The effect of increasing CO_2 concentration and flow rate on amine still performance in meeting gas sale specifications

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Abstract. The main purpose of this study is to examine the effect of increasing CO_2 removal and flow rate on performance of an amine still. The amine still is located in Field X in South East Sumatra at a new gas well producing gases with a rich CO_2 content. The still uses activated MDEA as the amine and has an IMTP 40-type packing column. Two film and desorption equilibrium curve theories were employed to analyse the amine still design conditions. Design equations were utilized to find the slope of the equilibrium curve. A slope of the equilibrium curve of 45° in the amine still is obtained in this study. The maximum liquid CO_2 composition of the amine still feedstock (x_o) which can be separated to produce lean amine according to the specification design flow rate is 0.0307. The total flow rate of CO_2-rich amine at x_o = 0.029 is 761,157.6 kg/hour; the total flow rate of CO_2-rich amine at x_o = 0.0295 is 628,861.1 kg/hour; the total flow rate of CO_2-rich amine at x_o = 0.03 is 513,962.6 kg/hour; and the total flow rate of CO_2-rich amine at x_o = 0.0305 is 409,575.3 kg/hour.

1 Introduction

A significant drop in the flow rate of gas wells has led to the creation of new gas sources in the study area. The recently created gas well in Field X in South East Sumatra has a rich CO_2 composition. The sudden surge of CO_2 from the well will have an immediate effect on the amine unit used for CO_2 separation. Design barriers result in this increased CO_2 composition directly leading to a decrease in gas production.

The amine unit referred to in this study is a processing unit used to remove CO_2 from gases. This separation is required because of the absence of heating value of CO_2 and its corrosive effect when it reacts with water. The CO_2 composition of gas for commercial sale must therefore be below specified limits to conform to the specifications of the gas buyer. Increased CO_2 from gas wells leads to increased CO_2 concentrations in rich amine in the still.

Increasing the CO_2 content of rich amine will require optimized amine still performance, so that lean amine returns to the amine contactor to further separate CO_2 within the still as needed. Desorption performance in the optimized amine still requires low pressure and high temperature. Low pressure creates the low partial pressure required in the gas phase and high temperature creates the high vapour pressure required in the liquid phase. The pressure deviation between the partial gas phase and the larger liquid phase are required for better mass transfer between phases.

This research is valuable because of the importance of identifying and understanding the conditions for amine unit design, specifically amine stills used for the desorption process. Height transfer unit (HTU) and number transfer unit (NTU) design equations are used to determine the amine still design conditions.

The amine still is the location in which the desorption process between MDEA and CO_2 occurs. The amine still design used in Field X uses packing with IMTP type 40. The amine still design data and design equations enable us to obtain the equilibrium slope curves (m_{yx}) which are used to analyse the limits of CO_2 increase and flow rate that can be processed.

2 Research Methodology

2.1 HTU and NTU equations designs for the amine still

The HTU and NTU equations are required to calculate the slope of the equilibrium curve (m_{yx}). The data required for this design equation are drawn from material design data, dimensions and the amine still process. High packing (H) is the design data used to determine the m_{yx} value.

In order to achieve a high packing value (H), the m_{yx} guess value must be entered at the beginning of the process. The value of m_{yx} is compared to the convergence criteria. In the condition where the value of m_{yx} is smaller or equal to the convergence criterion, the m_{yx} value is assumed to be achieved. If the m_{yx} value is greater than the convergence value, re-guessing of the the m_{yx}value is required.

Regardless of its current phase (gas or liquid), the HTU is a function of the mass transfer coefficient of both the liquid phase (k_L) and the gas phase (k_G). The NTU is a function of liquid load transfer and gas load transfer in both the bottom and overhead sections of the still towers.

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The slope of the equilibrium curve will be used to determine the amine still design conditions with variations of concentrations and flow rates.

2.2 Analysis of the impact of CO2 increase on amine still design capability

The analysis of the impact of CO_2 increase on amine still design capability is executed by varying the value of x_o (CO_2 composition in the liquid phase of the amine feed) at a fixed flow rate. Subsequently, the value of x_u (CO_2 composition in liquid phase of the amine still) is solved by employing trial and error. As a result, the high value of the amine still remains in accordance with the design. The numerical analysis is performed using the slope value at equilibrium (m_{xy}) which was obtained from this calculation.

