Original Research Article

CHEMICAL PROCESS ABSORPTION COLUMN DESIGN FOR CO_2 SEQUESTRATION

Abstract

The design of a prototype chemical process absorption column was carried out to facilitate the sequestration of CO_2 from flue gas emanating from an exhaust point of a power generating set. Factors such as ambient temperature and atmospheric pressure where factored into consideration before the fabrication of the absorption column. The rate of the absorbing liquid is 0.1056kg/min and contains 5% mole/mole carbon (iv) oxide. Also the energy and material balance of the entire sequestration process was verified as well as the equipment design for the process was carried out.

Keyword: material balance, energy balance, CO_2 sequestration, ammonia, equipment design, absorption column, knockout drum, absorber, evaporative gas cooler, solution cooler, solution heat exchanger, flash drum, stripper, and reboiler.

1. Introduction

Plant design is a technical term that embraces all engineering aspects involved in the development of either a new, modified, or expanded industrial plant (Coulson and Richardson, 1968). It involves the economic evaluation of new processes, design of industrial pieces of equipment for a new plant or the development a plant layout for the co-ordination of the overall operation. The development of a process involves many different steps starting from the inception of the basic idea. The atmospheric concentration of carbon (IV) oxide, i.e., the most critical greenhouse gas, has increased from 280 ppm in the pre-industrial age to more than 370 ppm now, and is expected to increase above 500 ppm by the end of this century, Watson R.T (2001). This is recognized to be due to anthropogenic activities, especially fossil fuels burning and land use changes, and associated with the increasing earth's average temperature.

Present strategies for the mitigation of the atmospheric carbon (IV) oxide build-up are relied on the energy use efficiency, and the reduction of fossil fuels consumption for increased use of renewable energy sources or nuclear power plants. However, the increasing world population accompanied with increasing consumption of energy and growth of industrial development in developing countries like china and India has posed a challenge in the efforts to reduce greenhouse gas emissions. Thus, the inevitable way of keeping the global CO_2 load in the atmosphere and hydrosphere below unbearable levels is the complementing of emission reduction efforts by the capture CO_2 before it emits from point sources, or from its carrying air stream emitting from the point of sources, and to store it permanently outside the atmosphere.

2. Materials and Methods

2.1 Methodology

Due to the nature of the equipment made of glassware and in order to control the experiment, standard conditions of ambient temperature and atmospheric pressure were adopted for the process, and also for the flow rate of the solution into the absorption column. Three independent variables were used: the concentration of solvent ranging from 2-10 mol/dm^3, contact time ranging from from 20-100 seconds and volume of solvent ranging from 40-200 ml.

For the carbon sequestration to be achieved, 10 mol/dm^3 concentration of aqueous ammonia was prepared and poured into a flask containing ammonia solution which supplies the solution to the absorber, the aqueous ammonia was evenly distributed across the inner surface of the column while in contact with the plates. The petrol generating set was turned on while the gas analyzer detected the components and quantity of gases before it being charged into the heat exchanger. The heat exchanger helped to attain the desired temperature of 40^{o}C before the flue gas was charged into the absorption column from the entry point near the base of the absorption column. The flue gas in the column contacted with the aqueous ammonia in a counter current form for a period of 60 seconds after which the tap at the exit point close to the top of the absorption column was opened and gas analyzer was used to determine the amount of CO_2 and CO leaving the column.

2.2 Materials

The materials made up of glass wares were purchased at science apparatus market; they were put together alongside other components fabricated to make a complete reactor. The equipment has an absorption column, flask containing the ammonia solution, reservoir to house the content of the mixture in the aftermath of the reaction, openings for flue gas entrant and exit point after the reaction, non-heat sensitive pipe connected to the entry point of the absorption column and the exhaust pipe of the gasoline generating set.

Equation for the reaction:

i) CO_2 Absorption

$2CO_2\,(g) + 2NH_3(aq) + H_2O \rightarrow NH_2COONH^+{}_4(aq) + H_2CO_3$

ii) Ammonia Regeneration

$NH_2COONH^+{}_4(aq) + H_2O \rightarrow H_2CO_3 + 2NH_3$

About 98% recovery of CO_2 occurs and the recovery liquid is a 20% w/w NH_3

Assumptions:

1) The rate of the absorbing liquid is 0.1056kg/min and contains 5% mole/mole carbon (iv) oxide.
2) The spent air effluent analysis, $0.000347ft^3/s$ at 30^0C, 1atm with % composition on dry basis of carbon (IV) oxide (3.5%), nitrogen (79%) and oxygen (17.5%). The exit air is saturated with water vapour at the absorbing liquid inlet temperature of 40^0C.
3) Recovery of 85% CO_2.
4) Reaction equation

The following reaction occurs:

i) CO_2 Absorption

$2CO_2(g) + 2NH_3(aq) + H_20 \rightarrow NH_2COONH^+{}_4(aq) + H_2CO_3$

ii) Ammonia Regeneration

$NH_2COONH^+{}_4(aq) + H_2O \rightarrow H_2CO_3 + 2NH_3$

About 98% recovery of CO_2 occurs and the recovery liquid is a 20% w/w NH_3

Assumptions:

i) The rate of the absorbing liquid is 0.1056kg/min and contains 3.5% mole/mole carbon (IV) oxide.

ii) Air effluent analysis, $0.000347ft^3/s$ at 30^0C, 1atm with % composition on dry basis of carbon (IV) oxide (3.5%), nitrogen (79%) and oxygen (17.5%). The exit air is saturated with water vapour at the absorbing liquid inlet temperature of 40^0C.

iii) Recovery of 85% CO_2.

