OPTIMIZATION AND SENSITIVITY ANALYSIS OF POST - COMBUSTION CARBON CAPTURE USING DEA SOLVENT IN A COAL FIRED POWER PLANT

Isah Yakub Mohammed
Department of Chemical Engineering,
Abubakar Tafawa Balewa University P.M.B 0248 Bauchi Nigeria

Abstract

Post combustion carbon capture is one of the methods for limiting CO_2 emissions from the combustion of fossil fuels. This technique continues to gain attention due its retrofitting option which offers many economic benefits. In this study, optimization and sensitivity analysis of a post combustion carbon capture process with secondary amine (DEA) in a coal fired power plant (500MW) using Aspen HYSYS^R was carried out. Effect of CO_2/DEA mole ratio in absorption process, CO_2 recovery and purity in stripping operation, and recycle stream temperature were investigated with respect to capital and operating costs. The optimum value of these parameters was found to be 0.32, 92% and 95% and 40-45ºC respectively. Sensitivity analysis of flue gas parameters (flow rate, CO_2 concentration and temperature) and DEA concentration was evaluated under the optimised conditions with respect to operating and running costs. Increasing the inlet flue gas flow rate and its temperature showed rise in operating cost while reduction in the cost was observed with CO_2 concentration. Similarly, a decrease in operating cost was also recorded with increasing DEA concentration. The Plant efficiency in terms of percentage of CO_2 captured throughout the sensitivity analysis was within the base point of 90%. Finally, these parameters may be used as optimum conditions for amine base post combustion carbon capture in a coal fired power plant.

Keywords: *Aspen HYSYSR; Optimisation; Sensitivity analysis; DEA solvent; post-combustion; carbon capture,*

I. INTRODUCTION

Emission of greenhouse gas from the use of fossil fuel continues to have negative impacts on our environment. Temperature is rising globally and has resulted in accelerated rise in sea level and increase in coastal flooding. As result, different regulation are issued a year after a year forcing polluters to cut these emissions. Carbon capture and storage (CCS) has been considered as an option for limiting CO_2 emissions from the combustion of fossil fuels [1]. This approach includes pre-combustion capture, post-combustion capture and oxy-fuel combustion [2, 3, 4, 5]. The post-combustion capture technology is seen as more feasible as opposed to the other carbon capture methods because of its lower cost and retrofitting option [6]. It allows implementation without incurring relatively larger capital and operating costs and allows more plant flexibility as well [7].

In general, carbon capture plants are still under the advancement stages with Hysys® software being used extensively in this direction [6]. Although, other software has been used recently in this direction. Raynal et al. 2013 [8] carried out studies on CO_2 capture cost reduction using a multiscale simulations strategy with the aid of computational fluid dynamics (CFD) software. Their findings reveal that the most important parameter during absorption process was mass transfer interfacial area. In our previous studies

[6], we have carried out technical and economic consideration of a post-combustion carbon capture with diethanolamine (DEA) in 500MW full capacity (420MW generation) coal fired power plant using Hysys® simulation and achieved above 90% recovery of CO_2 with a purity of 99%. Generally, economic consideration of amine based post combustion carbon capture has been fairly studied in the recent times. However, optimization and sensitivity analysis of the process parameters is needed in order to continuously bring down the unit cost of CO_2 [9, 10]. The objective of this work was to carry out optimization and sensitivity analysis of the process parameters such as the flue gas flow rate, CO_2 concentration, solvent temperature and pressure, recycle stream, heat and work duties. This is necessary in order to run the plant at optimum condition with reduced costs by checking how the operating and capital costs change with the process variables.
This article is organised in to different sections: Methodology, results and discussions, conclusion, future work, acknowledgment and references.

II. METHODOLOGY

The plant feed comprises of mainly carbon dioxide, nitrogen, water and oxygen which is obtained from a 500 MW plant. Table 1 below gives a typical composition of the flue gas from a coal fired power plant. The operational window of the power plant is assumed to be 8000 hours annually. The detail process description has been outlined in our earlier publication [6]. Briefly, Amine absorption processes was carried out 30%w/w DEA, which enters at 45°C on the top of the absorber while the acid gas enters in the tower at the bottom and leaves the equipment at the top as a sweet gas with very low CO_2 concentration (under 1.5% mole fraction) having absorption efficiency above 90%. The process temperature was maintained at 125 ºC with a bottom pressure of 215 kPa and a condenser temperature of 40 ºC. The bottom stream from the stripping column contains all the amine used in absorbing the acid gas and was recycled. Enthalpy of the recycled stream was used to preheat incoming feed to the tower as system heat integration. The process flow diagram is shown in Figure 1 below.