Variations are performed with the following assumptions

1. An increase in y_o with the assumption that all the increase in CO_2 in the amine still (x_o) will flow to the top of the amine still.
2. x_u is 0.01 mol/mol MDEA (assuming CO_2 loading of lean amine) is 0.0013 mole fraction. This value is the maximum value of CO_2 allowed in lean amine.
3. The increase in y_u from the design value is proportional to the increase in the value of x_u.

2.3 Analysing the impact of increase in flow rate on amine still design capability

This step of the analysis focuses on the impact of the amine still design conditions on the variation of the flow rate for several CO_2 compositions (x_o and y_o). The equilibrium curve slope value (m_{xy}) was obtained from the previous calculation. The x_o value uses numbers in-between the design value and the maximum value obtained from the previous x_o variation. The value of x_u is solved by employing trial and error to ensure that high amine value in the still is in accordance with the design specification.

Variations are performed with the following assumptions:

1. The liquid phase flow rate (L) and the gas phase flow rate (V) rise by the same ratio.
2. x_u is 0.01 mol/mol MDEA and is 0.0013 mole fraction. This value is the maximum value of CO_2 allowed in lean amine.
3. The increase in y_u is equivalent to the increase in x_u value.
4. y_o increases with the assumption that all the addition of CO_2 in the amine still feed (x_o) will flow to the top of the amine still.

3 Results And Analysis

3.1 Coefficient of gas CO2 diffusion and coefficient of liquid CO2 diffusion

The determination of the gas CO_2 diffusion coefficient can be obtained using equation 1.

$$D_G = \frac{1{,}86\,.\,10^{-3} T^{\frac{3}{2}} (1/M_1 + 1/M_2)^{1/2}}{P \sigma_{12}^2 \Omega} \qquad (1)$$

The data obtained from the mechanical data sheet of the amine still for the above calculation is as follows:

T = 193 °F = 362.594 °K
P = 7.1 psig = 0.486 barg = 1.5 bara

The molecular weight for each component is:
M_1 = 44.0097 g/mol
M_2 = 18 g/mol

$$\sigma_{12} = \frac{1}{2}(\sigma_1 + \sigma_2) \qquad (2)$$

then

$$\sigma_{12} = \frac{1}{2}(3{,}941 + 2{,}641) = 3{,}291$$

$$\varepsilon_{12} = \sqrt{\varepsilon_1 \varepsilon_2} \qquad (3)$$

ε/k_B value for each component is as follows:
ε_1/k_B= 195.2 °K
ε_2/k_B= 809.1 °K
Therefore,

$$\varepsilon_{12}/k_B = \sqrt{\varepsilon_1/k_B \times \varepsilon_2/k_B} = 397{,}4\ °K$$

Dimensionless quantity (Ω) is recognized as the function of $k_B T/\varepsilon_{12}$. T is the operation temperature obtained from the mechanical data sheet of the amine still. Thus, $k_B T/\varepsilon_{12}$ = 362.594/397.4 = 0.912

By looking at the Ω value for $k_B T/\varepsilon_{12} = 0{,}912$, Ω = 1.52

The CO_2 diffusion coefficient obtained from equation 1 is as follows:

$$D_G = \frac{1{,}86\,.\,10^{-3} 362{,}59^{\frac{3}{2}} (1/44{,}0097 + 1/18)^{\frac{1}{2}}}{1{,}5 \cdot 3{,}921^2 \cdot 1{,}52}$$

$$= 4{,}12\text{x}10^{-6}\ \text{m}^2/\text{s}$$

The diffusion value of the gas coefficient ranges from 10^{-5}–10^{-6} m²/s (10^{-1}–10^{-2} cm²/s). This can be seen in the example of the diffusion coefficient value of the gas in other experimental results. The diffusion coefficient of the gas can be increased by raising the temperature or lowering the pressure. The underlying cause of this phenomenon is the faster movement of molecules at high temperatures or at lower pressure.