Process Details:

Basis: 1 minute operation

Feed Stream

Stream 2: Spent air effluent (dry basis)

CO_2 = 3.5%

Nitrogen = 79%

Oxygen = 17.5%

Total volume of spent air effluent = 0.000347Ft^3/s

3. Results and Discussions

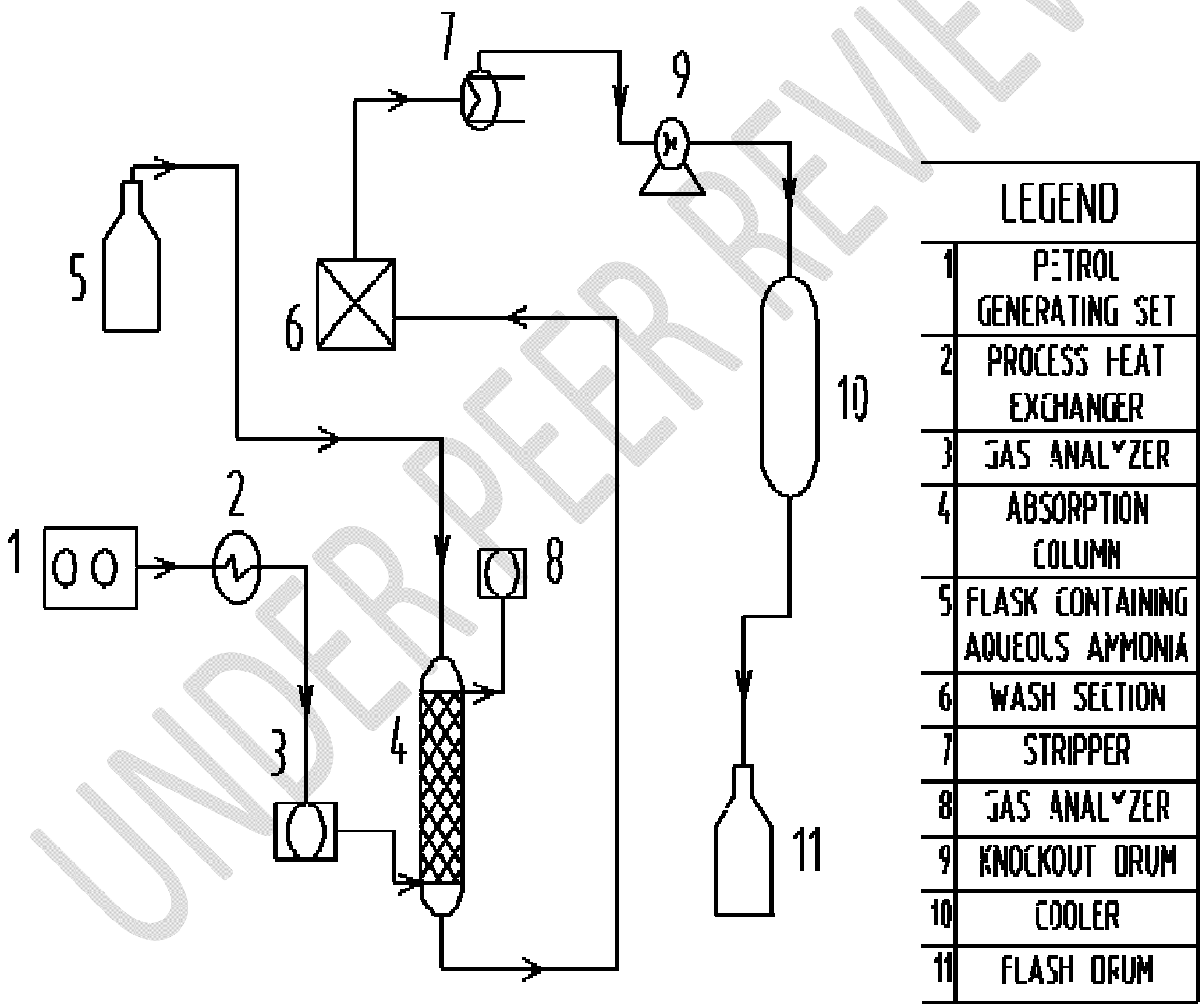

Fig.1 Experimental set-up and sketch diagram for absorption using the prototype semi-batch column

The capturing of CO_2 from spent air effluent was achieved through the absorption of CO_2 with ammonia solution to form ammonia carbamate which was later regenerated to recover the ammonia and CO_2. The raw gas (air effluent from a generating set) was cooled to about 40^0C (reaction temp.) and separated to remove any condensed water from the raw gas. Dry air effluent was charged to the adsorption column. In the absorption section the air was charged counter currently with ammonia solution from the top and the CO_2 was absorbed to form ammonium carbamate. The off air from absorption section is water washed in the wash section to remove any entrained liquid. The scrubbed gas recovered as overhead is sent to the knock-out drum to recover any entrained ammonia solution from the absorption column. The rich-amine solution from the bottom of the absorber is passed to energy recovery system and a solution heat exchanger where it is pre-heated to about 150^0C (regeneration temperature). The spent ammonia solution exchange heat with incoming regenerated ammonia solution from bottom of the regenerator. Pre-heated spent ammonia solution is separated to remove any gas associated with the spent ammonia solution. Regeneration of ammonia solution is carried out in the regenerator by the application of heat supplied by steam generated in the reboiler at the base of the regenerator. The top product of regenerator contains mainly CO_2 and steam which is cooled in the cooler to condense them. The steam is separated and returned to the reboiler.

The bottom product of regenerator containing regenerated ammonia solution is passed through solution heat exchanger where it exchanges heat with spent ammonia solution from the absorber. It is further cooled to bring its temperature to about 40^0C (absorption temperature).

