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Economic Evaluation of Selexol – Based CO_2 Capture Process for a Cement Plant Using Post – Combustion Technology

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ABSTRACT

This research work focuses on the economic evaluation of post-combustion technology to capture CO_2 from a based Cement Plant using a physical absorption solvent called Dimethyl Ether Polyethylene Glycol-DEPG (Selexol). The low cost Selexol absorption unit captured 97% of the CO_2 with 98% purity by mole of the CO_2 through absorption into a 0.37 mole CO_2/mole Selexol lean loading of the physical solvent. A detailed cost estimation of the CO_2 post-combustion unit of the plant was carried out in order to evaluate the economic performance of the process and cost of CO_2 captured, the additional utility costs associated with this technology. The CO_2 capture cost per tonne of CO_2 captured was found to be $58 (₦9,333). The Total Operating Cost was estimated at $27,542,469 (₦4.5Billion) and the Total Capital cost was estimated at $19,222,886 (₦3.08 Billion). The raw material cost was the highest cost in the CO_2 capture process with a value of $19,500,000 (₦3.1 Billion) representing 71% of the total operating cost. Sensitivity analysis cases of the impact of absorber temperature, pressure and absorber inlet gas temperature on liquid and vapour flow, percentage CO_2 recovery, energy consumption, annual operating and capital costs and cost of CO_2 captured were studied. The overall result of the analysis shows that Selexol has proven to be thermally, chemically stable and commercially justifiable under the operating conditions used.

Keywords: Absorption, Carbon Capture, Costs, Post-Combustion, Selexol, Sensitivity.

I. INTRODUCTION

Anthropogenic CO_2 emissions are being increasingly viewed as a problem by policy makers in Nigeria, and it is reasonable to expect that they may be regulated in the future. The Cement Industry emits large amounts of CO_2 into the atmosphere (i.e. about 900 kg of CO_2 per tons of cement produced) with the industry facing a sharp increase in cement demand worldwide for years to come as well as prospect of climatic change mitigation policies that could call for reduction in emissions of greenhouse gases. Hence, the proportion of CO_2 released or emitted per unit cement produced could adversely have effects on the environment. Monoethanol amine (MEA) is more energy – intensive for CO_2 capture to take place [1], hence contribute to the overall cost of the capture process. It is also highly corrosive on equipments and easily degraded by acid gases.

Against this backdrop, it becomes increasingly important to consider building flexibility into Cement Plant design such that they can be retrofitted, both from a technical and economical perspective, to capture CO_2 (Rubin [2].

The International Energy Agency (IEA) estimated that, to have a 50% reduction in global CO_2 emissions by 2050 (which is widely believed to be equivalent to reducing the increase in global temperature by 2 degrees), the available Carbon Capture and Sequestration (CCS) techniques should receive nearly one-fifth of GHG emissions from the power and industrial sectors.

By 2050, as estimated by IEA, the cost of reducing climate change without CCS could be around 70% higher than with CCS. Already it will be around 40% by 2030 as estimated [3]. Therefore, CCS is currently the

only option for decarbonizing the steel, chemical and cement industries. This process has been reported to have the ability of reducing annual carbon dioxide emissions by 9 – 16 billion tonnes worldwide by 2050 [4].

Cement industry has been one of the world's largest industrial sources of CO_2 emissions. It accounts for about 1.8 Gt/year CO_2 emission in recent years [3]. Improved energy efficiency, replacing fossil fuels with wastes which may be regarded as 'carbon neutral', increasing the cement : clinker ratio by increasing the use of additives, and use of biomass have been over the years, the substantial means of reducing CO_2 emissions per tonne of cement in the cement industry. The scope for further reductions by these means has become limited, yet there is an increasing need to reduce this emission to avoid any further increase in the contribution to anthropogenic climate change.

Thus CCS enables the usage of well – established technologies with almost the same base infrastructure and significantly lowers CO_2 emissions. Also, CCS in cement industry enables the reduction of other pollutants such as SO_X, NO_X, and particulate matters. Despite all these advantages, the bottlenecks concerning CCS calls for the feasibility of the technology in question. These bottlenecks include: the missing regulations, health, safety and environmental risks of CCS and the possibility of public acceptance with the technology being relatively energy-consuming and cost-intensive.

This research study is motivated by the desire to mitigate global warming, by capturing CO_2 emissions from Cement Plant. Thereby help to accomplish the goals set out by the Kyoto Protocol. CO_2 is captured with the intention of being stored. The analysis of CO_2 storage is beyond the scope of this research study.