Table 1: Coal Fired Power Plant Flue Gas [3]

Capacity (MW)	500
Temperature (°C)	50
Pressure (Kpa)	110
Molar Flow (Kmole/h)	71280
Volume Flow (m^3/h)	1914000
Composition (mole percent)	
Carbon Dioxide (CO_2)	15.00
Nitrogen (N_2)	77.00
Sulphur Dioxide (SO_2)	0.00001
Nitrogen Oxides (NO_x)	0.00005
Water (H_2O)	5.00
Carbon Monoxide (CO)	0.00001
Oxygen (O_2)	3.00

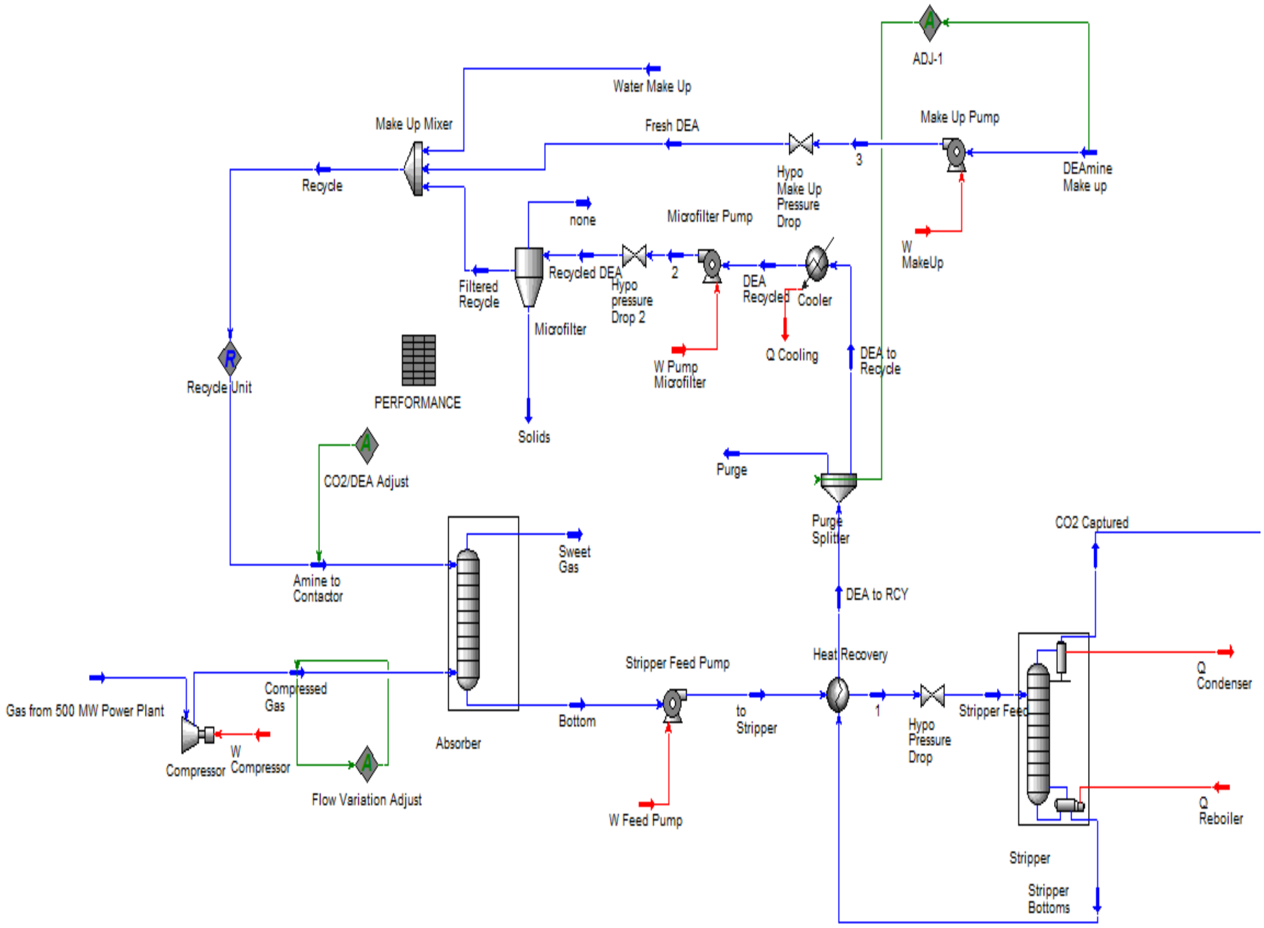


Figure 1: Process Flow Diagram [6]

The list of variables used in the simulation is given in Table 2, some of which can be modified during operation and hence the need for optimisation. Some others depend on external conditions which have impact on the total cost and can be investigated by means of a sensitivity analysis.

Table 2: List of variables to be analysed

Variable	Analysis
Recycle Temperature (ºC)	Optimization
CO_2 Recovery in Stripper (%)	Optimization
CO_2 Purity (%)	Optimization
CO_2/DEA (mol/mol)	Optimization
Flue Gas Flow Rate m^3/s IN	Sensitivity
[CO_2] %mol in the inlet flue gas	Sensitivity
[DEA] (% w/w)	Sensitivity
Inlet Flue Gas Temperature (ºC)	Sensitivity

III. Results and Discussions

3.1 Optimization

CO_2 Recovery in stripping

This parameter is based on a balance between the amount of solution recycled in the whole system, energy requirements in the reboiler and energy removal from the condenser. At low recovery, bigger size equipment is needed in all the process which translates to increase in the capital cost. This trend is shown in Figure 2. Effect of CO_2 recovery on the operating cost seems to be less compared to the capital cost up till CO_2 92%. Beyond this point, a rapid increase operating cost set-in which may be attributed to the higher energy requirement to strip off the absorbed CO_2 in addition to the cooling requirement at the condenser. Some peaks were also seen especially on the capital cost curve. This is attributed to the sensitivity of adjust and recycle units used in the simulation.