3.1 Material Balance Results

CALCULATIONS

To get the volumetric flow rate:

$$Volume = \pi r^2 h$$

The absorption column specifications are:

- Length of column: 40cm
- Diameter of column: 5cm
- Number of plates: 10
- Distance between plates: 2cm
- Distance between outlet and plates in the column: 5cm

- Distance between outlet and bottom of column: 5cm
- Distance between inlet and plate contact: 5cm

$$\text{Radius} = \frac{\text{Diameter}}{2} = \frac{5}{2} = 2.5\text{cm}\ (0.025\text{m})$$

$$\text{Volume} = \pi x\ 0.025^2 x\ 0.4 = 7.8539\ x\ 10^{-4} m^3$$

Convert to feet: where $1\text{ft}^3 = 0.0283\text{m}^3$

$$\frac{0.0007845}{0.3048^3} = 0.0277 ft^3\ x\ 60 = 1.6642\ ft^3/hr$$

Assuming 75% absorption capacity for CO_2 and converting the calculated values from ft^3/hr to ft^3/sec

$$\frac{3}{4}\ x\ \frac{1.6642}{1} = \frac{1.24815}{3600} = 0.0003467\ \text{ft}^3/\text{sec}$$

To get the mass flow rate:

At optimum condition: Vol. of solvent = 120ml

Multiply by the density; 120 x 0.88 x 1gram = 105.6 g/min = **0.1056 kg/min**

Balance around the absorber

CO_2 in F_3 = 0.0000364kg (0.000000827kmol)

For 85% recovery, CO_2 scrubbed

= 0.85 X $C0_2$ Fed in F_3 = 0.0000309kg

Kmol of CO_2 scrubbed = 0.000000701kmol

Reaction equation in Absorber

$2CO_2(g) + 2NH_3(aq) + H_20 \rightarrow NH_2COONH^+{}_4(aq) + H_2CO_3$

Ammonium carbomate

From above equation

= (0.000000701 x 2) kmol of CO_2 required (0.000000701 x 2) kmol NH_3

Total mole of liquid consumed

= 0.000001402 + 0.000000701 = 0.000002103 kmol

Total mole of absorbing liquid = 0.1056kmol/min

Recovery liquid is a 20% w/w NH_3

Average molecular weight of recovery

$$\text{Liquid} = \frac{20(17)}{100} + \frac{80(18)}{100} = 17.8$$

Total mole of recovery liquid

$$= \frac{0.1086}{17.8} = 0.0059\text{kmol}$$

Mole of NH_3 in recovery liquid = 0.00118kmol

Mass of Ammonia in recovery liquid = 0.02006 kg/min

Kmol of H_20 in recovery liquid = 0.00472kmol

Mass of H_20 in recovery liquid = 0.08496 kg/min

Unreacted NH_3 = 0.00118kmol

Unreacted H_20 = 0.004719 kmol

Balance check

Flow stream F_3 (kg)

Total F_3 = 0.0006954kg/min

Flow stream F_8

CO_2 = 0.0000118kmol x 44 = 0.0005192kg

Total F_8 = 0.02006 + 0.08496 + 0.0005192 = 0.1055kg/min

Flow stream F_4

Unscrubbed CO_2 = 0.000484kg/min

From specifications, the exit air is saturated at 40^0C.

Vapour pressure of water at 40^0C, 760mmHg.

$$\text{Ln}\, \rho^0 w = \frac{A-B}{T+C} = Antione's\ equation$$

Where A, B and C are Antione's constant, T = Temperature

ρ^0_w = 232. 293 mmHg

Mole fraction of water vapour in flow F_4

$$\frac{\text{Vapour pressure of water vapour}}{\text{Total pressure}}$$

Total F_4 = 0.000887 + 0.000526 + 0.000133 + 0.000484 = 0.00203

NH_3 solution = $1X10^{-6}$ X 0.00203 = 0.00000000203kg

Flow stream F_5 (spent amine solution)

CO_2 = 0.0005192kg

Flow stream F_3^1

Water used for washing = 0.5 X total gas washed = 0.001015kg

Flow stream F_4^1

Let assume H_20 in F_4^1 = H_20 in F_3^1 = 0.001015kg

H_2O in F_5 = H_2O in F_8 + H_20 in F_3^1 – H_2O in = 0.08406

Total F_5 = 0.000053+ 0.000043+ (0.00118 x 17) + 0.08406 + 0.0005192 = 0.1047kg

Balance

At steady state

Total input = total output

$F_3 + F_8 + F_3^1 = F_4 + F_4^1 + F_5$

0.1072104 = 0.107745

3.1.1 Material Balance Summary Tables

3.1.1.1 Absorber

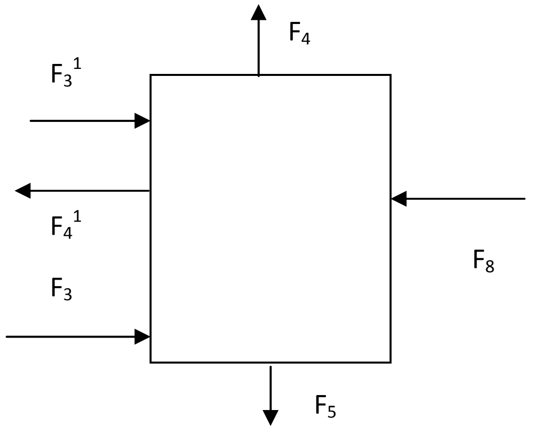

Fig. 2: Material Balance diagram for Absorber

Table 1: Absorber Input Streams

		F_3		**F_8**		**F_3^1**	
Comp	**Mol. Wt**	**Mole kmol/ hr**	**Mass kg/hr**	**Mole kmol/ hr**	**Mass kg/hr**	**Mole kmol/ hr**	**Mass kg/hr**
CO_2	44	0.0000118	0.0000364	0.0000118	0.0005192	-	-
O_2	32	0.000526	0.000133	-	-	-	-
N_2	28	0.000133	0.000526	-	-	-	-
NH_3	17	-	-	0.00118	0.02006	-	-
H_2O	18	-	-	0.08496	0.08496	-	0.001015
H_2CO_3	61	-	-	-	-	-	-
Carbamate	62	-	-	-	-	-	-
Total			0.0006954		0.01055		0.001015