II. METHODS AND MATERIAL

1.1 The Emissions Reduction Challenge:

The CO_2 Emission Reduction Challenges by 2020 has no definite answer on what the reductions will be by this set year, particularly because it is not only a scientific and economic choice, but also a societal choice. However, it is possible to use science and economics to begin to frame the scope of the challenge.

Assumptions:

1. The world commits to a pathway of stabilizing atmospheric concentrations at twice pre-industrial levels.
2. Economic and population growth occurs, increasing the demand for cement significantly in developing countries and at a slower pace in developed countries.
3. The cement industry meets society's demand for increased amounts of products.
4. All industries follow a theoretically minimum cost approach to reduce CO_2 emissions.
5. The world first slows the rate of growth of CO_2 emissions and then begins decreasing global emissions all the while simultaneously allowing for economic growth.
6. The fraction of CO_2 emissions that the cement industry's contributes to total global fossil fuels and industrial CO_2 emissions is never higher than it is today (Ken *et al.*, 2003).

Implications for 2020:

1. By 2020, global demand for cement will have increased by 115 to 180% over 1990 levels. In the highest growth scenarios, the developed countries demand increases an estimated 13% with the remainder of the growth coming from developing economies. Demand in developing countries grew 55% during the 1990s.
2. If the cement industry contributes to the stabilization of atmospheric greenhouse gas concentrations, in accordance with the assumptions above, this would require reducing the CO_2 generated per tonne of cement by 30 to 40% over 1990 levels, on average across the entire global industry.
3. The industry would need to develop alternative cement formulations and new technologies to prepare for future reductions that are far more challenging, which by 2050 approach 50% reductions in CO_2 generated per tonne of cement over 1990 levels, on average across the industry [5].

This research work is limited to the economic evaluation of CO_2 capture process for flue gas from a Cement Plant (Ashaka Cement Plc) involving flue gas analysis of the plant which will be used as the basis for the plant design using Aspen Hysys. Equipment sizing and cost of CO_2

captured will be estimated using Aspen Process Economic Analyzer. The results obtained from both the simulation and economic analysis will be used for the sensitivity analysis to test the robustness, stability and performance of the Selexol-Based CO_2 capture process. Hence, determine how economical and reliable the CO_2 capture process will be; based on the operating conditions.

1.2 The Post – Combustion Capture Technology Concept for CO_2 Capture of the Cement Plant

The research team proposed the post-combustion capture technology for a cement plant that combines the possible measures which will significantly reduce the high costs displayed by the normal state-of-the-art chemical solvent, MEA – based post combustion capture in some cement plants with the physical solvent Selexol^{TM} considering the cost of capturing one ton of CO_2. The schematic diagram of the Selexol-Based CO_2 capture process for the plant is presented in Figure 1 using Aspen Hysys software. As depicted in Figure 1, the plant flue gas from the rotary-kiln after calcination of the limestone to form clinkers is physically treated in the Selexol-Based absorption unit, where most of the CO_2 content of the flue gas is separated, while the remaining content of the flue gas is released into the atmosphere through the clean-gas exit on the absorber.

Cement production is both energy and emissions intensive: 60–130 kg of fuel and 110 kWh of electricity are required to produce a ton of cement, leading to emissions of around 900 kg CO_2/t [8]. The production of cement releases greenhouse gas emissions both directly and indirectly: the heating of limestone releases CO_2 directly, while the burning of fossil fuels to heat the kiln indirectly results in CO_2 emissions. The direct emissions of cement occur through a chemical process called *calcination*. Calcination occurs when limestone, which is made of calcium carbonate, is heated, breaking down into calcium oxide and CO_2. This process accounts for ≈50% of all emissions from cement production [2, 6]. Indirect emissions are produced by burning fossil fuels to heat the kiln. Kilns are usually heated by coal, natural gas, or oil, and the combustion of these fuels produces additional CO_2 emissions, just as they would in producing electricity. This represents around 40% of cement emissions. Finally, the electricity used to power additional plant machinery, and the final transportation of cement, represents another source of indirect emissions and account for 5-10% of the industry's emissions [7].

