and is the only energy intensive part which needs reduction. The solvent which is free of CO₂ is pumped to cross-heat exchanger where it enters the absorber after reduction in temperature. Before entering the absorber makeup water and makeup MEA solution is added to fulfil the deficiency of the flow rate after stripping of the CO₂ from top of the stripper.

### Table 1. Survey of data characterizing the pilot plant Notz et al. [14]

| Parameters                          | Characteristics                      |
|-------------------------------------|---------------------------------------|
| Flue gas source                     | Natural gas power plant/Coal power plant/Exhaust gas recycle |
| CO₂ partial pressure in the flue gas| 3-16 mbar                             |
| Diameter of columns (absorber and desorber) | 0.125 m                             |
| Height of absorber                  | 4.2 m                                 |
| Height of desorber                  | 2.52 m                                |
| Column internals in absorber, desorber | Structured packing Sulzer Mellapak 250Y™ |
| Pressure in the absorber            | Atmospheric Pressure                  |
| Pressure in the desorber            | 1-3 bar                               |
| Temperature of flue gas             | 40 °C                                 |

Furthermore, a variety of simulations were performed using different conditions of solvent flow rate, CO₂ loading, solvent strength and stripper pressure. The diversity of results allowed a broad understanding of the absorption/desorption process especially at the pilot-scale level. For the number of research work presented in the literature, the liquid flow rate was kept constant [16, 17]. However, Notz et al. [14] and Tobiesen et al [4] studies showed the maximum liquid flow was up to 4.5 times higher than the smallest value. Hence, the data reported by Notz et al. [14] is used for the model validation and subsequent sensitivity analysis in the present work due to diversity of the reported experimental results.

2.2. Chemical reactions

Chemical reactions happen only in liquid phase where ionic species of H₂O, MEA and CO₂ are involved. As amines and acid gases are weak electrolytes and the partially dissociates in water, resulting in a complex mixture of non-volatiles (H₂O plus amines) [18]. A variety of equilibrium constant that depends on temperature are derived from the literature [19]. The number of chemical reactions involved in the reactive absorption and desorption of CO₂ with MEA are given as:

**Hydrolysis reactions:**

\[
\text{MEOAcOO}^- + \text{H}_2\text{O} \leftrightarrow \text{MEA} + \text{HCO}_3^- 
\]

(1)

**Dissociation of dissolved carbon dioxide:**

\[
\text{CO}_2 + 2\text{H}_2\text{O} \leftrightarrow \text{HCO}_3^- + \text{H}_3\text{O}^+ 
\]

(2)
Dissociation of bicarbonate:
\[ \text{HCO}_3^- + \text{H}_2\text{O} \leftrightarrow \text{H}_3\text{O}^+ + \text{CO}_3^{2-} \]  \hspace{1cm} (3)

Dissociation of protonated MEA:
\[ \text{MEA}^+ + \text{H}_2\text{O} \leftrightarrow \text{MEA} + \text{H}_3\text{O}^+ \]  \hspace{1cm} (4)

Ionization of water:
\[ 2\text{H}_2\text{O} \leftrightarrow \text{OH}^- + \text{H}_3\text{O}^+ \]  \hspace{1cm} (5)

2.2.1. Equilibrium data

The equilibrium constants for the above given reactions are calculated by using Table 2 that represents the data imported from Arachchige and Melaaen [19] to develop model mathematically using the equation (6).

\[
\ln K_j = A_j + \frac{B_j}{T} + C_j \ln T + D_j T
\]  \hspace{1cm} (6)

2.2.2. Rate kinetic data

To understand the reacting system, it is compulsory to have a strong knowledge about rate kinetic data involving the following chemical reactions.

\[ \text{CO}_2 + \text{OH}^- \leftrightarrow \text{HCO}_3^- \]  \hspace{1cm} (7)

\[ \text{MEA} + \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{MEACOO}^- + \text{H}_3\text{O}^+ \]  \hspace{1cm} (8)

\[ \text{HCO}_3^- \leftrightarrow \text{CO}_2 + \text{OH}^- \]  \hspace{1cm} (9)

\[ \text{MEACOO}^- \text{H}_3\text{O}^+ \leftrightarrow \text{MEA} + \text{CO}_2 + \text{H}_2\text{O} \]  \hspace{1cm} (10)