Table 2: Absorber Output Streams

		$F_4{}^1$		F_4		F_5	
Comp	**Mol. Wt**	**Mole kmol/ hr**	**Mass kg/hr**	**Mole kmol/ hr**	**Mass kg/hr**	**Mole kmol/ hr**	**Mass kg/hr**
CO_2	44	-	-	0.02006	0.000484	0.0000118	0.0005192
O_2	32	-	-	0.08406	0.000526	-	-
N_2	28	-	-	0.000043	0.000133	-	-
NH_3	17	-	-	-	0.0005713	0.0000118	0.02006
H_2O	18	-	0.001015	-	0.000286	0.000000701	0.08406
H_2CO_3	61	-	-	-	-	0.000000701	0.000043
Carbamate	62	-	-	-	-	0.000000701	0.000053
Total			0.001015		0.00203		0.1047

3.1.1.2 Knock-Out Drum 1

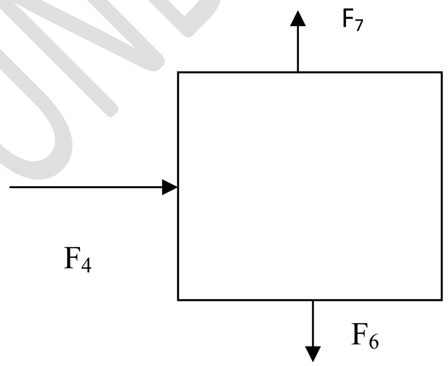

Fig. 3: Material Balance diagram for Knock Out Drum 1

Table 3: Knock-Out Drum 1 Calculation Details

	INPUT (F_4)			**OUTPUT (F_6)**		**OUTPUT (F_7)**	
Comp	**Mol. /wt**	**Mole Kmol/h**	**Mass kg/hr**	**Mole kmol/hr**	**Mass Kg/hr**	**Mole Kmol/hr**	**Mass Kg/hr**
CO_2	44	0.000484	0.000484	-	-	0.000484	0.0005192
O_2	32	0.000526	0.000133	-	-	0.000526	0.000133
N_2	28	0.000133	0.000133	-	-	0.000133	0.000133
NH_3	17	-	-	-	0.0029	-	-
H_2O	18	-	-	-	0.00116	-	-
Total			0.000203		0.00000000203		0.0011782

3.1.1.3 Flash Drum

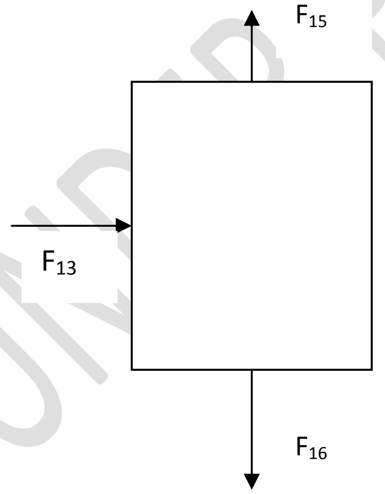

Fig. 4: Material Balance diagram for Flash Drum

Table 4: Flash Drum Input and Output Streams

INPUT STREAM			**OUTPUT STREAM**			
	F_{13}		**F_{15}**		**F_{16}**	
Comp	**Mole kmol/hr**	**Mass kg/hr**	**Mole kmol/hr**	**Mass kg/hr**	**Mole kmol/hr**	**Mass kg/hr**
CO_2	-	0.0005192	-	0.0005192	-	-
NH_3	-	0.02006	-	-	0.86	0.02006
H_2O	0.000000701	0.08406	-	-	0.000000701	0.08406
H_2CO_3	0.00118	0.000043	-	-	0.00118	0.000043
Carbamate	0.00118	0.000053	-	-	0.00118	0.000053
Total		0.1047		0.0005192		0.104216

3.1.1.4 Stripper

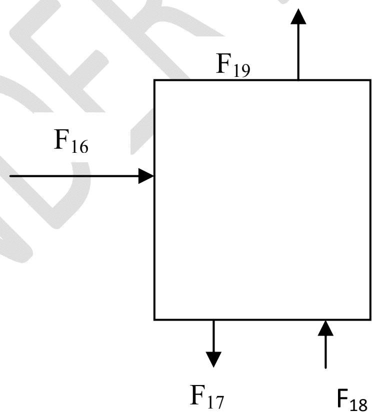

Fig. 5: Material Balance diagram for Stripper

Table 5: Stripper Input and Output Streams

INPUT STREAMS					**OUTPUT STREAMS**			
	F_{16}		**F_{18}**		**F_{17}**		**F_{19}**	
Comp	**Mole kmol/ hr**	**Mass kg/hr**	**Mole kmol/ hr**	**Mass kg/hr**	**Mole kmol/ hr**	**Mass kg/hr**	**Mole kmol/ hr**	**Mass kg/hr**
NH_3	-	0.02006	-	-	-	0.02006	-	-
H_2O	0.00000701	0.08406	-	0.00004326	-	0.1690	-	0.00004326
H_2CO_3	0.00118	0.000043	-	-	-	-	-	-
Carbamate	0.00118	0.000053	-	-	-	-	-	-
CO_2	-	-	-	-	-	0.0005192	-	0.00055004
Total		0.104216		0.00004326		0.1896		0.0005933