The CO_2 capture plant was designed to remove 97% of the CO_2 from flue gas stream coming from the flue stack of the cement plant. The flue gas goes through the cooler to be cooled to 40^{o}C from 180^{o}C. The flue gas leaves the cooler 1 with a pressure and temperature of 100kPa and 40^{o}C which is the appropriate for the absorber's performance. The flue gas from the cooler 1 enters the bottom of the absorber and the lean Selexol (33.4 wt. %) with a CO_2 loading of 0.37 mole CO_2/mole Selexol enters from the top of the column counter-currently at a pressure of 100kPa and 27.99^{o}C. It is very important to keep the lean Selexol solution temperature as low as possible for two crucial reasons: (i) to reduce Selexol and water make – up and (ii) to increase the CO_2 capture efficiency. The number of stages for the absorber obtained in this research is 10, to achieve a rich Selexol-CO_2 loading of 0.4 mole CO_2/mole Selexol and 97% recovery. Clean gas from the top of the absorber is now released into the atmosphere since it has now met the standard limits set by World Bank and USEPA. The absorber operates at a temperature of 50^{o}C and a pressure of 2360 kPa. This pressure enhances the absorption rate because from Henry's law of CO_2 solubility in physical solvents shows that as the partial pressure of the gas increases, absorption also increases, which made the absorber pressure to be set at ≈ 2360 kPa.The entire process within the absorber is an exothermic process where Selexol reacts physically with CO_2 in the column. This interaction between the solvent and gas forms a weak bond between the compounds at higher pressure which can be regenerated physically by reduction in pressure within Flash Tanks in series so that the CO_2 would be released. The rich Selexol from the bottom of the absorber goes to the rich Selexol valve to reduce the pressure from 2403 kPa to 1800 kPa. The rich Selexol then flows into the GASFLASH where it is separated into vapour and liquid phases, with the vapour containing about 0.9980 mol-fraction of CO_2 while the rich Selexol flows from the bottom to VALVE2 where the pressure is further reduced from 1800 kPa to 980.7