The determination of the liquid CO_2 diffusion can be acquired from equation 4.

$$D_{CO2,H2O} = 2{,}35\,.\,10^{-6}\exp(-2119/T) \quad (4)$$

T = 193 °F = 362.594 °K
then

$D_{CO2,H2O} = 2{,}35\,.\,10^{-6}\exp(-2119/362{,}594)$
= 6.792 x 10^{-9} m^2/s

$$D_{N2O}.\mu_B{}^{\gamma} = D_{N2O,H2O}.\mu_W{}^{\gamma} \quad (5)$$

The viscosity values of each component at the temperature and pressure of column operations obtained from Simulation are as follows:

μ_B = 1.084 cp = 0.001084 Pa.s
μ_W = 0.3179 cp = 0.0003179 Pa.s

therefore

$$\frac{D_{N2O}}{D_{N2O,H2O}} = \frac{\mu_W{}^{\gamma}}{\mu_B{}^{\gamma}} = \frac{0{,}0003179^{0{,}8}}{0{,}001084^{0{,}8}} = 0{,}375$$

$$\frac{D_{L\,CO2}}{D_{CO2,H2O}} = \frac{D_{N2O}}{D_{N2O,H2O}} \quad (6)$$

From equation 6, the CO_2 diffusion coefficient value is as follows:

$D_{L\,CO2} = D_{CO2,H2O}\frac{D_{N2O}}{D_{N2O,H2O}}$
= 6.792 x 10^{-9} x 0.375
= 2.5457 x 10^{-9} m^2/s.

From the above calculation of the gas diffusion coefficient it is found that the obstacles faced by the liquid diffusion coefficient have resulted in its lower value in comparison to the gas diffusion coefficient.

The value of the diffusion coefficient in the liquid can be increased by raising the temperature, as a result of the faster movement of liquid molecules at higher temperatures than at low temperatures. This can be seen by referring to the sample diffusion coefficient value of the other experimental results. The diffusion value of the CO_2 coefficient in water at temperature 293 °K (20 °C) is 2.5 x 10^{-5} cm^2/s (2.5 x 10^{-9} m^2/s). In the amine still with a temperature of 89.4 °C, the diffusion value of the CO_2 coefficient in water is 6.8 x 10^{-9} m^2/s, which is higher than the diffusion coefficient at 20 °C.

3.2 Effective wetted packing area (aw)

Equation 7 can be used to determine the effective wetted packing area (a_w).

$$a_w = a_p\left\{1 - exp\left[-1{,}45 Re_L^{0{,}1} Fr_L^{-0{,}05} We_L^{0{,}2}\left(\frac{\sigma}{\sigma_c}\right)^{-0{,}75}\right]\right\} \quad (7)$$

The data obtained from the mechanical data sheet for the amine still is as follows:

ρ_L= 64.4 lb/ft^3 = 1,032.04 kg/m^3
μ_L= 1.18 cp = 0.00118 kg/m.s

The mechanical data sheet figures for the amine still used to determine the liquid speed are as follows:
L = fluid flow rate = 740,745.6 lb/h = 335,996.3 kg/h
D = diameter column = 110 in = 2.794 m
thus, the fluid speed is as follows:

$$u_L = \frac{L/\rho_L}{\pi d^2/4} = \frac{335996{,}3/1032{,}04}{\pi \times 2{,}794^2/4} = 53{,}1 m/h = 0{,}01475\ m/s$$

At the packing area per volume (a_P) for IMTP type 40 rate of 151 m^2/m^3, the Reynold number (Re_L) obtained is as follows:

$$Re_L = \frac{0{,}01475 \times 1032{,}04}{151 \times 0{,}00118} = 85{,}58 \quad (8)$$

$$Fr_L = a_P u_L{}^2/g \quad (9)$$

The Froude number (Fr_L) at the gravity value of 9.8 m/s is as follows:
$Fr_L = 151 \times 0{,}01475^2/9{,}8$ = 0.00335

$$We_L = u_L{}^2\rho_L/a_p\sigma \quad (10)$$

From the mechanical data sheet figures for the amine still, it is found that:
σ = 46.4 dyne/cm = 0.0464 kg/s^2
therefore,

$$We_L = \frac{0{,}01475^2 \times 1032{,}04}{151 \times 0{,}0464} = 0{,}032$$

The surface tension packing material (σ_c) value for packing metal is 75 mN/m:
σ_c = 75 mN/m = 0.075 kg/s^2

By employing equation 7, the effective wetted packing area is as follows:

$$a_w = 151\left\{1 - exp\left[-1{,}45 \times 85{,}58^{0{,}1} \times 0{,}00335^{-0{,}05} \times 0{,}032^{0{,}2}\left(\frac{0{,}0464}{0{,}075}\right)^{-0{,}75}\right]\right\}$$
= 91.75 m^2/m^3

In comparison to the surface area per packing volume, the effective wetted packing area value is 60.76%. This number signifies the effectiveness of fluid system contact in the packing. As shown in the calculation in equation 7, the value of the wetted area is inversely proportional to the surface tension of the packing material (σ_c). Hence, the smaller the value of σ_c, the greater the wetted area and the more effective the contacts in the packing. The effective wetted packing area can be increased by changing the packing material to one that has a lower surface tension. Polyethylene plastic has the lowest surface tension value compared to other materials according to the table of surface tension material values.