3.1.1.5 Knock-Out Drum 2

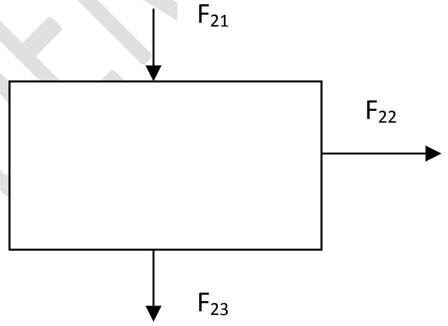

Fig. 6: Material Balance diagram for Knock Out Drum 2

Table 6: Knock-Out Drum 2 Input and Output Streams

INPUT STREAMS				**OUTPUT STREAMS**			
	F_{21}			**F_{22}**		**F_{23}**	
Comp	**Mole/ wt**	**Mole kg/hr**	**Mass kg/hr**	**Mole kmol/hr**	**Mass kg/hr**	**Mole kmol/hr**	**Mass kg/hr**
CO_2	44	-	0.0005501	-	0.0005501	-	-
H_2O	18	-	0.00004326	-	-	-	0.00004326
Total			0.0005933		0.0005501		0.00004326

3.2 Energy Balance Results

The conservation of energy differs from that of mass in that energy is generated (or consumed) in a chemical process. Material can change form; new molecular species was formed by chemical reactions where the total mass flow into a process unit must be equal to the flow out at the steady state. The same is not true of energy. The total enthalpy of the outlet streams will not equal that of the inlet streams if energy is generated or consumed in the processed, such as that due to heat of reaction.

3.2.1 Energy Balance Summary Tables

3.2.1.1 Absorber

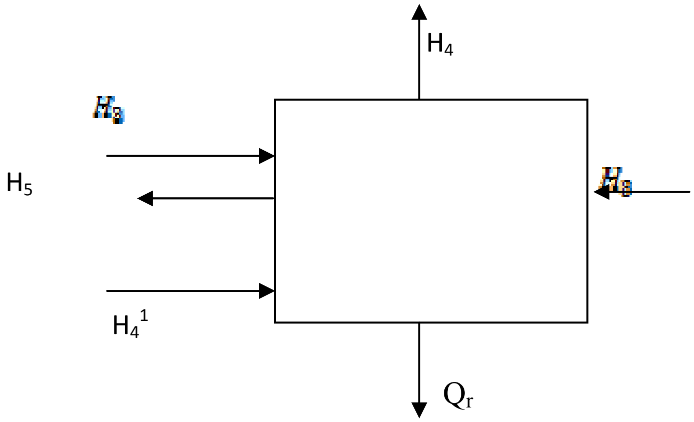

Fig. 7: Energy Balance diagram for Absorber

Where Qp = heat of the process, in this case Qp = 0 (Adiabatic process)

Qr = Heat of the reaction = Σ- ΔHr^0)

Total heat input = $H_3 + H_3^1 + H_8$

Total heat output = $H_5 + H_4 + H_4^1$

$$\text{Enthalpy input}, H_3 = \int_{T_{ref}}^{T_3} \epsilon_n\, C_p\, dT$$

Table 7: Absorber Energy Balance Summary

ENERGY	INPUT (KJ/hr)	OUTPUT (KJ/hr)
H_3	0.1704	-
H_4	-	0.3329
H_4^1	-	0.1705
H_8	3.9952	-
H_5	-	102.4708
Q_r	98.8085	-
Total	102.9741	102.9741

3.2.1.2 Stripper

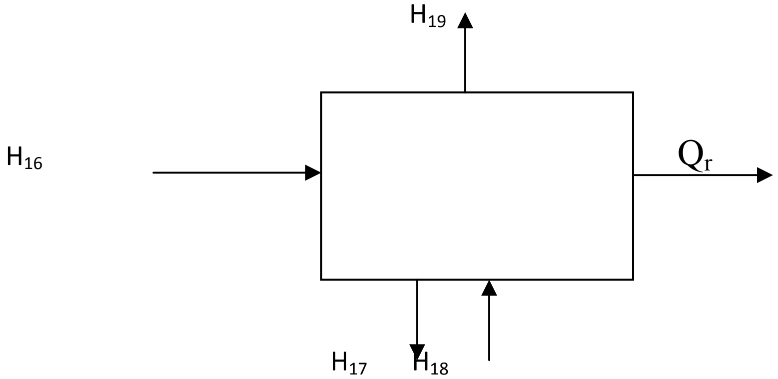

Table 8: Stripper Energy Balance Summary

ENERGY	INPUT (KJ/hr)	OUTPUT (KJ/hr)
H_{16}	47.4869	-
H_{18}	0.1326	-
H_{17}	-	127.77
H_{19}	-	- 76.5845
Q_r		- 98.805
Total	47.6195	- 47.6195

3.2.1.3 Gas Cooler 5

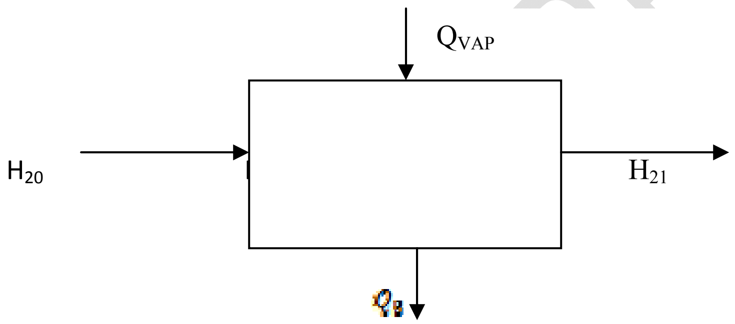

Fig. 9: Energy Balance diagram for Gas Cooler 5

Table 9: Gas Cooler 5 Energy Balance Summary

ENERGY	INPUT (KJ/hr)	OUTPUT (KJ/hr)
H_{20}	5.0624	-
H_{21}	-	2.5312
Q_{VAP}	0.09769	-
Q_5	-	2.62889
TOTAL	5.16009	5.16009

3.2.1.4 Solution Heat Exchanger

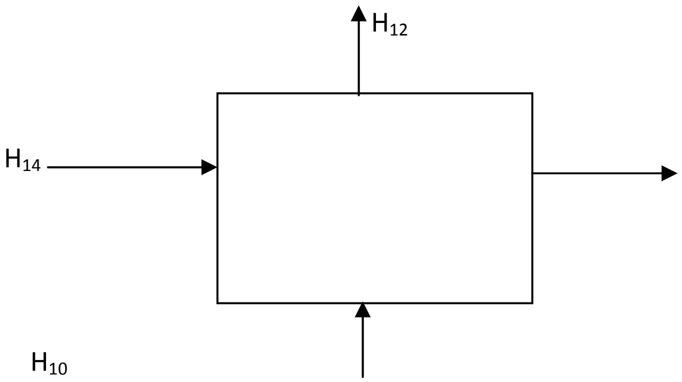

Fig. 10: Energy Balance diagram for Solution Heat Exchanger

Balance

$H_{10} + H_{14} = H_{12} + H_{13}$

ASSUMPTIONS

(1) The reboiler only generate steam for desorption process.