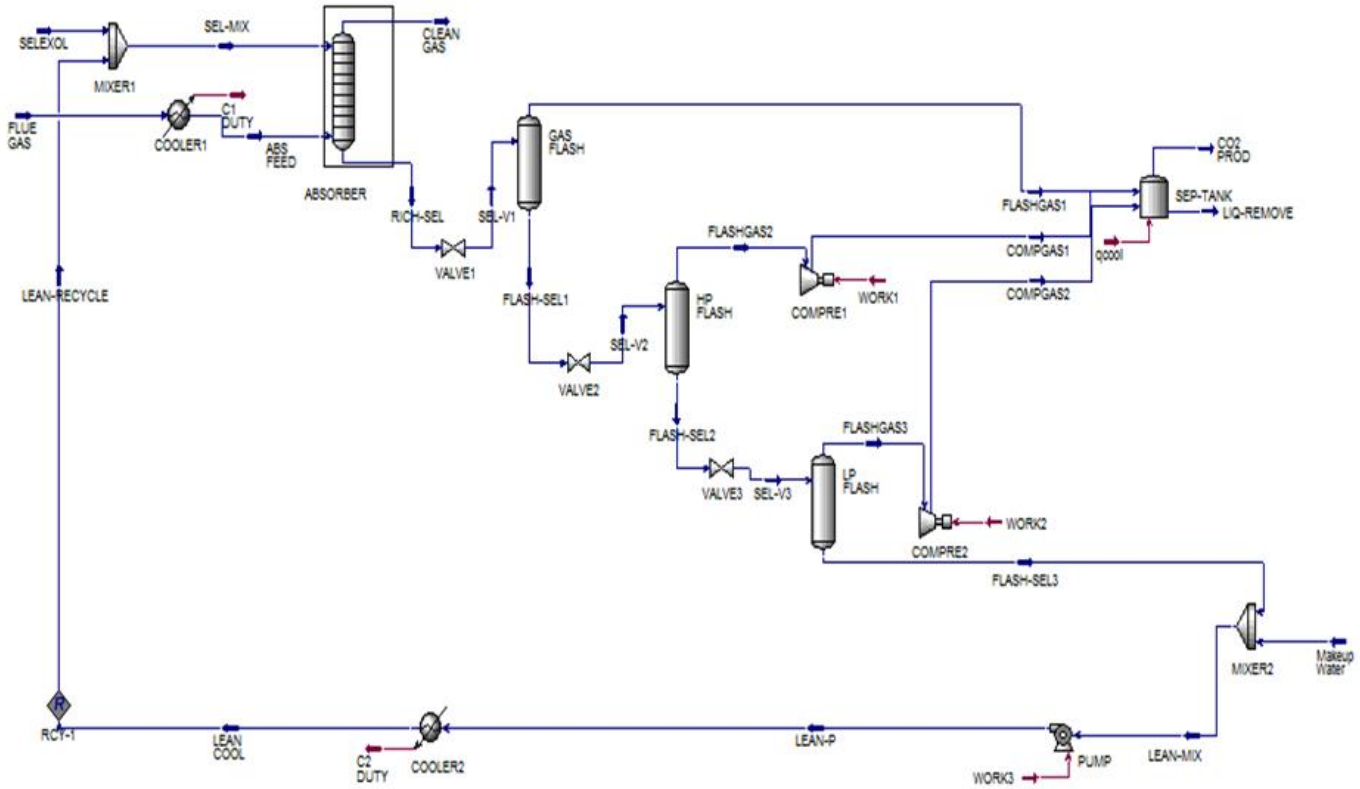

Figure 1: Aspen Hysys Simulation Process Flow Diagram for the Selexol Capture Unit for the Cement Plant

kPa. This continues till the rich Selexol finally enters LP FLASH where it operates at 98.07 kPa (≈ atmospheric pressure) to release virtually all the CO_2 absorbed within the rich Selexol. The separation in this Low Pressure Flash Tank composed of about 0.9814 mol-fraction of CO_2 which is then compressed in COMPRES2 to increase the pressure from atmospheric to 1961 kPa which meet with other CO_2 streams coming from FLASHGAS1 and COMPGAS2 for onward separation of liquid traces in a separation tank to allow CO_2 captured or produced to be compressed depending on its utilization. This research made provision for the CO_2 to be compressed to a pressure of 1800 kPa and temperature of 179.7^{o}C for the pipeline transportation which is out of the scope for this study. Type and amount of packing are selected so that the maximum recovery is obtained using the minimum consumption of the solvent - Selexol. The flue-gas composition for the base case is shown in Table 1.

Table 1: Cement Plant Flue Gas Composition for Process Simulation using Aspen Hysys

Parameters	Kiln Operating at Highest Capacity
Temperature (^{o}C)	180
Pressure (Bar)	1
Mole Flow (kmol/hr)	1210.26
Mass Flow (kg/hr)	53,243.55
Volume Flow (m^3/hr)	252,000
Mass Flow, kg/hr:	
CO_2	52,999.659
SO_2	2.588
NO_2	191.372
O_2	49.930
Mole Flow, kmol/hr:	
CO_2	1204.5
SO_2	0.0404
NO_2	4.1603
O_2	1.5603
Mass Fraction:	
CO_2	0.99540
SO_2	0.00005
NO_2	0.00359
O_2	0.00094
Mole Fraction:	
CO_2	0.99520
SO_2	0.00003
NO_2	0.00344
O_2	0.00129

2.0 Economic Evaluation and Analysis

2.1 Sizing and Cost Evaluation Using Aspen Process Economic Analyzer

Aspen process Economic Analyzer which was formerly known as Icarus Process Evaluator is an integral part of the Aspen Hysys Software package that was designed to automatically prepare the detail designs, estimates and carryout the investment analysis of the process plant simulated using Aspen Hysys with information supplied from the simulation result or the equipment sized. Sizing or mapping can be done either by mapping one equipment at a time or all equipments at once in the APEA.

The total cost of the CO_2 capture unit was evaluated when the cost of each component is estimated. This is necessary because the Aspen Process Economic Analyzer uses those costs together with information from simulation results and other specifications to evaluate the total capital investment cost (CAPEX) and total operating cost (OPEX) automatically.

The development of a new CO_2 capture plant cannot be complete without the plant cost analysis. Hence, this aspect describes the cost analysis of a Selexol-Based CO_2 Capture Process for Ashaka Cement plant flue gases with the plant operating at its maximum capacity. The CO_2 capture cost analysis was evaluated for the designed process with 97% recovery and 98% purity by mole of the CO_2 with a CO_2 lean loading of 0.37 mole CO_2/mole Selexol, since it was observed that, at a lean loading of 0.37%, the maximum and best CO_2 absorption in the column was obtained. In order to test the robustness, stability and performance of the capture unit results obtained from the simulation, a number of sensitivity analyses were carried out for the capture process. The key inputs are Capital Costs, Operating Costs and CO_2 Capture Costs. Aspen Process Economic Analyzer was used for the cost analysis with the total cost, involving both operating and capital costs transformed to ₦/tonne of CO_2 captured.

2.2 Basic Assumptions for the Costing of the Capture Unit

The basic assumptions made for this research work were based on the international standards criteria which have been developed for Cement Plant with CO_2 capture process from its flue gas. These key parameters for the Selexol-Based CO_2 Capture Process are summarized in Table 2.