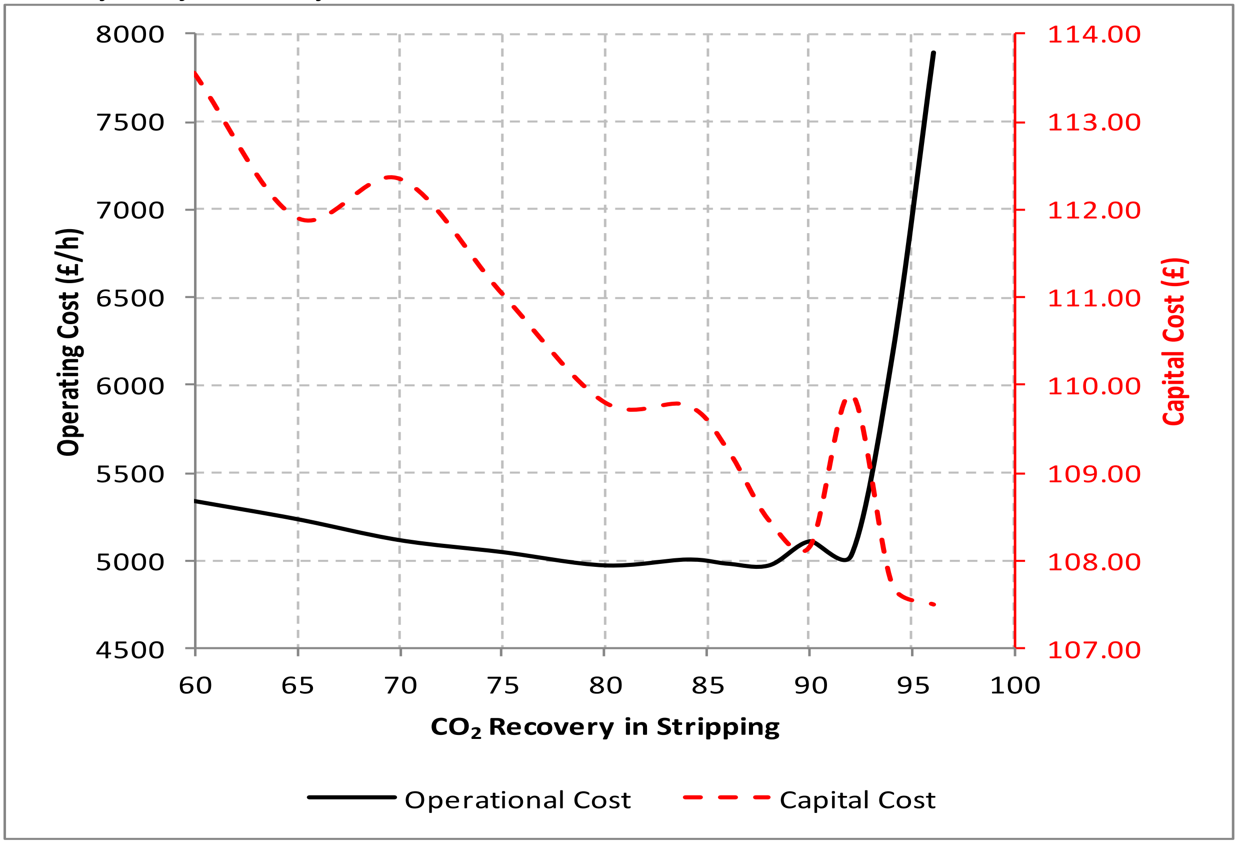


Figure 2: Capital and Operating cost variation during CO2 recovery in stripping optimisation

CO2/DEA ratio in Absorption

Amount of DEA used in the absorption is an important parameter as it affects both capital and operating cost. High value of CO_2/DEA mole ratio in the feed to the absorbers implies less amine to absorb the same amount of CO_2. In addition, this will also lead to less DEA make up requirement. The overall effect will be reduction in both capital and operating costs. This is shown in Figure 3. However, there is an implicit constraint related to the corrosiveness of the solution and the solubility of the CO_2 in DEA. As result, an operating point of 0.32 CO2/DEA mol ratio was achieved. This is quite a good improvement compared to the literature of be 0.26 mol CO_2/mol DEA [7].

