

COMPARATIVE PERFORMANCE STUDY OF CO₂ CAPTURE WITH MONOETHYL AND DIETHYL AMINES USING ASPEN PLUS®

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ABSTRACT

One of the major causes of climate change is the CO₂ emission from fossil fuel-based power plants. To mitigate this effects CO₂ capture and storage is proposed for future plants. CO₂ capture using amines is the most matured technology for this purpose. Different amines or mixtures of those are proposed as solvents for this process. In this paper a comparative evaluation of the estimated performance using Aspen Plus® for two most common amines i.e. monoethylamine and diethylamine is reported. Effects of some design and operating parameters for these two solvents and a comparative study are also reported. DEA is found to be better performing than MEA for identical operating conditions as it achieves higher CO₂ capture efficiency with lower heat load for the stripper column. Moreover optimum number of stages of the absorber column for the best CO₂ capture from the same flue gas composition is smaller for DEA. Effects of variation of temperatures of the solvents and the flue gas as well as that of pressure of the stripper column on the CO₂ capture performance are also discussed.

Keywords: MEA, DEA, CO₂ capture performance, parametric variations

1. INTRODUCTION

Economic prosperity of a country is grossly indicated by per capita energy consumption .The most useful form of energy in modern civilization is electricity [1]. Thus efficient conversion of primary energy to electricity is very critical for the growth of civilization. Over a long period, fossil fuels have been the major source of energy for modern civilization. This trend is expected to continue for a substantial period as assessed [2]. Coal is still the major fossil fuel for large scale electric power generation and this trend is expected to continue for a long time [2, 3]. As fossil fuels mostly contain carbon and hydrogen as combustibles, carbon-dioxide and moisture are the inevitable products of combustion from fossil fuels. Anthropogenic addition of carbon-dioxide to atmosphere over the ages has caused one of the most serious challenges for the survival of human society on earth [4]. The major source of this anthropogenic CO₂ addition is from fossil fuel based power plants (mostly coal-fired) [3,5].

Shifting to renewable energy replacing these coal-based power plants is not feasible in near future from technological and economical viewpoints. Rather development of advanced coal-based power plants with low or no CO₂ emission may be a better option during transition from fossil fuel based energy to renewable energy [6]. Modern power plants with suitable carbon capture process is urgently needed for reducing CO₂ emissions from power plants without reducing energy use [7,8]. Three distinct routes of carbon capture are being presently developed – pre-combustion CO₂ capture, post-combustion CO₂ capture and oxy fuel combustion. In pre-combustion CO₂ capture, physical solvent is used to absorb CO₂ from a mixture of gases having relatively higher mole fraction of CO₂ [7]. On the hand flue gas containing relatively lower mole fraction of CO₂ after combustion using air is scrubbed using suitable solvent to absorb CO₂ from the flue gas. This CO₂ rich solvent is then heated in another column to regenerate CO₂ by heating [7, 8, 9].

In oxy fuel combustion pure oxygen is used for combustion and resulting CO_2 without moisture is directly captured as it is unmixed with other gases [10]. The most common solvent for post-combustion CO_2 capture are different amine solutions [9, 11].

In this paper a comparative evaluation of performance of CO_2 capture by two different amines is reported. Parametric analysis for variations of some design and operating parameters on CO_2 capture performance has also been reported. Simulation is done using chemical processing software Aspen Plus[®] [12].

2. POST-COMBUSTION CO_2 CAPTURE BY AMINE SOLUTIONS

In flue gas after combustion with air, mole fraction of CO_2 is relatively low i.e. 4-8% by volume in natural gas- fired and 12-15% by volume in coal-fired power plants [11]. Though different methods are under laboratory scale development for post combustion capture of CO_2 including membrane separation process, amine based capture of CO_2 from flue gas after combustion is most developed and reliable technology till date [7, 9, 11]. In this process organic liquids in the form of aqueous solution of various alkanolamines are used to absorb CO_2 from the flue gas. Flue gas needs to be cooled to about 40°C before being used for CO_2 capture. Also flue gas needs to be cleaned. Specifically removal of some compounds is needed before being used for CO_2 capture. For example presences of SO_x and NO_x in flue gas affect this process. The amine system is sensitive to SO_2 with which it forms stable salts that cause fouling of the system. Similar effect happens for NO_x also. Thus amount of NO_x and SO_x in flue gas must be limited before it is processed for CO_2 capture using amine solutions. Fortunately, recommended NO_x level of less than 20 ppmv [13] is achieved by modern low NO_x burners and hence presence of NO_x in flue gas does not create serious problem in modern power plants. However regarding SO_x , specifically for high sulphur coal, a tradeoff between the cost of flue gas desulphurization and the cost of makeup solvent to compensate the degraded solvent due to SO_x is to be estimated. Traces of some others elements like mercury are preferably removed before carbon capture process [3]. Pre-cooled and pre-treated flue gas is then used for CO_2 capture using amine solutions.