Table 2: Key Parameters for Economic Evaluation of Selexol-Based CO_2 Capture Process

S/N	Parameter	Description
1.	Currency Description	USD (Converted to Nigerian Naira)
2.	Operating Hours per Period	8030
3.	Tax Rate	40% per year
4.	Interest Rate	20% per year
5.	Economic Life of Project	20 years
6.	Salvage Value (Fraction of Initial Capital Cost)	20%
7.	Depreciation Method	Straight Line
8.	Project Capital Escalation	5% per year
9.	Products Escalation	5% per year
10.	Raw Material Escalation	3.5% per year
11.	Operating and Maintenance Labour Escalation	3% per year
12.	Utilities Escalation	3% per year
13.	Labour Cost	\$20/hr/Operator ≡ ₦3,200/hr/Operator
14.	Supervisor Cost	\$35/hr/Supervisor ≡ ₦5,600/hr/Supervisor
15.	Electricity Cost	\$0.0775/kWh ≡ ₦12.4/kWh
16.	Cooling Water Cost	0.0393/m^3 ≡ ₦6.288/m^3
17.	Selexol Cost	\$1.8/kg ≡ ₦288/kg
18.	Operators per Shift	3 Operators
19.	Supervisor per Shift	1 Supervisor
20.	Operating Charges	25% of Operating Labour Cost per year
21.	Plant Overhead Cost	50% of Operating Labour and Maintenance Cost per year
22.	General and Administrative Expenses	8% of Subtotal Operating Cost
23.	Working Capital	5% of Total Capital Investment

III. RESULTS AND DISCUSSION

3.1 Capital and Operating Costs Allocation for the Selexol-Based CO_2 Capture Process for the Cement Plant

Total operating cost for the Selexol-CO_2 capture process includes all expenses such as costs for producing the products, selling the products, and recovering of capital cost. This cost is subdivided into Manufacturing costs and General Expenses. Manufacturing costs are all expenses connected to production; this cost is sometimes called Operating Cost or Production Cost. Summaries of these costs are presented in Table 3.

Table 3: Capital and Operating Costs Allocation of the Selexol-Based CO_2 Capture Process for the Cement Plant

Capital Cost Components:	**Cost ($)**	**Cost (₦)**
Total Direct Cost	8,780,266	1,404,842,560
Total Indirect Cost	3,770,899	603,343,840
Working Capital	640,162	102,425,920
CO_2 Drying System	6,031,559	965,049,440
Grand Total Capital Cost	19,222,886	3,075,661,760
Annual Capital Cost	1,747,535	279,605,600
Salvage Value (20% CAPEX)	3,844,577	615,132,320
Annual Salvage Value	69,901	11,184,160
Operating Cost Components:		
Total Variable Production Cost	21,872,570	3,499,611,200
Operating Cost (at Second Year)	24,096,648	3,855,463,680
Annual Operating Cost (across 20 years; annuity factor of 14.3%)	27,542,469	4,406,795,040

3.2 CO_2 Captured Cost

The cost of CO_2 captured for the case study will be calculated based on the total costs the plant incur based on calculated values obtained during the analysis (i.e. the total annual costs; TAC). To calculate this aspect of cost analysis, Table 4 shows the annual operating cost, annual capital cost, annual salvage value, total annual cost and the CO_2 capture cost per tonne of CO_2 captured for the capture plant design for the Cement plant [8]. The total annual cost (TAC) for the Selexol-Based CO_2 Capture Plant for Ashaka Cement Plant is calculated thus:

Total Annual Cost = Annual Capital Cost + Annual Operating Cost + Annual Salvage Value

$$CO2\ Capture\ Cost = \frac{Total\ Annual\ Costs}{Total\ CO2\ Captured}$$

Table 4 shows the various costs incurred for the CO_2 Capture Unit, as can be seen, the total annual CO_2 captured (tonne) was obtained by calculating 97% recovery of the CO_2 from the rich selexol, accounting for 504,356 tonne CO_2 captured from the annual total of 519,955 tonnes. From the calculation, a value of $58 (₦9,280) was obtained as the cost of capturing one tonne of CO_2 from Ashaka Cement Plant flue gases.