The mathematical equation utilized in Aspen Plus to calculate kinetic equations for the above chemical reactions is given below with constants in Table 3.

\[
r_j = k_j \left(\frac{T}{T_o}\right)^{n_j} \exp \left[-\frac{E_j}{R} \left(\frac{1}{T} - \frac{1}{T_o}\right)\right]
\]  \hspace{1cm} (11)

| Parameter | Reaction 1 | Reaction 2 | Reaction 3 | Reaction 4 | Reaction 5 |
|-----------|------------|------------|------------|------------|------------|
| A_j       | -0.52      | 231.46     | 216.05     | -3.038     | 132.89     |
| B_j       | -2545.53   | -12092.1   | -12431.7   | -7008.3    | -12445.9   |
| C_j       | 0          | -36.78     | -35.48     | 0          | -22.47     |
| D_j       | 0          | 0          | 0          | -0.00313   | 0          |

| Parameter | Reaction 7 | Reaction 8 | Reaction 9 | Reaction 10 |
|-----------|------------|------------|------------|-------------|
| K_j       | 4.32x10^{13} | 9.77x10^{10} | 2.38x10^{17} | 2.7963x10^{20} |
| n_j       | 0          | 0          | 0          | 0           |
| E_j (cal/mol) | 13249     | 9855.80    | 29450.89   | 17229.79    |
| T_o(K)    | 298        | 298        | 298        | 298         |
Figure 2. Model results as a function of the experimental results reported by Notz et al. [14] (a) parity plot for rich loading (b) parity plot for CO2 capture (c) parity plot for specific reboiler duty

Figure 3. Model results as a function of the experimental results for the absorber temperature profiles reported by Notz et al. [14]
2.3. Model validation

The obtained data from experimental study of CO₂ capture pilot plant at the Laboratory of Engineering Thermodynamic in TU Kaiserslautern, Germany, is used for rate based model validation for different cases as reported in the literature [14] using MEA as a solvent. Comprehensive and detailed set of experiments were performed and were categorized according to key performance parameters. The experiments regarding variation of CO₂ partial pressure in flue gas, stripper pressure and dynamic load were simulated to validate rate based model. The detailed process flow diagrams with process parameters for the experimental setup can be found in reference [14]. All the errors regarding i.e. capture rate, solvent flow rate, lean/rich loadings, reboiler duty and specific reboiler duty are kept under 5%.

The results shown in Figure 2 are in good agreement with the experimental results. Temperature profiles express clearly how absorption/desorption is occurring along the length of absorber and stripper. In Figure 3 and Figure 4, the temperature profiles of absorber and stripper is shown, respectively.

3. Results and discussions

Sensitivity analysis

To perform sensitivity analysis, four operational parameters i.e. stripper pressure, lean loading, MEA weight percentage in the solution and CO₂ concentration in the flue gas are varied. For each of the operational parameter, all other parameters are fixed and only prescribed parameter is varied to check the impact of the varied parameter on the performance parameters which are specific reboiler duty and degree of regeneration.

3.1. Stripper pressure

The desorber pressure is varied from 1-3 bar (absolute) keeping all other parameters constant as shown in Table 4. Changes in pressure results in the variance for the required energy of regeneration as provided in the literature [14]. Increase in stripper pressure is effective as the reboiler temperature and pressure are directly related to each other. As the flow rate and the CO₂ loading of the solvent is constant so a specified amount of the CO₂ is absorbed in the absorber, before entering in the stripper. Hence, L/G ratio and CO₂ loading of the rich solvent is unchanged no matter what ever the pressure is used. By increasing the pressure in the stripper, the temperature rises and provides an increase gradient to strip out more CO₂. Therefore, the reboiler duty decreases as lower amount of water is to be evaporated which means the regeneration task is getting easier as lesser amount of water is present with CO₂ to strip it out.
Hence, the reboiler at bottom of the stripper requires less energy due to the elevated pressure. As a consequence, the specific reboiler duty is decreased as also found in the literature [20].