In Fig. 1 the basic process of CO_2 capture using amine solution from the treated and cooled flue gas is shown schematically. CO_2 content of the flue gas is absorbed in amine solution in absorber column. Flue gas and amine solution are in contact in packed bed of the absorber in a efficient counter-flow process.

Rich amine solution containing absorbed CO_2 comes out at the bottom of the absorber while CO_2 -depleted exhaust gas is vent to atmosphere from the top of it. Rich amine solution is then pumped to a higher pressure for stripping of this absorbed CO_2 to recycle the amine solution in absorber again. This regeneration or stripping of CO_2 from amine solution needs heating in the stripper column. Separated CO_2 is collected from the top of the stripper for subsequent processing and sequestration. Heat required in regeneration process is a critical parameter influencing the economy of the CO_2 capture process by amine solutions. The lean amine solution from the bottom of the stripper column needs to be cooled before being recycled to the absorber column again. On the other hand heat required in the stripper column can be reduced if the rich amine solution is heated by the rejected heat of the lean amine solution from the stripper column. Hence a heat exchanger is used as shown in Fig. 1.

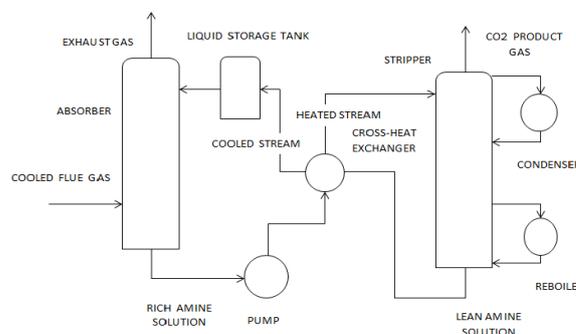


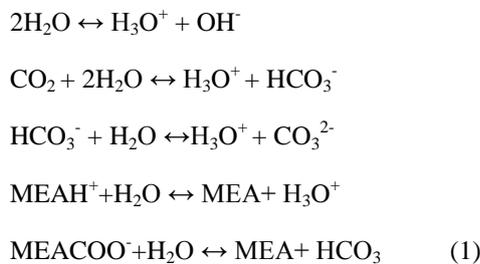
Fig.1. Schematic of CO_2 capture by amine solvent

The CO_2 capture process is influenced by different design and operating conditions of the absorber and the stripper columns as well as mass fraction of CO_2 in flue gas. The overall performance of CO_2 capture by amines also depends on the degree of CO_2 separation from rest of the gases of the flue gas mixture as well as amount of energy required (mostly heat load in the stripper column). In addition cost of infrastructure and makeup amines may also be determining factors for CO_2 capture in this process. Increased cost and decreased efficiency of the overall power plant can be justified against the penalty on CO_2 emission.

3. ASPEN PLUS[®] MODEL FOR SIMULATION

The simulation of CO_2 capture using amine solutions is done using chemical process software Aspen Plus[®]. The screen image of the model for the simulation using Aspen Plus[®] is shown in Fig. 2. Simulation is done using equilibrium model in steady state. RadFrac column model of Aspen Plus[®] is used for both the absorber and the stripper column.

This model is valid for steady state and assumes theoretical stages in which liquid and vapor phases attain equilibrium and perfect mixing occurs. No after-processing of separated CO₂ or pre-processing and cooling of flue gas is implemented in this simulation. However flue gas is assumed to enter into the absorber column at the desired temperature and is also free from undesired gases and other impurities. Some important input specification for this simulation model is given in Table 1. The property values of the amines were available from library of Aspen Plus[®]. The physical property method used for this simulation is the electrolyte non-random-2-liquid (NRTL) model with electrolyte inserts for monoethylamine (MEA) and diethylamine(DEA). Amine electrolyte solution chemistry is used to predict the equilibrium mass fractions in the liquid and vapor phases. The following are the set of equilibrium reactions for MEA describing this chemistry.