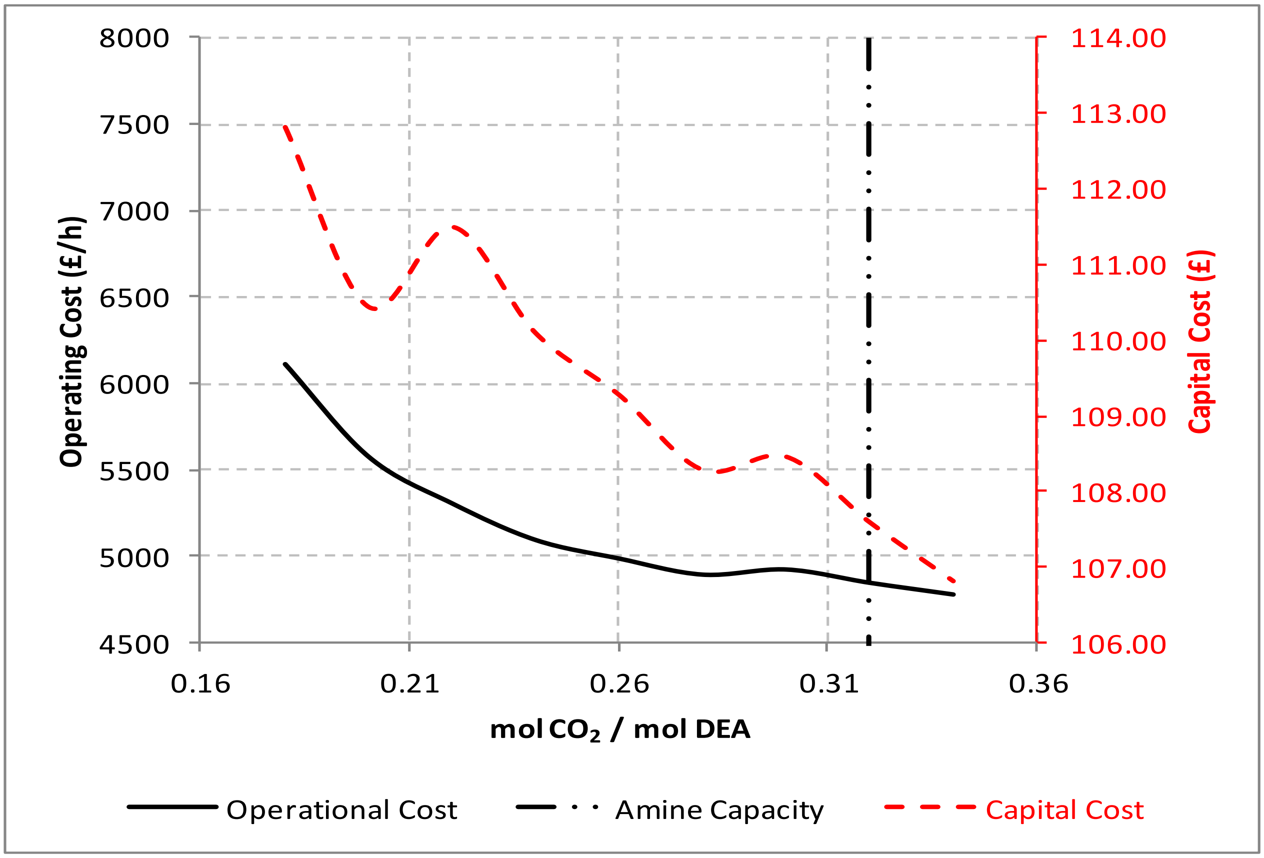


Figure 2: Capital and Operating cost variation during CO2/DEA molar ratio in absorption optimisation

CO2 purity in stripping tops

Figure 3 shows the variation of both capital and running costs for the overall process. The running cost rises along with the CO_2 purity at the top of stripper. This is an indication of increase in the cooling requirement at the condenser as well as the flow rate of water coming from the cooling towers. On the other hand, a sharp decrease is observed in the capital cost as the fraction of CO_2 increases at the top. However, this analysis does not consider any process limitation associated to the minimum temperature reachable in the condenser. As this temperature is limited by the temperature of the cooling water which was set at maximum possible of 25ºC water stream available from the cooling towers. With this condition, CO_2 purity of 95.5% was achieved.