Table 4. Process variables for varying stripper pressure

| Process variables                        | Ranges          |
|-----------------------------------------|-----------------|
| Desorber pressure (bar)                 | 1-3             |
| Flue gas mass flow rate (kg/h)          | 72              |
| CO₂ composition (mol%)                  | 9.7             |
| Solvent mass flow rate (kg/h)           | 321             |
| Reboiler duty (kW)                      | 37-11.946       |
| CO₂ removal rate (%)                    | 85              |
| Lean Loading (mol CO₂/mol MEA)          | 0.209           |
| MEA weight % (g/g)                      | 30              |

However, increasing the pressure causes elevated temperature throughout the stripper resulting in the degradation of the MEA. MEA degradation is minor around 110°C, however, it accelerates as temperature is approached to 130°C [21]. So, the temperature should be limited around 120-124°C in order to avoid any degradation. It is found with increase in pressure from 2 to 3 bar the reduction in the specific reboiler duty is 31%. It is obvious from the Figure 5 where the pressure is increased from 1 to 1.5 bar the reduction in the specific reboiler duty brings abrupt change. However, as it moves further, the curve shows less gradient and reduction is relatively slower than previous one. As pilot plant is designed for 2 bar stripper pressure, hence it should be limited as MEA degradation starts at higher pressure due to the restrictions of stripper design limitation.

3.1.1. Degree of regeneration

Degree of regeneration is defined as how much percentage of CO₂ is captured from rich solvent when it exits the stripper. It is percentage difference of rich and lean loading with respect to rich loading.

\[
\text{Degree of Regeneration (\%)} = \frac{\text{Rich Loading} - \text{Lean Loading}}{\text{Rich Loading}} \times 100
\]

As in case of varying stripper pressure the solvent which has absorbed CO₂ in the absorber remains unaffected after how much change in stripper pressure is brought. So, the stripper pressure has no effect on the degree of regeneration as can be seen in Figure 5-2.

![Figure 5. Effect of varying pressure on specific reboiler duty and degree of regeneration](https://doi.org/10.37358/RC.21.4.8459)
Figure 6. Effect varying lean loading on specific reboiler duty and degree of regeneration

Table 5. Process variables for varying lean loading

| Process variables             | Ranges  |
|------------------------------|---------|
| CO₂ partial pressure (mol%)  | 9.7     |
| Flue gas mass flow (kg/h)    | 72      |
| Desorber pressure (bar)      | 2       |
| CO₂ removal rate (%)         | 85      |
| MEA weight % (g/g)           | 30      |
| Lean Loadings (mol CO₂/mol MEA) | 0.10-0.30 |

3.2. Lean loading

For each simulation the lean loading is varied and all other process parameters are kept constant as given in Table 5. When solvent lean loading is increased and the MEA weight percentage is fixed then the water content in the solvent stream is reduced. Increased CO₂ concentration and less water content in rich solvent results in lower specific reboiler duty [20]. Increase in the CO₂ concentration require higher flow rate of the solvent to absorb the CO₂ from the flue gas. So, reboiler duty is increased with increase in the higher solvent flow rate. However, captured CO₂ flow rate is increased further and as a result the specific reboiler duty is reduced. Furthermore, the specific reboiler duty becomes almost constant after some specific value of the lean loading. Hence, the lean loading can be considered as a parameter of optimization to find the best value for the operating condition. For the present case, the specific reboiler duty is considered as optimum at a value of 0.15 mol CO₂/mol MEA of lean loading.

3.2.1. Degree of regeneration

Degree of regeneration and specific reboiler duty are dependent on each other. As its obvious in Figure 6 that with increase in lean loading the reboiler duty as well as degree of regeneration decreases. With increase in lean loading, the solvent capacity to absorb CO₂ is limited as CO₂ concentration in solvent itself is increasing. So, the concentration of CO₂ in the rich stream is reduced along with the reduced rich loading resulting in less solvent regeneration.