Table 4: Calculated CO_2 Capture Cost of the Capture Plant for the Cement Plant

Parameter	**Value ($)**	**Value (₦)**
Annual Capital Cost	1,747,535	279,605,600
Annual Operating Cost	27,542,469	4,406,795,040
Annual Salvage Value	69,901	11,184,160
Total Annual Cost	29,359,905	4,697,584,800
Total Annual CO_2	504,356	504,356
Captured (tonne)	58	9,280
Cost of CO_2 Captured/tonne of CO_2		

3.3 Sensitivity Analysis

The effect of Absorber Inlet Gas Temperature on percentage CO_2 recovery, Energy Consumption, Annual Operating Cost, Annual Capital Cost and Cost of CO_2 Captured was studied. A case study has been performed in order to investigate economic performance when changing the flue gas inlet temperature into the absorber. This was achieved by keeping the flue gas inlet pressure and number of stages constant.

The CO_2 recovery was specified at 97% and the carbon dioxide product purity at 98% by mole. The Net liquid flow and Net Vapour flow profiles varies depending on the absorber column temperature, and the total CO_2 removal efficiency.

CASE 1: Sensitivity of Liquid and Vapour Flows to Absorber Temperature and Pressure

Figure 2 and 3 shows the sensitivity of the Net liquid and net vapour flows to the change in absorber column temperature and pressure. As can be depicted from the graphs; as the absorber column temperature increases, the net liquid and vapour flows increases steadily with net vapour forming plateau around 51.8°C while net liquid increases steadily with increasing temperature.

The effect of absorber column pressure on the net liquid flow and net vapour flow was studied. Figure 4.14 shows that as the column pressure varies, the net liquid flow (selexol) increases steadily, this is evidenced that, at higher pressure, the more ability for physical solvent (selexol) to absorb carbon dioxide effectively and efficiently.

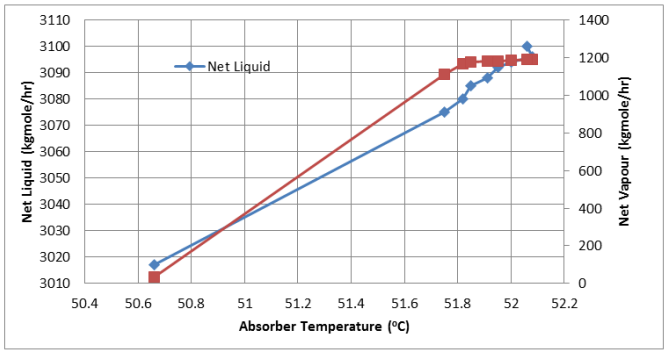

Figure 2: Results of Net Liquid flow and Net Vapour flow as a function of Column Temperature.

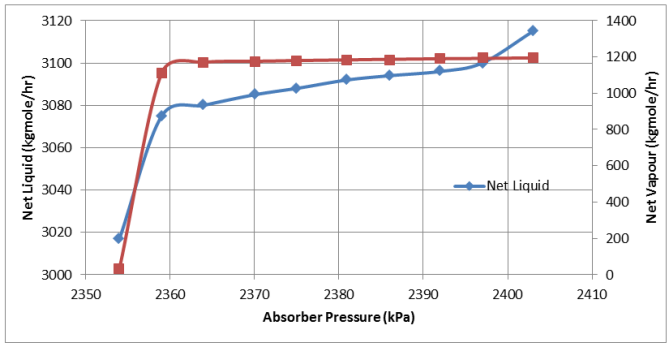

Figure 3: Results of Net Liquid flow and Net Vapour flow as a function of Column Pressure.

CASE 2: Sensitivity of CO_2 Removal and Energy Consumption to Absorber Inlet Gas Temperature

The effect of inlet flue gas temperature on the CO_2 removal across the column and energy consumption was studied, it was observed that as the temperature increases the capture rate decreases. This is evidenced that at higher temperature, physical solvent performance decreases while the energy consumption increases linearly from its lowest value at 0.684 up to 0.7027kJ/kg CO_2 at temperatures of 30 and 55°C respectively. This signifies that, as temperature increases, less CO_2 is captured, as shown in Figure 4.

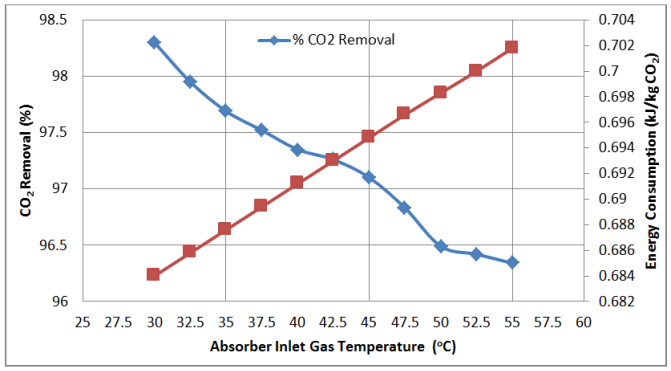

Figure 4 : Results of Percentage CO_2 Removal and Energy Consumption as a function of Inlet Flue Gas Temperature.