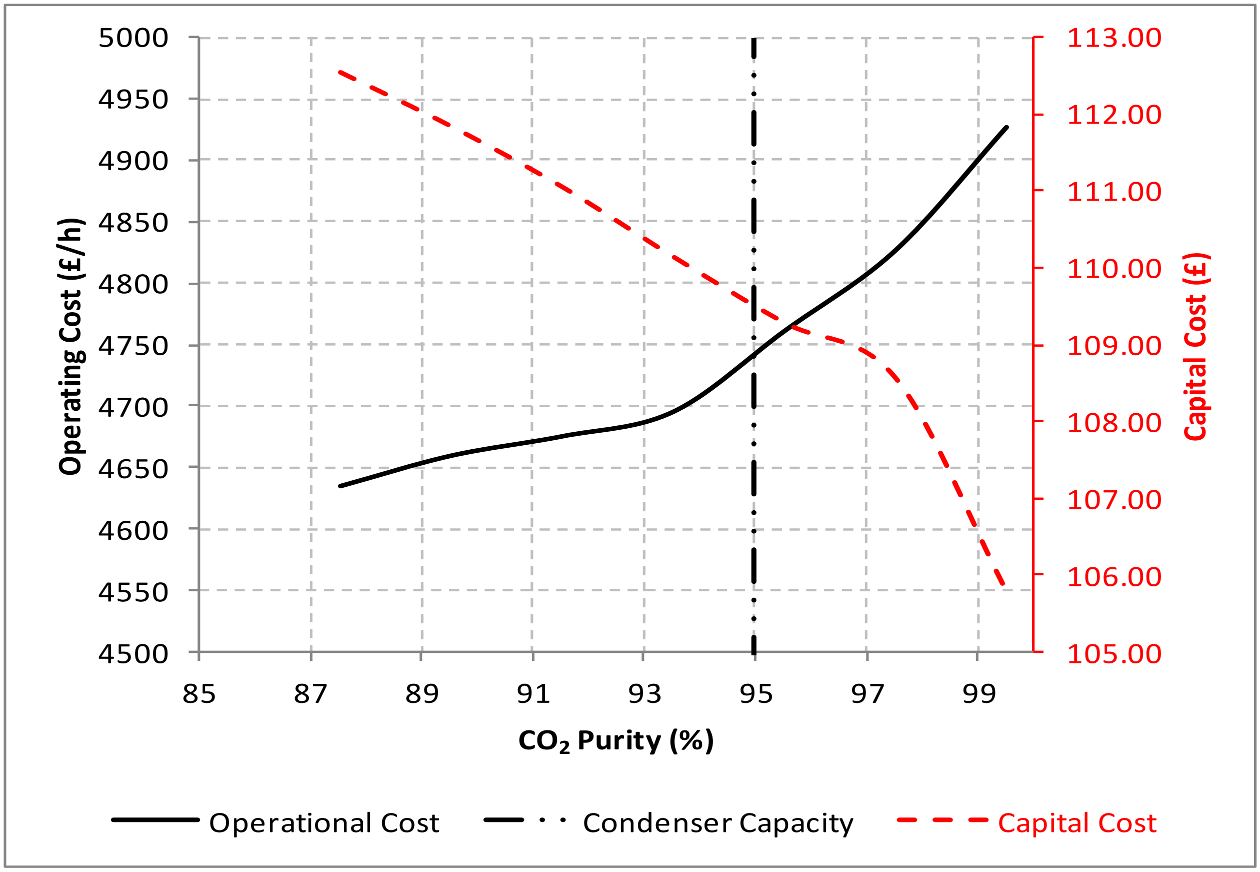


Figure 1: Capital and Operating cost variation during CO2 Purity in stripper top optimisation

Recycle temperature

This variable has a direct impact on the capital and running costs by modifying the absorption and evaporation in the absorbers. A decrease in the temperature will reduce the CO_2 capture due to the chemical nature of the absorption process but this change will also diminish the amount of water evaporated and consequently the makeup and the cooling requirement of the recycled stream. There is also an implicit cost that must be considered related to the corrosiveness of the solution which increases with temperature and can damage expensive equipment such as the microfilters. Therefore a compromise between the CO2 capture and the recycle stream temperature is needed. Temperature between 40-45ºC seems feasible.

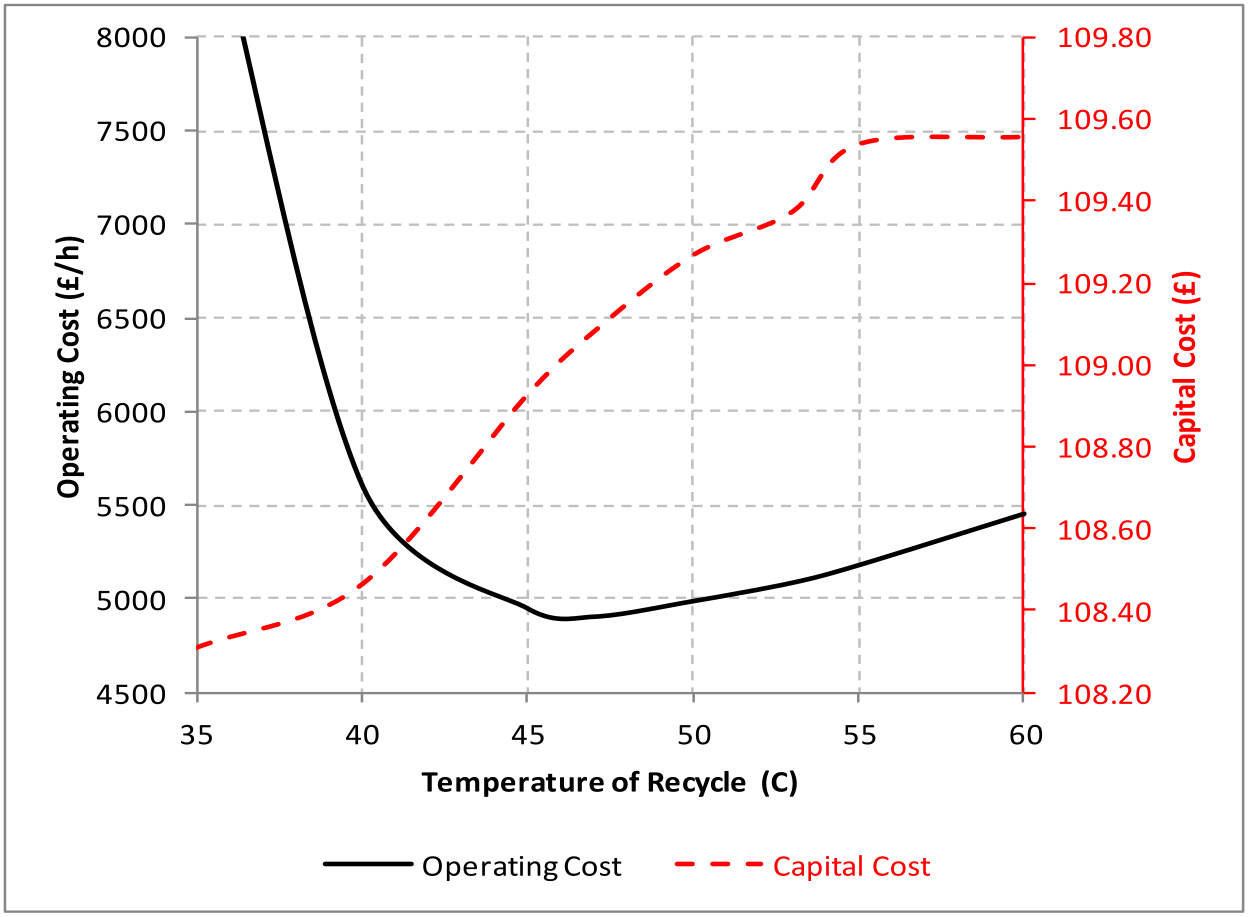


Figure 2: Capital and Operating cost variation during Recycled DEA temperature optimisation

3.2 Sensitivity Analysis

In an attempt to have detailed economic analysis of our carbon capture process, the optimized parameters were further investigated to identify effect of flue gas flow rate, its CO_2 composition and temperature and amine concentration on the operating cost.