3.3 Liquid mass transfer coefficient (kL) and gas mass transfer coefficient (kG)

Equation 11 can be used to determine the liquid mass diffusion coefficient:

$$k_L(\frac{\rho_L}{g\mu_L})^{1/3} = 0{,}0051\left(\frac{\bar{L}}{a_W\mu_L}\right)^{\frac{2}{3}} Sc_L^{-0{,}5}(a_p d_p)^{0{,}4} \quad (11)$$

The Schmidt number (Sc_L) of the liquid is determined using equation 12. The Schmidt number (Sc_L) of the liquid is 448.372.

$$Sc_L = \mu_L/\rho_L D_L \quad (12)$$

From the mechanical data sheet for the amine still and the calculation from the previous section, the following number is obtained:
μ_L = liquid viscosity = 1.18 cp = 0.00118 kg/m. s
ρ_L = fluid density = 64.4 lb/ft^3 = 1,032.04 kg/m^3
D_L = fluid diffusion coefficient = 2.546 x 10^{-9} m^2/s
then

$$\mathrm{Sc}_L = \frac{0{,}00118}{1032{,}04 \times 2{,}546 \times 10^{-9}}$$
= 448.37

Specification data for the IMTP 40 packing is:
a_p = 151 m^2/m^3
d_p = 40 mm = 0.04 m

The value of $\bar{L}$, which is the fluid flow rate per area, is calculated as follows:

$$\bar{L} = \frac{L}{\pi d^2/4} = \frac{335996{,}3}{\pi \times 2{,}794^2/4}$$
= 54,801.416 kg/m^2.h
= 15.223 kg/m^2 s

Therefore, the value of liquid mass transfer (kL) from equation 11 is as follows:

$$k_L(\frac{1032{,}04}{9{,}8 \times 0{,}00118})^{1/3}$$
$$= 0.0051\left(\frac{15{,}223}{91{,}75 \times 0{,}00118}\right)^{\frac{2}{3}} 448{,}37^{-0.5}(151 \times 0{,}04)^{0.4}$$
k_L = 2.99 x 10^{-4} m/s = 1.08 m/h

The calculation using equation 11 reveals evidence that the coefficient value of liquid mass transfer is inversely proportional to the Schmidt number. The Schmidt number is inversely proportional to the fluid diffusion coefficient. The resolution reached is that the greater the fluid diffusion coefficient, the greater the value of the fluid mass transfer coefficient.

Equation 13 can be used to determine the gas mass transfer coefficient (k_G).

$$k_G \frac{RT}{a_p D_G} = K_5\left(\frac{\bar{V}}{a_p \mu_G}\right)^{0.7} Sc_G^{1/3}(a_p d_p)^{-2} \quad (13)$$

The value of $\bar{V}$ can be calculated using the mechanical data sheet for the amine still as follows:
V = gas flow rate = 58,333.7 lb/h = 26,459.7 kg/h

$$\bar{V} = \frac{V}{\pi d^2/4} = \frac{26459{,}7}{\pi \times 2{,}794^2/4}$$
= 4315.6 kg/m^{2}h
= 1.2 kg/m^{2}s

Data for Raschig rings and saddles of less than 15 mm were correlated by conducting an alteration of the K_5 constant to 2. This change from k_Ga data for packing smaller than 15 mm tended to decrease constantly with increasing a_P. For IMTP 40, the K_5 constant used is 5.23.