Similar reactions are assumed for DEA-based CO₂ capture process.

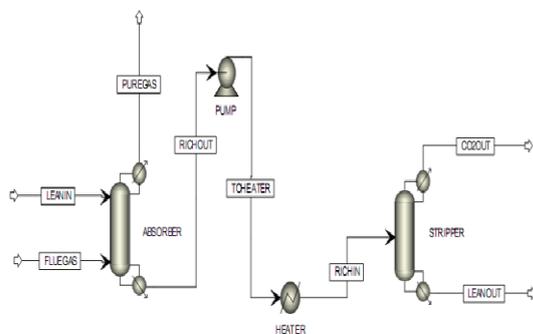


Fig.2. Aspen Plus[®] simulation model for the process

One of the greatest sources of greenhouse gases responsible for climate change is the fossil fuel-based (mostly coal-based) power plants. Replacement of these power plants by renewable alternatives without CO₂ emissions is also not feasible in near future.

Hence development of large scale power plants with CO₂ capture or retrofitting of existing plants with CO₂ capture equipment will provide smooth transition for the transformation from fossil fuel-based power to renewable power. Out of different processes of CO₂ capture, amine-based CO₂ capture from flue gas is relatively matured technologically. Different amines or their mixtures in different ratios can be used as CO₂-capture solvents [11]. Wide variations of performance of CO₂ capture are observed for different solvents as well as due to the variation of the design and operating parameters. Proper selection of the solvent depending on CO₂ fraction in the flue gas and the desired degree of stripping of it is very critical for optimum performance as well as economy of the process. In this work the performance variation of CO₂ capture for two common amine solvents, i.e. monoethylamine (MEA) and diethylamine (DEA) has been studied using equilibrium model of Aspen Plus[®].

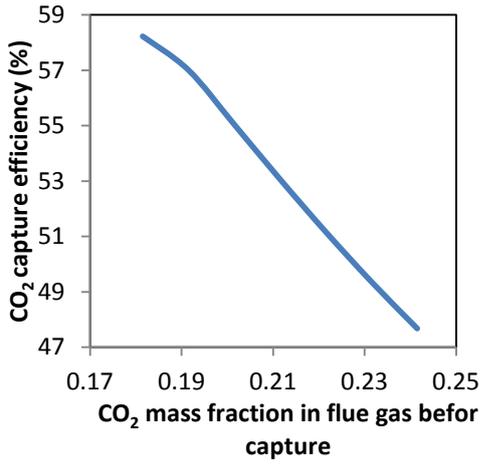
From Fig. 3 it is observed that efficiency of CO₂ capture decreases for both the solvents with higher concentration of CO₂ in the flue gas. As the reaction rate in equilibrium model decreases with higher concentration of CO₂ in the flue gas, efficiency of CO₂ capture decreases for both the solvents. Hence with given design and operating conditions, efficiency of CO₂ capture will decrease as CO₂ fraction in the flue gas increases. However it is interesting to note that the efficiency of CO₂ capture is significantly higher for DEA than MEA for identical mass fraction of CO₂ in the flue gas.

The heat load in the stripper column is another important parameter for practical implementation of the CO₂ capture process as it increases the auxiliary energy input resulting decrease of overall plant efficiency as well as operating cost. Fig. 4 shows the variation of reboiler heat load in stripper column per mole of CO₂ capture for the assumed range of variation of CO₂ mass fraction in the flue gas. Heat load in stripper column decreases with increasing CO₂ mass fraction in flue gas for both the solvents. For higher CO₂ mass fraction in the flue gas, efficiency of CO₂ capture decreases as shown in Fig. 3. Also Heat required for stripping of unit amount of CO₂ from its solvent decreases as the CO₂ concentration increases in rich solution. These two effects together reduce the heat load in stripper column with increasing CO₂ mass fraction in the flue gas. However DEA appears to be favourable than MEA as heat duty for it is lower than MEA for identical CO₂ mass fraction in the flue gas even with higher capture efficiency as shown in Fig. 3.