Flue gas flow rate

Figure 5 (a) below shows the variation of operating cost with flue gas flow rate. It present a general trend of how increase in flue gas rate will bring about proportionate rise in the operating cost. This is further examined in terms of the running cost to find the major contributor to the cost rise for any increase in the flue gas rate. Figure 5 (b) illustrates the effect of steam and power requirements, DEA and water make-up on the process. Among these parameters, power requirement seems to be the main contributor to the cost rise. This is in line with the fact that the more flue gas we have in the system more power will be required in the compressors and pumps. Plant efficiency in terms of percentage of CO_2 captured with increasing flue gas rate does not fall below the base point of 90%. This is shown in Figure 5 (c). The plot signifies that the plant performance is less affected by any increase or decrease in flue gas rate within 20% from the operating point. However, the situation may be different with change in CO_2 composition of the flue gas.

CO_2 concentration in the inlet gas

Relationship between operating cost and CO_2 concentration in the flue gas is shown in Figure 6 (a). A decline trend in the operating cost is observed with respect to the increase in CO_2. This is due to the increase in mass transfer rate in the absorption process and thus making the regeneration easier. Hence reduces the amount of DEA makeup required as well as the power requirement for the makeup pump. The absorption efficiency does not fall below the set point of 90% and a direct proportion of the efficiency is seen with the increase in CO_2 concentration within the selected deviation from optimum operating conditions. These are shown in Figure 6 (b and c) respectively.

Gas inlet temperature

Operating cost with respect to inlet flue gas temperature increases proportionately. Increase in running cost is more pronounced with the power requirement. This is because the chemisorption process is exothermic and therefore any rise in feed temperature will deterred the process and result in high tendency of DEA lost in the system. More DEA makeup will be required which in turn will bring about more power requirement in the pumps and compressors. These scenarios are demonstrated in Figure 7 (a-c).

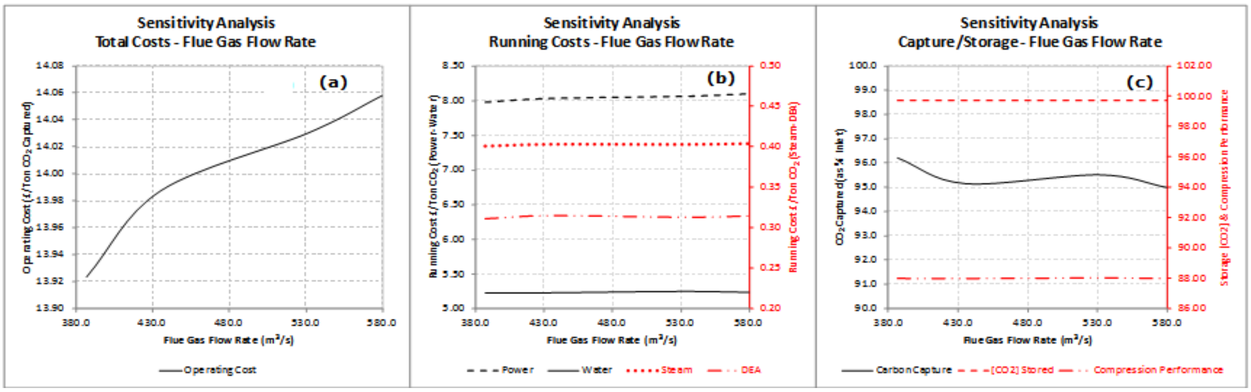
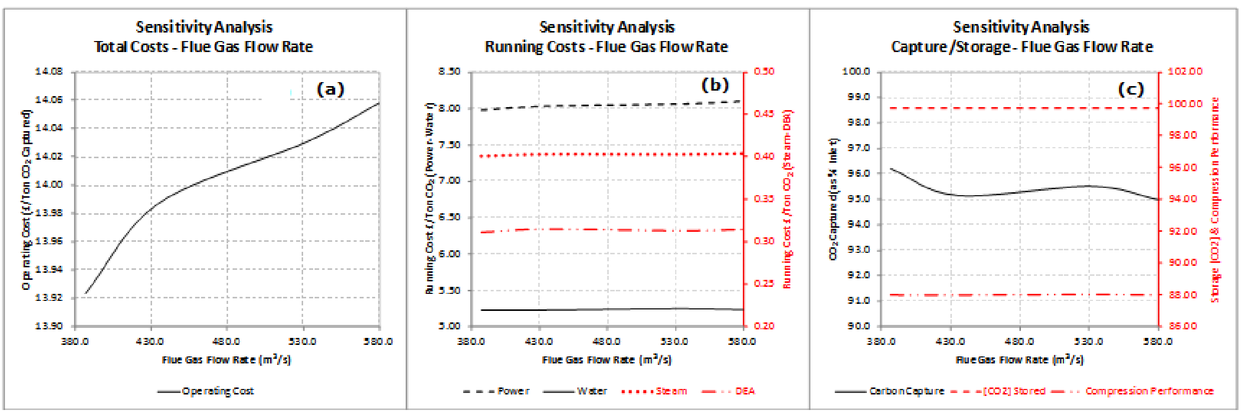