(2) Regenerated Amine solution does not pass through the reboiler so that $H_{17} = H_{14}$

(3) That the energy recovery system is dominant.

Table 10: Solution Heat Exchanger Energy Balance Summary

ENERGY	INPUT (KJ/hr)	OUTPUT (KJ/hr)
H_{10}	102.4708	-
H_{12}	-	182.7006
H_{13}	-	47.5402
H_{14}	127.77	
Total	230.2408	230.2408

3.2.1.5 Solution Cooler 4

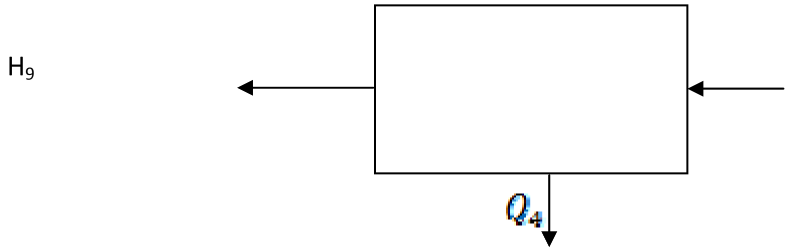

Fig. 11: Energy Balance diagram for Solution Cooler 4

Hence $Q_4 = (H_{12} \;=\; H_{11}) \;-\; H_9$

Table 11: Solution Cooler 4 Energy Balance Summary

ENERGY	INPUT (KJ/hr)	OUTPUT (KJ/hr)
H_9	-	3.9952
H_{11}	182.7006	-
Q_4	-	178.7054
Total	182.7006	182.7006

3.2.1.6 Evaporative Gas Cooler 2

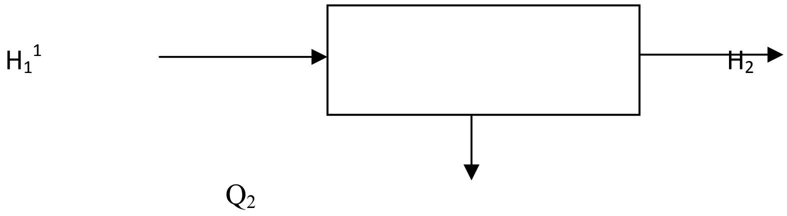

Fig. 12: Energy Balance diagram for Evaporative Gas Cooler 2

$$H_{1^1} \int_{30}^{80} \in_n C_p \, dT$$

Table 12: Gas Cooler Energy Balance Summary

ENERGY	INPUT (KJ/Hr)	OUTPUT (KJ/Hr)
H_1^1	0.8712	-
H_2	-	0.1704
Q_2	-	0.7008
TOTAL	0.8712	0.8712

3.3 Process Equipment Specifications

3.3.1 Absorber Specifications

Absorption of CO_2 in 20% w/w NH_3 solution

- $G\partial y = KGa\,(P_A - P_{AC})\,\partial h$

P_{Ae} = partial pressure that would be in equilibrium with the bulk of liquid, because the liquid is a concentrated solution of NH_3, the partial pressure of CO_2, P_{Ae} in equilibrium with it is virtually zero. Also PA = yp where P is the total pressure.

- $G\partial y = KGayp\partial h$

Rearranging and integrating

$$\frac{1}{K_{Ga}} = \frac{1}{K_{Ga}} + \frac{H}{K_{La}}$$

Table 13: Results Summary of Absorber Specifications

Equipment name	Absorber
Type	Wetted wall column
Packing type	Ceramic intallox paddle
Packing size	38mm
Packing factor	170m^{-1}
Column area	0.0003142m^2
Column diameter	0.01m
Height of absorption section	1.0m
Height of wash section	0.2m
Bottom liquid depth	0.000044m
Top gas disengagement height	0.3048m
Packing height	0.235m
Column material	Stainless steel
Design temperature	50^{0}C
Design pressure	1.1atm
Column wall thickness	5mm
Column cover thickness	5mm (terrispherical)

The design of wet scrubbers or any air pollution control device depends on the industrial process conditions and the nature of the air pollutants involved. Inlet gas characteristics and dust properties are of primary importance. Scrubber was designed to collect particulate matter and/or gaseous pollutants (Coulson and Richardson, 2005). Wet scrubbers remove dust particles by capturing them in liquid droplets. Wet scrubbers remove pollutant gases by dissolving or absorbing them into the liquid. Droplets that are in the scrubber inlet gas were separated from the outlet gas stream by means of another device referred to as a mist eliminator or entrainment separator.

3.3.2 Evaporative Gas Cooler 2 specifications

$$\text{Area of cooler } A = \frac{\acute{\varnothing}}{U\Delta\zeta m}$$

The evaporative cooler (also swamp cooler, desert cooler and wet air cooler) is a device that was designed to cool air through the evaporation of water. Evaporative cooling differs from typical air conditioning systems which use vapour-compression or absorption refrigeration cycles. Evaporative cooling works by employing water's large enthalpy of vaporization. The temperature of dry air can be dropped significantly through the phase transition of liquid water to water vapour, which requires much less energy than refrigeration.