Case 3(a): Sensitivity of Capital Cost and Operating Cost to Absorber Inlet Gas Temperature.

Figure 5 shows the summary of annual capital cost and annual operating cost as a function of absorber inlet gas temperature. As can be observe, at low inlet temperature of 30°C, the annual capital cost and operating cost are all maximal and at inlet temperature of 40°C, the capital cost and operating cost are minimal. Reason being that, as the temperature increases, the less the ability of physical solvent (Selexol) to absorb the CO_2 leading to lower circulation of the solvent, hence decreasing the diameter of the absorber and consequently the direct cost, indirect cost and fixed capital cost decreases as evidenced in Figure 5. It was also observed that, at 40°C inlet gas temperature, both the annual capital and annual operating costs were minimum which signifies that, the process was best operated at this temperature; operation above this temperature increases these costs as evidenced in the graph.

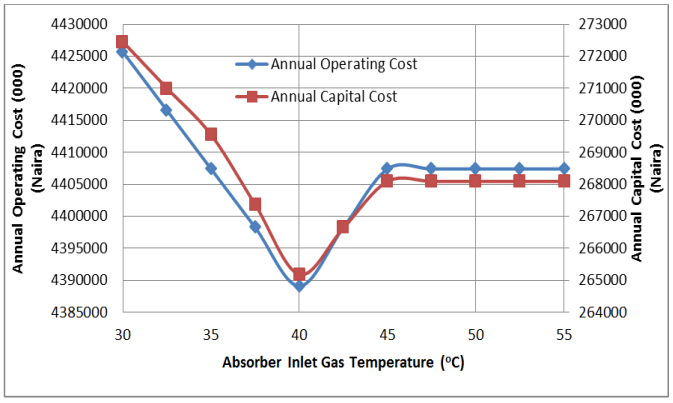

Figure 5: Results of Annual Capital Cost and Annual Operating Cost as a function of Inlet Flue Gas Temperature.

Case 3(b): Sensitivity of CO_2 Removal and Cost of CO_2 Captured per tonne to Absorber Inlet Gas Temperature.

Figure 6 shows the CO_2 capture cost per tonne of CO_2 captured at absorber inlet gas temperature from 30°C to 55°C. As can be seen from the figure, the absorber inlet gas temperature that gives the minimum CO_2 capture cost per tonne of CO_2 captured for a CO_2 recovery of 97% is 40°C which correspond to a cost of $58.33 (₦9,333) per tonne of carbon dioxide captured and the capture cost is maximum at absorber inlet gas temperature of 30°C which corresponds to CO_2 capture cost of $58.90 (₦ 9,424) per tonne of CO_2 captured. It could be deduced from the figure also, that higher CO_2 removal ability of the process correspond to higher cost of the capture. The process shows a deviation from this fact after absorber inlet gas temperature of 40°C, indicating that, as the CO_2 removal ability of the process decreases, the CO_2 capture cost per tonne increases, signifying that, at higher temperature(s), the physical solvent ability to absorb the CO_2 decreases, hence leading to larger absorber diameter which in turn increases fixed capital cost, direct costs and indirect costs.

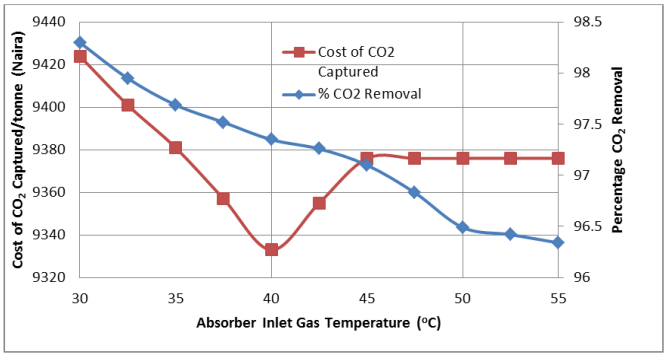

Figure 6: Results of CO_2 Removal and Cost of CO_2 Captured per tonne as a function of Inlet Flue Gas Temperature.