Figure 3: Sensitivity Analysis of the CCS plant with respect to the inlet flue gas flow rate



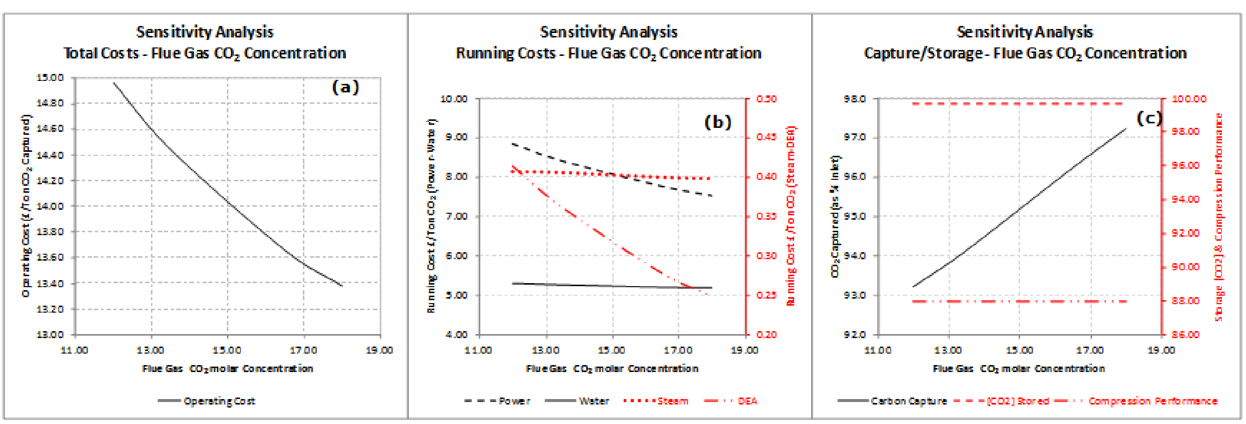


Figure 4: Sensitivity analysis of the CCS plant with respect to CO_2 concentration in the inlet flue gas.

DEA concentration in absorption

Increase in concentration of DEA charged to the system lowers the operating cost within the selected offset from the optimum operating condition. Makeup water, power and steam requirements are the major contributors to the cost reduction. Decrease in makeup water is based on the fact that more DEA portion is required in solution makeup. Decline in power and steam requirements are attributed to reduction in solvent volume and less energy requirement during regeneration respectively. The effects of these parameters with respect to running cost are shown in Figure 8 (a-c) below. The removal efficiency remains stagnant within this situation.

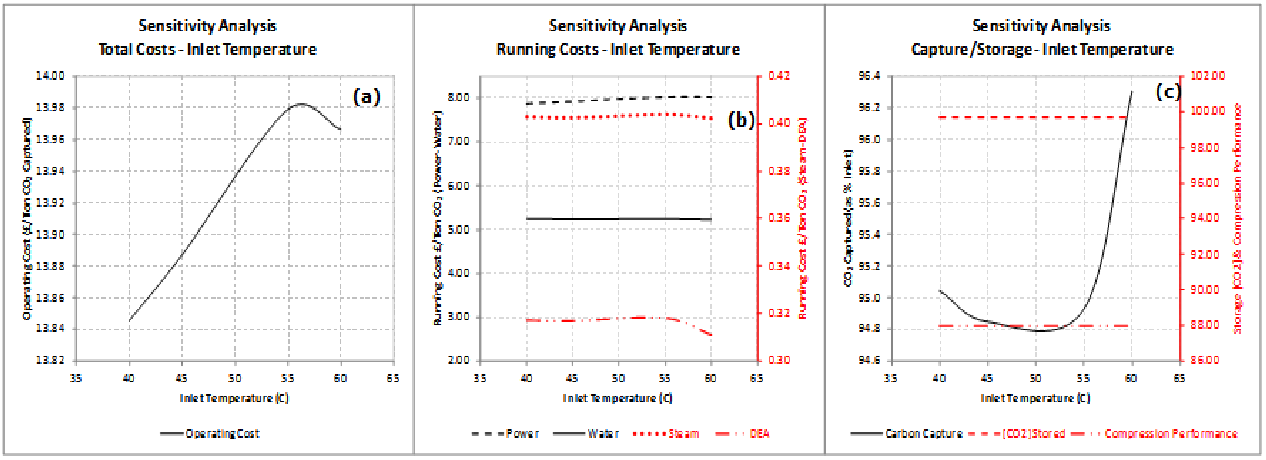


Figure 7: Sensitivity analysis of the CCS plant with respect to the flue gas inlet temperature