Table 14: Results summary of Evaporative Gas Cooler 2 specifications

Equipment name	Gas Cooler 2
Type	Horizontal C & R
Sub-type	Split-ring floating Head
Shell type	Split-flow
Number of tubes	130
Number of tubes per pass	65
Surface area of exchange	0.003m^2
Heat load	0.7008KJ/min
Tube bundle diameter	37.5mm
Shell inside diameter	48.5mm
Bundle clearance	11mm
Overall heat coefficient	0.082w/m^2 ^{0}C
Tube-side heat coefficient	11.935 w/m^2 ^{0}C
Shell-side heat coefficient	3.1391 w/m^2 ^{0}C
Tube-side fouling factor	5000w/m^2 ^{0}C
Shell-side fouling factor	5000w/m^{20}C
Tube pitch	25mm
Tube arrangement pattern	Triangular
Baffle spacing	9.7mm
Baffle cut	25%
Baffle type	Segmented
Baffle height	76.275mm
No of support place nods	8
Diameter of nods	9.5mm
Tube-side design press	2.2atm
Tube-side design temp.	70 ^{0}C
Tube-side pressure drop	0.215kpa
Shell-side design press	1.1atm
Shell-side design temp.	90 ^{0}C
Shell-side design pressure Drop	169.77 kpa
Tube material	Mild steel
Shell material	Stainless steel.

3.3.3 Solution Cooler 2 Specifications

Basic design equation

$\varphi = UA\Delta Tm$

Shell – side heat transfer coefficient

$$\frac{h_s d_e}{k_f} = Jh \; x \; Re \; x \; pr \; x \; 0.33 \left(\frac{\mu}{\mu w}\right)^{0.14}$$

hs = shell – side heat transfer coefficient, de = equivalent diameter

Jh = heat transfer correction factor, Re = Reynolds number, Pr = prandth number

μ = viscosity of fluid at mean temp, μw = viscosity of fluid at wall temp.

$(\mu/\mu w)^{0.14}$ = viscosity correction factor.

Overall heat coefficient

Kw for mild steel = 45w/m^{0}C (Sinnott and Towler)

$$\frac{1}{U_0} = \frac{1}{ho} + \frac{1}{hod} + \frac{do \ln \frac{do}{di}}{2kw} + \frac{do}{di} \; x \; \frac{1}{h_i} \; x \; \frac{do}{di} \; x \; \frac{1}{hid}$$

Shell – side pressure drop

$$\Delta P_s = 8Jf \; x \left(\frac{D_s}{de}\right) x \; \frac{L}{IB} \left(\frac{\rho us^2}{2}\right) \frac{\mu^{0.14}}{\frac{\mu}{w}}$$

Neglecting viscosity correction factor

From figure 12 (Coulson and Richardson)

Jf = 5.5 x 10^{-2}

Table 15: Results summary of Solution Cooler 2 specifications

Equipment name	Solution cooler
Type	Horizontal shell & tubes
Sub-type	Split-ring floating head
Shell-type	Split-flow
Surface area of exchange	0.304m^2
Tube-inside diameter	16mm
Tube-outside diameter	20mm
Heat load	178.7054KJ/min

Tube length	4.88m
Tube-sheet	0.03m
Shell inside diameter	87.55mm
Tube bundle diameter	37.55mm
Bundle clearances	50mm
Number of tubes	1
Number of tube pass	1
Number of tubes per pass	1
Baffle spacing	17.51mm
Baffle cut	25 % (segmented type)
Tube pitch	25mm
Tube arrangement pattern	Triangular
Overall heat coefficient	362.9896 w/m^2 ^{0}C
Tube-side pressure drop	0.000013kpa
Shell-side pressure drop	243.17kpa
Tube-side design pressure	2.7atm
Shell-side design pressure	2.2atm
Tube-side design temp.	100 ^{0}C
Shell-side design temp.	212 ^{0}C
Shell wall thickness	5mm
Tube material	Mild steel
Shell material	Stainless steel

3.3.4 Cooler 5 (Condenser 5) Specifications

A = surface area of exchange.

$$= \frac{\varphi}{U\Delta T_m}$$

Tube bundle diameter (D_b)

$$D_b = d_o\left(\frac{N_t}{K_i}\right)^{\frac{1}{ni}}$$

From Table 15 (Coulson and Richardson), for triangular pitch.

$K_1 = 0.175, \; ni = 2.285$

Tube inside coefficient.

Cross – sectional area of one tube

$$= \frac{\pi(du^2)}{4}$$

Shell – side heat transfer coefficient

$$h_s = \frac{Kf}{de} \; x \; Jn \; x \; Re \; x \; pr^{0.33} \; x \; (\frac{\mu}{\mu w})^{0.14}$$

where hs = shell – side heat coefficient, Kf = thermal conductivity of fluid

Jh = heat transfer coefficient, R = Reynolds number, Pr = prandth

$\left(\frac{\mu}{\mu w}\right)^{0.14}$ = viscosity correction factor.

Table 16: Results summary of Cooler 5 (Condenser 5) specifications

Equipment name	Cooler 5
Type	Shell & tube H.E
Sub-type	Split-ring floating head
Head load	2.62889kJ/min
Shell type	Two shell pass
Number of tubes	1
Number of tubes pass	4
Number of tubes per pass	1
Tube bundle diameter	5.88mm
Surface area of cooler	0.00245m^2
Shell inside diameter	63.88mm
Baffle spacing	494mm
Baffle cut	25%
Baffle height	0.75 Ds = 47.91mm
Baffle type	Segmented
Tube pitch	31.25mm
Tube pattern	Triangular pattern
No of rods	12
Diameter of rods	9.5mm
Shell-side design press	5.984atm
Tube-side design press	2.75atm
Shell-side design temp.	310^{0}C
Tube-side design temp.	160^{0}C
Shell material	Stainless steel
Overall heat coefficient	3.5142w/m^{20}C

Shell wall thickness	5mm
Shell cover thickness	5mm
Tube-side pressure drop	0.0000079kpa
Shell-side pressure drop	791.388kpa.