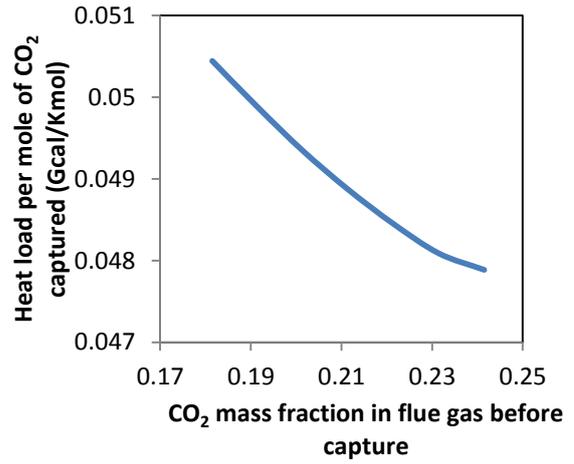
4. RESULTS AND DISCUSSION

TABLE 1: Base case assumptions

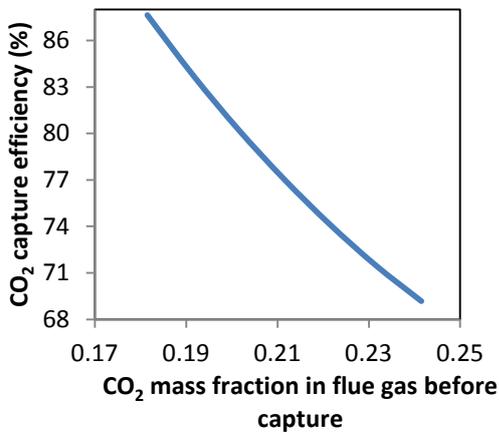
Stream/column specifications		
Flue gas	Mass flow (Kg/s)	0.158
	Temperature (K)	332.38
	Pressure (bar)	1.033
	Gas composition	(wt.%)
	H2O	1.93
	CO2	24.15
	N2	73.92
Lean amine solution	Mass flow (Kg/s)	0.642
	Temperature (K)	313.32
	Pressure (bar)	1.703
	Gas composition	(wt.%)
	H2O	63.34
	CO2	6.18
	MEA/DEA	30.48
Absorption column	Column model	Equilibrium-based
	Number of Stages	7
	Packing material	Metal
	Physical property method	Electrolyte NRTL
	Flow model	Plug Flow
Heater	Outlet temperature (K)	355.37
Pump	Pressure rise (psia)	20
Stripping column	Column model	Equilibrium-based
	Number of Stages	7
	Flow model	Plug Flow
	Condenser	Partial vapor
	Reboiler	Kettle
	Distillate rates (Kg/hr)	96
	Mass reflux ratio	1