3.4 Comparison of CO_2 Captured Cost with Other Research Work

Research works have been carried out in this field of study for decade which involves design and costing of CO_2 Capture Process for fossil fuel-based power plants. Such as gas, biomass, coal, pet coke e.t.c. The results from these studies were used for comparison with data obtained in this study.

Figure 7 compares the different results in terms of cost per tonne of CO_2 captured for both the amine and selexol case which ranges from $48 (₦7,680) to €59.9 (₦10,728) per tonne of CO_2 captured.

CO_2 capture from an existing cement plant was studied by [1] with the conventional amine stripping approach. The cost of CO_2 captured however, for the amine case was reported to be $54 (₦8,640) with CO_2 composition in the flue gas to be 31.8% on molar basis. CO_2 capture from an existing coal fired power plant was studied by [10] using chemical solvent amine as well as an upcoming alternative commonly known as O_2/CO_2 recycles combustion. The cost of CO_2 captured however, for the amine absorption process was $55 (₦8,800) with CO_2 composition of 14.6% on molar basis in the flue gas. Alston Case [11] as studied have higher capital cost and lower operating cost, reported a CO_2 capture cost of $53 (₦8,480) per tonne of CO_2 captured. [12] operated a fixed plant size of 290 tonnes/day, observed increase in total plant cost with CO_2 consumption of 13% on molar basis, with that above conditions, the CO_2 capture cost was approximately $48/tonne CO_2 captured (₦7,680). [9] Studied the CO_2 capture process of a dry-feed cement plant in NE Scotland, UK based on the use of post-combustion amine scrubbing using monoethanolamine (MEA) and found out the cost of CO_2 captured to be €59.6 (₦10,728) per tonne of CO_2 captured. [13] Studied the assessment of the value of retrofitting cement plant for carbon capture with a case study of a cement plant in Guangdong, China, using a Post-Combustion, MEA process, with 85% capture rate of 2.15 million tonnes of CO_2 captured. The study found out the cost of CO_2 captured to be $70 (₦11,200) per tonne of CO_2 emissions avoided.

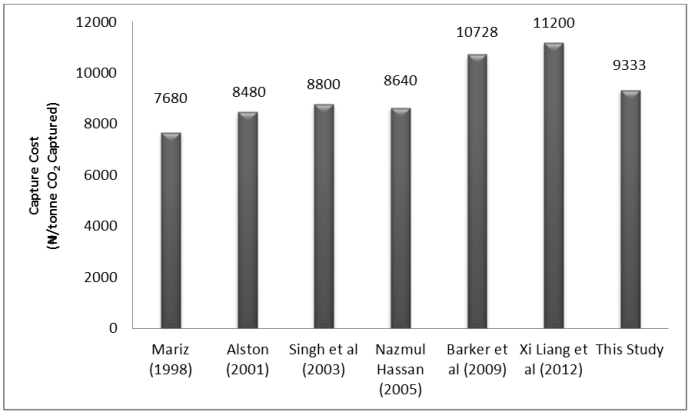

Figure 7: Comparison of CO_2 Capture Cost

IV. CONCLUSION

CO_2 released by Ashaka Cement plant was reduced from 4.86% to 0.13% compared to world standard (0.05%). The CO_2 capture cost per tonne of CO_2 captured was found to be $58 (₦9,333). The Total Operating Cost was estimated at $27,542,469 (₦4.5Billion) and the Total Capital cost was estimated at $19,222,886 (₦3.08 Billion). The raw material cost was the highest cost in the CO_2 capture process with a value of $19,500,000 (₦3.1 Billion) representing 71% of the total operating cost. The capture cost obtained in this study was within the range obtained by other researchers, i.e. between ₦7,680 to ₦11,200. The cost of Post-Combustion CO_2 capture at Ashaka Cement Plant using Selexol is expected to be slightly higher than at a power plant, reason, basically due to lower economies of scale and the need to install FGD, NOx reduction and Dust control devices. Finally, both minimum and maximum capture cost, energy consumption and maximum annual cost per annum to be paid should be considered, hence this will lead to the best Cement Plant, putting into consideration, carbon price development and regulatory requirement during the plant's lifetime.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

The work was carried out in collaboration between all authors. Tsunatu D. Yavini. designed the study, carried out the simulation of the capture unit, performed the data analysis and revised the manuscript. Ibrahim A. Mohammed-Dabo supervised the economic evaluation aspect and wrote and revised the manuscript. Saidu M. Waziri provided valuable suggestions for the sensitivity analysis and interpreted the graphs and revised the manuscript. All authors read and approved the final manuscript.

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