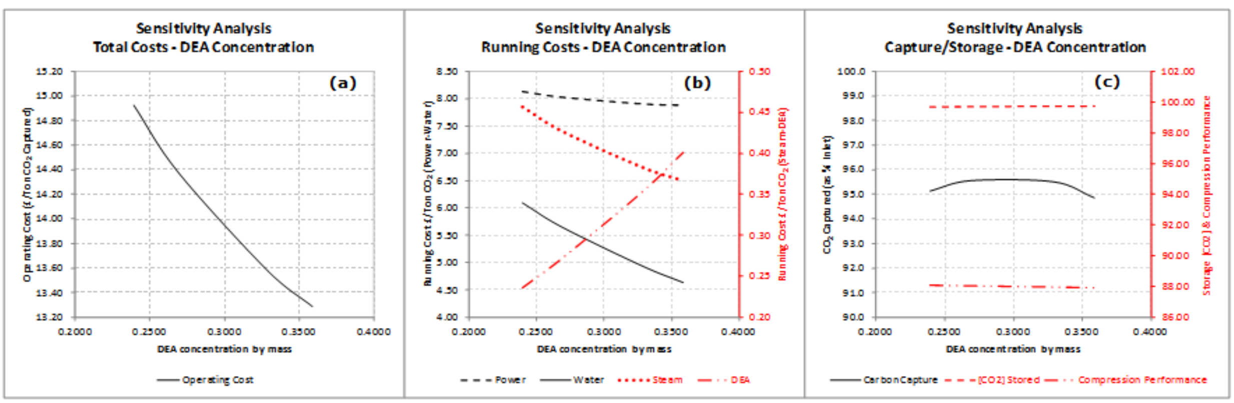


Figure 5: Sensitivity analysis of the CCS plant with respect to the DEA concentration used for absorption

IV. CONCLUSION

Optimization and sensitivity analysis of post-combustion carbon capture plant in a 500MW coal fired power plant was carried with DEA solvent using Aspen HYSYS^{R}. Effect of CO_2/DEA mole ratio CO_2 recovery and purity, and recycle stream temperature were investigated with respect to capital and operating costs and the optimum conditions established. Sensitivity analysis of flue gas flow rate, CO_2 concentration, temperature and DEA concentration was evaluated under the optimised conditions. Increase in flue gas rate and temperature showed rise in operating cost. On the other hand, reduction in the cost was observed with increase CO_2 and DEA concentrations. However, The Plant efficiency in terms of percentage of CO_2 captured throughout the analysis was within the base point of 90%. These conditions may be used as optimum parameters for amine base post combustion carbon capture in a coal fired power plant.

V. FUTURE WORK

Techno-economic analysis, parameter optimisation and sensitivity analysis of carbon capture in a gas fired power plant is necessary in order to provide basis for comparison with the coal fired process.

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REFERENCES

[1] Steeneveldt, R., Berger, B., Torp, T.A. (2006). CO_2 Capture and Storage Closing the Knowing-Doing Gap. Chemical Engineering Research and Design 84 (A9): pp. 739-763.
[2] Woudstra, N., Woudstra, T., Pirone, A., Stelt, T., (2010) Thermodynamic evaluation of combined cycle plants, Energy Conversion and Management, Volume 51, Issue 5; 1099-1110.
[3] Drage, T.C., (2012) Carbon Abatement Technologies, from H84PGC Power Generation and Carbon Capture. At University of Nottingham WebCT, Blackboard. [Accessed 27/03/14]
[4] Trapp, C., and Colonna, P., (2013). Efficiency improvement in pre-combustion CO_2 removal units with a waste-heat recovery ORC power plant. J. Eng. Gas Turb. Power, 135(4):042311–1—12
[5] Henson, J., (2014) Carbon abatement technologies at: https://connect.innovateuk.org/web/carbon-abatement-technologies accessed 10th August 2014
[6] Yakub, M. I., Mohamed, S., & Danladi, S. U. (2014) TECHNICAL AND ECONOMIC CONSIDERATIONS OF POST-COMBUSTION CARBON CAPTURE IN A COAL FIRED POWER PLANT. International Journal of Advances in Engineering & Technology, 7(5), 1549-1581
[7] Mitra, S., (2010). A Technical Report On Gas Sweetening by Amines at : http://www.share-pdf.com/6feca286bac2473282c2b7c4fbb7379f/Gas_sweetening_process.pdf accessed 1st April, 2014
[8] Raynal, L., Gomez, A., Caillat, B. and Haroun, Y., (2013). CO2 Capture Cost Reduction: Use of a Multiscale Simulations Strategy for a Multiscale Issue. Oil & Gas Science and Technology – Rev. IFP Energies nouvelles, 68 (6), pp. 1093-1108
[9] Prasad, P. S. and Raghavan, K. V., (2012) Techno-economic aspects of the post-combustion CO2 capture processes. Indian Journal of Chemistry Vol. 51A, pp. 1201-1213
[10] Cohen, S.M., Chalmers, H. L., Webber, M.E. and King, C.W., (2011).Comparing post-combustion CO2 capture operation at retrofitted coal-fired power plants in the Texas and Great Britain electric grids

AUTHORS BIOGRAPHY

Isah Yakub Mohammed was born in Bida, Niger State, Nigeria on the 22nd March, 1982. He obtained BEng and MSc degrees in Chemical Engineering from Federal University of Technology Minna, Nigeria and the University of Nottingham United Kingdom in 2006 and 2012 respectively. He is currently a PhD student in Chemical Engineering at University of Nottingham and a lecturer at Abubakar Tafawa Balewa University Bauchi, Nigeria.
Isah Yakub Mohammed is a registered Engineer with Council for the regulation of Engineering in Nigeria (COREN), a Coporate member of Nigerian Society of Engineers (NSE) and Nigerian society of Chemical Engineers (NSChE). Member American Institute of Chemical Engineers (AIChE), International Water Association (IWA) and Associate Member Institution of Chemical Engineers (IChemE).