a) For MEA

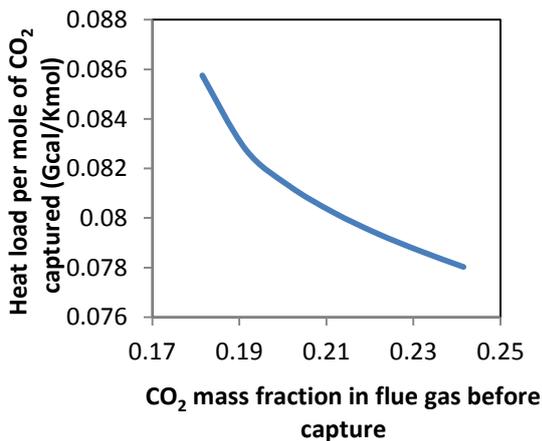


b) For DEA

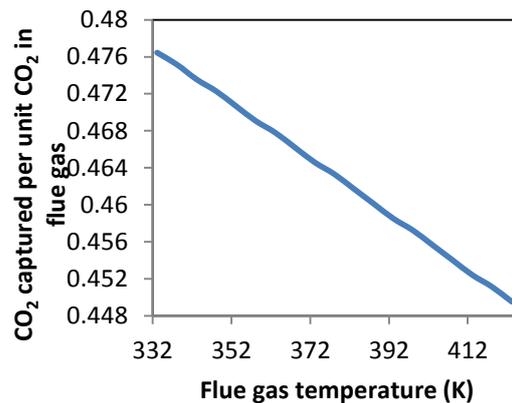


b) For DEA

Fig.3. Effect of CO₂ mass fraction in flue gas on CO₂ capture efficiency



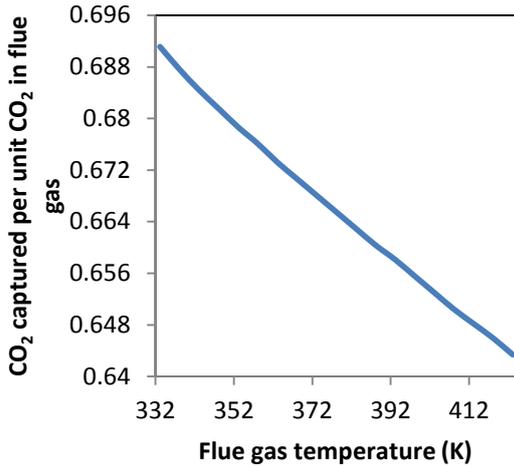
a) For MEA



a) For MEA

Fig.4. Effect of CO₂ mass fraction in flue gas on heat load in stripper column

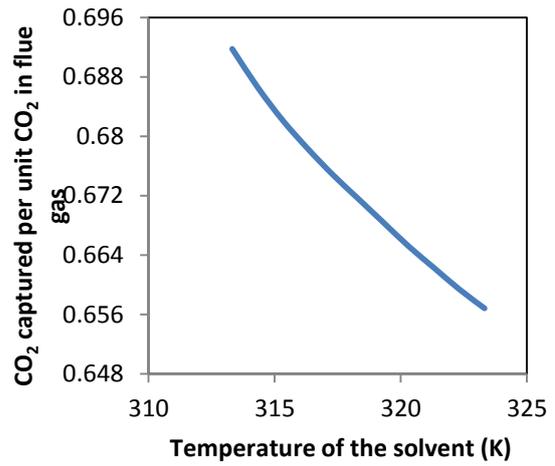
The effect of the flue gas temperature on CO₂ capture for both solvents is shown in Fig.5. The exhaust flue gas from a power plant boiler is at a temperature significantly higher than that is suitable for CO₂ capture from it. This demands substantial pre-cooling of the flue gas before scrubbing of it in the absorber column. Lesser the cooling required, more convenient and economic is the process. However it is observed from Fig. 5 that CO₂ capture from the flue gas decreases with higher flue gas temperature. The variation is almost linear for both the solvents. This is obvious as the CO₂ absorbed in absorber column will decrease for higher flue gas temperature. Hence pre-cooling of the flue gas may be decided on the basis of specified degree of CO₂ capture from flue gas.



b) For DEA

Fig.5. Effect of flue gas temperature on CO₂ capture performance

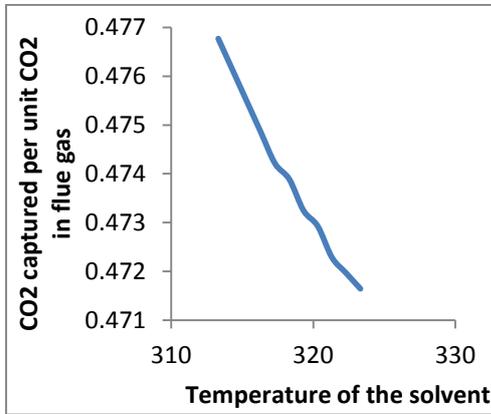
Similar effects are observed for variation of temperature of the solvent as shown in Fig. 6. As the flue gas and the solvent react in a counter-flow mixing of the two fluids in the absorber column, the CO₂ capture is expected to decrease for higher temperature either due to the flue gas or due to the solvent. Thus the variation of Fig. 6 is expected due to the same reason as explained for Fig. 5.