3.3.5 Knock-Out Drum 1 Specification

Vapour–liquid separator was designed to separate a vapour–liquid mixture. The vapour–liquid separator is also referred to as a flash drum, knock-out drum, knock-out pot, compressor suction drum or compressor inlet drum (Kister, 1992). The vapour travels gas outlet at a design velocity which minimizes the entrainment of any liquid droplets in the vapour as it exits the vessel.

Table 17: Results summary of Knock Out Drum 1 specification

Equipment name	Knock-out drum I
Type	Vertical vessel
Drum diameter	0.002m
Drum length	0.004m
Mist eliminator type	Knitted wire-mesh
Mist eliminator thickness	0.152m
Clearance b/w liquid surface and centre of nozzle	0.3m
Clearance b/w centre of inlet Nozzle and mist eliminator	0.1524m
Clearance b/w mist eliminator and drum top edge	0.31m
Drum material of construction	Stainless steel
Drum wall thickness	7mm

Head and closure type	Ellipsoidal
Head and closure type	7mm
Mist eliminator material	Stainless steel.

3.3.6 Knock-Out Drum 2 Specifications

Table 18: Results summary of Knock Out Drum 2 specifications

Equipment name	Knock-out drum 2
Type	Vertical cylinder vessel
Drum diameter	0.002m
Drum length	1.0m
Mist eliminator type	Knitted wire-mush
Mist eliminator thickness	0.152m
Liquid depth	0.1374m
Clearance b/w liquid surface and centre of nozzle	0.05m
Clearance b/w the centre of nozzle and the mist eliminator	0.1m
Clearance b/w the mist eliminator and drum top	0.31m
Drum wall thickness	5mm
Head and closure type	Tom spherical
Head and closure thickness	5mm
Mist eliminate material	Stainless
Drum material	Stainless steel

3.3.7 Solution Heat Exchanger Specifications

A heat exchanger was designed for efficient heat transfer from one medium to another. The media is separated by a solid wall, so that they never mix, or they may be in direct contact (Kister, 1992). They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, and sewage treatment.

Table 19: Results summary of Solution Heat Exchanger specifications

Equipment name	Solution Heat exchanger
Type	Horizontal S&T
Sub-type	Split-ring floating head
Head load	- 54.9306 KJ/min
Shell type	Split flow
Number of tubes	1
Number of tubes pass	1
Number of tubes per pass	1
Tube bundle diameter	37.5504mm
Surface area of exchanger	0.019m^2
Shell inside diameter	87.5504mm
Baffle spacing	17.6mm
Baffle cut	25%
Baffle height	135mm
Baffle type	Segmented
Tube pitch	25mm
Tube pattern	Triangular pattern
No of rods	8
Bundle diameter	124mm
Shell inside diameter	180mm
Tube outside diameter	20mm
Tube inside diameter	16mm
Tube length	4.88mm
Tube-sheet thickness	0.03m
Bundle clearance	50mm
Diameter of rods	9.5mm
Shell-side design press	1.1atm
Tube-side design press	1.1atm

Shell-side design temp.	160^0C
Tube-side design temp.	360^0C
Shell material	Stainless steel
Overall heat coefficient	300w/m$^{2\ 0}$C
Shell wall thickness	5mm
Tube -side coefficient	261.13w/m$^{2\ 0}$C
Shell-side coefficient	361.324w/m$^{2\ 0}$C
Shell cover thickness	5mm

3.3.8 Flash Drum Specifications

Table 20: Results summary of Flash Drum specifications

Equipment name	Flash drum
Type	Vertical gas
Drum diameter	Liquid separator
Drum length	0.002m
Mist dominator type	Knitted wore mesh
Mist dominator thickness	0.152m
Liquid depth	0.30m
Clearance between liquid surface and centre of nozzle	0.30m
Clearance between centre wilet nozzle & mist dominator	0.61m
Clearance between mist dominator and drum top	0.31m
Drum material of construction	Stainless steel
Head and closure type	Ellipsoidal

3.3.9 Optimal values of CO_2 and validation of the experimental data

Table 21: Optimum conditions for CO_2 capture

Conc of Solvent (Mol/dm^3)	**Contact Time (Secs)**	**Volume of Solvent (ml)**	**Predicted Amount of CO_2 (%)**	**Experimental Amount of CO_2 (%)**	**Percentage Error (%)**
6.15	59.21	107.84	5.021	5.41	2

The optimum conditions obtained are concentration of solvent 6.15 mol/dm^3, contact time 59.21 seconds, volume of solvent 107.84 with 5.021 percent of CO_2 absorbed as shown in Table 21. Table 21 also depicts the validation of the optimal results of the sequestration process by performing the experiment with predicted optimum conditions, from the table it can be observed that the percentage error between the actual and predicted was 2 percent, this showed that the model was adequate in predicting the response for the absorption of CO_2.

4. Conclusion:

The design of a plant to recover CO_2 from spent air from aerobic fermentation was successfully carried out. Material and energy balances were carried out on each equipment and then over the entire process. These balances were used in the chemical and mechanical engineering design of the following equipment: absorber, knock out drum, flash drum, gas cooler, reboiler and stripping column. The data obtained in this design were used to fabricate an absorption column by the research for CO_2 and CO capture. The empirical relationship between amount of CO_2, CO captured and the independent variables were obtained with the aid of a statistical package. The statistical package was useful in analyzing and optimizing the amount of CO_2 and CO captured. The Analysis of Variance (ANOVA) result for the model terms were obtained and were applied for estimating the significance of the model. The experimental data were also analyzed to ascertain the correlation between the experimental and predicted gases captured, normal probability and residual plot as well as actual and predicted plots while the 3D response surface plots were generated to estimate the effect of the combinations of the independent variables on the amount of the captured gases.

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