3.3. MEA Weight percentage

In this set of simulations, MEA weight percentage is varied and all other parameters are kept constant as can be seen in Table 6. To absorb one molecule of CO₂, stoichiometricaly two molecules of MEA are required for one molecule of CO₂, hence maximum CO₂ loading can be 0.5 mol CO₂/mol MEA. As CO₂ loading of lean solvent is kept constant and MEA composition in the solvent is increased, it means there is higher potential for solvent to attach more numbers of CO₂ molecules. So, the flow rate of solvent
which is required to absorb CO$_2$ in the absorber is decreased, resulting in lower L/G ratio. More and more CO$_2$ is absorbed as MEA weight percentage increases resulting in the higher rich loading. Higher rich loading ensures higher CO$_2$ partial pressure in the stripper. In industrial plants, rich loading can reach upto 0.4-0.47 mol CO$_2$/mol MEA [20]. However, in the pilot plant, it rises to a maximum of 0.425 due to the length of the stripper which is limited and it becomes difficult to achieve a value of 0.47 mol CO$_2$/mol MEA. The decreased load of solvent flowrate and higher rich loading results in the deduction of the reboiler duty. Consequently, the specific reboiler duty is reduced from 7.90 to 5.5 GJ/TCO$_2$ as MEA weight percentage is increased from 20 to 40 %, respectively. MEA content was limited to 20 % only because of corrosivity, so corrosion inhibitors are added to make it 30 % or higher. If the MEA contents are increased to 40% then the corrosion effect is drastic [14].

| Process variables                  | Ranges                        |
|-----------------------------------|-------------------------------|
| Desorber pressure (bar)           | 2                             |
| Flue gas mass flow rate (kg/h)    | 72                            |
| CO$_2$ composition (mol%)         | 9.7                           |
| L/G ratio                         | 8.8-2.1                       |
| Reboiler duty (kW)                | 21-14.17                      |
| CO$_2$ removal rate (%)           | 85                            |
| Rich Loading (mol CO$_2$/mol MEA) | 0.318-0.425                   |
| Lean Loading (mol CO$_2$/mol MEA) | 0.208                         |
| MEA weight % (g/g)                | 20-40                         |

**Table 6. Process variables for varying MEA strength**

![Figure 7. Effect varying MEA weight % on specific reboiler duty and degree of regeneration](figure.png)

### 3.3.1. Degree of regeneration

There is inverse relation of specific reboiler duty and degree of regeneration when strength of MEA solvent is varied. As MEA concentration in the solvent is increased, the absorption capacity of solvent is increased with increase in molecules of MEA which results in more absorption of CO$_2$ from flue gas as shown in Figure 7. Increased concentration of MEA in solvent ensures higher rich loading and which results in increased difference of rich and lean loading and hence degree of regeneration increases. The percentage of captured CO$_2$ in the stripper is increased making the stripping easier and as a consequence the reboiler duty of the stripper is reduced.
3.4. CO₂ Composition in flue gas

Specific reboiler duty decreases with increase in CO₂ partial pressure in the flue gas as given in Figure 8. The CO₂ contents in flue gas is varied in range of 3 - 16 mol %. Figure 8 shows three curves that are classified as variance in solvent loadings. For each loading, CO₂ partial pressure is varied and other process parameter are kept constant as given in Table 7.

3.4.1. Impact of CO₂ concentration on L/G ratio

Increase in CO₂ content increases the partial pressure of CO₂ in flue gas, resulting in the higher flow rate of the solvent. Hence, the increase in the CO₂ concentration requires more solvent molecules to absorb them. For the case of 0.15 mol CO₂/mol MEA loading the solvent flow rate is in range of 85-210 kg/hr as CO₂ concentration in flue gas is varied from 3 mol% to 16 mol%. An increase of 60 % is noted for the loading of 0.15 mol CO₂/mol MEA. As solvent loading is further increased to 0.20 molCO₂/mol MEA, the required flow rate is varied further from 160 kg/h for 3 mol% to 406 kg/h for 16 mol% CO₂ for the flue gas. Again, the increase in flow rate of solvent is around 60 %. Hence, the increase in the solvent CO₂ loadings due to increase in the CO₂ concentration in the flue gas results in increased flow rate of the solvent.