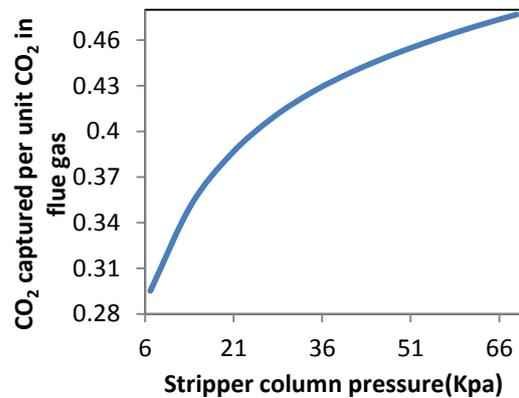
b) For DEA

Fig.6. Effect of solvent temperature on CO₂ capture performance

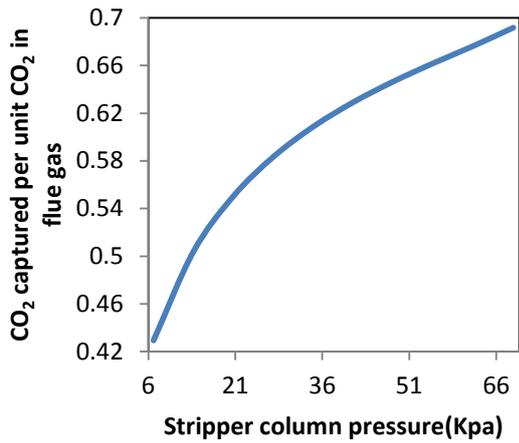
The pressure at which CO₂ is absorbed in the absorber column is usually maintained atmospheric. The flue gas is normally available at that pressure and also the CO₂ capture does not vary significantly with the variation of absorber pressure. However rich solution from the absorber is pumped to higher pressure for subsequent stripping of CO₂ in the stripper column. Thus the stripper column pressure is always higher than the absorber column and there exists a scope for improving CO₂ capture process by increasing the stripper column pressure as shown in Fig. 7. With increasing pressure in the stripper column, temperature of the rich solution at the inlet to the stripper column increases. For constant heat load in the stripper column, stripping of CO₂ effectively improves at higher pressure of the stripper column as shown in Fig. 7. Similar variations are observed for both MEA and DEA.



a) For MEA

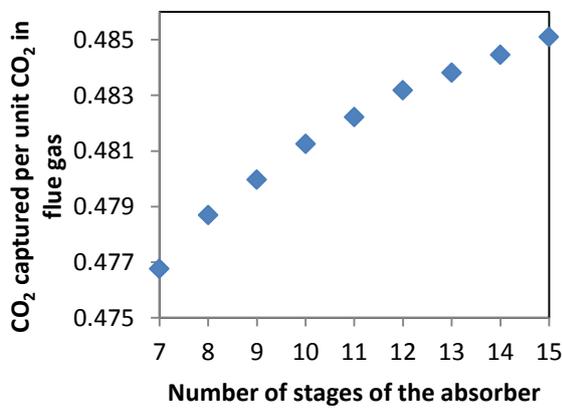


a) For MEA

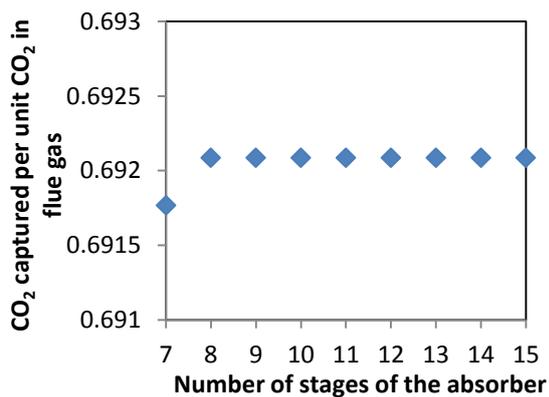


b) For DEA

Fig.7. Effect of solvent pressure in stripper column on CO₂ capture performance



a) For MEA



b) For DEA

Fig.8. Effect of number of stages of the absorber column on CO₂ capture performance

With increasing number of stages of the absorber column CO₂ absorption in solvent increases initially. However this process ‘saturates’ for an optimum number of stages beyond which effect of increase of number of stages is insignificant regarding CO₂ capture. It is interesting to note that this optimum number of stages for the MEA is much higher than that of DEA as shown in Fig. 8. DEA is a more convenient solvent relative to MEA as optimum number of stages for a given flue gas is smaller than MEA. It indicates that DEA will perform better than MEA with an absorber even with a lower number of stages of it, which is a practically and economically more convenient option.

5. CONCLUSION

CO₂ capture from flue gas is critical to minimize climate change effect from future generation power plants. Out of different options for CO₂ capture from the flue gas of power plants, ‘post-combustion capture’ of it using organic solvents, generally called amines is a relatively matured technological option. Different amine based solvents or their mixtures have been tested for this purpose. In this work a comparative study of the performance of CO₂ capture for two different common solvents i.e. monoethylamine(MEA) and diethylamine(DEA) has been presented. Simulation results are obtained from equilibrium model of Aspen Plus®. Comparative variations of performance for these two solvents with some varying design and operating parameters are also reported. It is noted that DEA is a better solvent than MEA as it needs lower heat in the regenerator though it has better efficiency of CO₂ capture for the same mass fraction of CO₂ in the flue gas. Moreover optimum number of stages of the absorber column is smaller for DEA than MEA leading to lower capital and operating cost for better performance using DEA. Increase in the temperature of either the flue gas or the solvent degrades the CO₂ capture process. However the same improves with higher stripper column pressure for both the solvents.

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