Table 7. Process variables for varying CO₂ concentration in flue gas

| Process variables             | Rages     |
|------------------------------|-----------|
| CO₂ partial pressure (mol%)  | 3-16      |
| Flue gas mass flow (kg/h)    | 72        |
| Desorber pressure (bar)      | 2         |
| CO₂ removal rate (%)         | 85        |
| MEA weight % (g/g)           | 30        |
| Lean Loadings (mol CO₂/mol MEA) | 0.15-025 |

3.4.2. Impact of CO₂ concentration on specific reboiler duty

CO₂ concentration in flue gas is plotted against specific reboiler duty in Figure 8. The drop in the specific reboiler duty is mainly due to the increased concentration of CO₂. As CO₂ concentration is increased, the partial pressure of CO₂ is also increased which act as a driving force for the absorption reaction with MEA solution. More CO₂ is absorbed in the solvent making it easier to strip it out [10]. Akram et al. [20] performed experiments of CO₂ concentration starting with 4.5 mol % CO₂ keeping the flow rate of solvent fixed and the CO₂ capture rate was varied. However, in current study the CO₂ capture rate is fixed at 85 %, so solvent flow rate is varied to capture the required amount of the CO₂, therefore
in both cases the reboiler duty shows same trends as CO$_2$ concentration is increased from 3 mol % to 16 mol %.

When solvent lean loading is increased and the MEA weight percentage is fixed then the water content in the solvent streams is reduced. Increased CO$_2$ concentration and less water content in rich solvent results in lower specific reboiler duty [20]. Increase in CO$_2$ concentration require higher flow rate of solvent to absorb the CO$_2$ from flue gas. So, the reboiler duty is increased with increase in the solvent flow rate. However, the captured CO$_2$ flow rate is increased further and as a result the specific reboiler duty is reduced.

For 3 mol % CO$_2$ in flue gas the specific reboiler duty is 10.44 GJ/tCO$_2$ using the solvent of 0.15 mol CO$_2$/mol MEA lean loading while it is decreased to 9.66 GJ/tCO$_2$ using 0.209 mol CO$_2$/mol MEA lean loading. Reduction of 7.47 % in specific reboiler duty is observed when solvent loading is increased from 0.15 to 0.209 mol CO$_2$/mol MEA. So, 0.25mol CO$_2$/mol MEA offers further reduction in specific reboiler duty.

3.4.3. Impact of CO$_2$ concentration on degree of regeneration

Degree of regeneration is related with ease of separation that ensures less reboiler duty. As more molecules of CO$_2$ are available to absorb in given the quantity of MEA solvent, the rich loading tends to increase. Increase in rich loading offers higher difference between rich and lean loading which results in escalated degree of regeneration. With increase in the lean loading of the solvent the capacity to absorb CO$_2$ from the flue gas is decreased and as a result the rich loading does not have the same potential to go as high as in previous scenario of lower lean loading. In Figure 9, it is clear as the lean loading 0.15-0.25 mol CO$_2$/mol MEA changes, the amount of the CO$_2$ captured and degree of regeneration is reduced. The degree of regeneration at 0.15 mol CO$_2$/mol MEA is 54 % at 3 mol % CO$_2$ in flue gas, however, in the case of 0.25 mol CO$_2$/mol MEA, it is only at 18 % while CO$_2$ concentration in flue gas is kept as above.

4. Conclusions

The process simulation model is successfully developed in ASPEN PLUS and clearly replicate the experimental results of post combustion CO$_2$ capture process at pilot scale level. The error between simulated and experimental values is under 5 % overall for lean loading, capture rate, rich loading and reboiler duty. Work performed in the present research includes a wide range of CO$_2$ emissions from different sources i.e. natural gas fired power plant, exhaust gas recycle and coal fired power plants. Process simulation performed clearly point out the effects of lean loading, stripper pressure, MEA concentration and CO$_2$ concentration in the flue gas on energy requirement of reboiler and degree of regeneration using MEA as a solvent. The conclusions from the present research can be summarized as below:

- Reduction of 7.47 % in specific reboiler duty is observed when solvent loading is increased from 0.15 to 0.209 mol CO$_2$/mol MEA.
- The specific reboiler duty is reduced 30% as MEA weight percentage is increased from 20 to 40 (g/g).
- The specific reboiler duty is reduced 60 % as stripper pressure is increased from 1-3 (bar).
- With increase in lean loading and CO$_2$ concentration results in the decrease of the specific reboiler duty. Therefore, the specific reboiler duty will be less for the coal-fired power plant in comparison to the natural-gas fired and exhaust gas recycled power plants, keeping the flowrate of the flue gas constant.

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