Schmidt number (Sc_G) is determined using equation 14. The value of the Schmidt number (Sc_G) of the gas is 2.2773.

$$Sc_G = \mu_G/\rho_G D_G \quad (14)$$

From the mechanical data sheet for the amine still and the calculation from the previous section, the following number is obtained:
μ_G = gas viscosity = 0.016 cp = 1.6 x 10^{-5} kg/m.s
ρ_G = gas density = 0.1 lb/ft^3 = 1.705 kg/m^3
D_G = gas diffusion coefficient = 4.12 x 10^{-6} m^2/s
Therefore,

$$\mathrm{Sc}_G = \frac{1{,}6 \times 10^{-5}}{1{,}705 \times 4{,}12\mathrm{x}10^{-6}} = 2{,}277$$

The value of gas mass transfer coefficient (k_G) from equation 13 is as follows:

$$k_G \frac{0{,}08314 \times 362{,}6}{151 \times 4{,}12\mathrm{x}10^{-6}}$$
$$= 5{,}23\left(\frac{1{,}2}{151 \times 1{,}6\mathrm{x}10^{-5}}\right)^{0.7} 2{,}277^{1/3}(151 \times 0{,}04)^{-2}$$
k_G = 3 x 10^{-4} kmol/sm^2 bar = 1.08 kmol/hm^2 bar

The diffusion coefficient of the gas affects the value of the mass transfer coefficient. The greater the gas diffusion coefficient, the greater the value of the gas mass transfer coefficient.

3.4 Height transfer unit (HTUL) liquid and height transfer unit (HTUG) gas

Equation 15 is used to calculate the height transfer unit (HTU_L) for liquid. From the equation for height transfer unit (HTU_L) the value for fluid is 5.37 x 10^{-1} m.

$$HTU_L = \frac{L}{k_L a_W C_t} \quad (15)$$

in which
L = molar fluid flow rate per area (kmol/m^{2}s)
C_t = total concentration = ρ_L/molecular weight of the solution (kmol/m3)

$$\mathrm{HTU}_L = \frac{0{,}48}{1{,}08 \times 2{,}99\mathrm{x}10^{-4} \times 91{,}75 \times (1032{,}04/31{,}7)}$$
= 0.537 m

As depicted in equation 15, the liquid HTU is inversely proportional to the mass transfer coefficient of liquid. Thus, the higher (the more effective) the fluid mass transfer coefficient, the liquid HTU required will be smaller.

Equation 16 is used to calculate the gas height transfer unit (HTU_G). From the equation, HTU_L value of fluid is equal to 7.14 x 10^{-1} m.

$$HTU_G = \frac{G}{k_G a_W P} \quad (16)$$

where
G = gas molar flow rate per area (kmol/m^{2}s)
P = pressure of operation column (atm or bar)

$$HTU_V = \frac{0{,}0294}{3 \text{ x } 10^{-4} \times 91{,}5 \times 1{,}5}$$
= 0.71 m

Similar to liquid HTU, gas HTU is inversely proportional to the mass transfer coefficient of the gas. Thus, the higher (the more effective) the coefficient of mass transfer of gas the smaller the HTU of gas needed.

3.5 Calculation of equilibrium slope (myx)

The equilibrium curve for the linear desorption process for low-load component transfer in gas Y and in liquid X. In other words, the slope of m_{yx} in relation to Y = f (X) can be considered fixed. The equilibrium curve can be found using equation 17.

$$Y = m_{yx} X \quad (17)$$

The goal-seek value for high packing (H) is obtained in accordance with the design data for the HTU–NTU model to determine the height of bed packing. Overall height transfer unit (HTUo) for the liquid phase (HTU_{OL}) relates to the respective phases of HTU_V and HTU_L using stripping factor λ. High packing (H) is determined from the unit transfer in the liquid phase (NTU_{OL}). NTU_{OL} is a function of the load factor for liquid load components at both overhead (X_o) and bottom (X_u) levels and the load factor components of both the overhead (Y_o) and bottom (Y_u) levels.

From the flow diagram process the fraction of liquid mole data obtained are as follows:
x_o = 0.0287 (fraction at amine still operating pressure using HYSYS because the PFD data is still at high pressure).

x_u = 0.00085

therefore,

$$X_o = \frac{0{,}0287}{1-0{,}0287} = 0{,}0295$$

$$X_u = \frac{0{,}00085}{1-0{,}00085} = 0{,}0008507$$

$$Y = \frac{y}{1-y} \quad (18)$$

From the flow diagram process the fraction of liquid mole data obtained are as follows:

y_o = 0.5347
y_u = 0.00977

therefore,

$$Y_o = \frac{0{,}5347}{1-0{,}5347} = 1{,}15$$

$$Y_u = \frac{0{,}00977}{1-0{,}00977} = 0{,}00987$$

The value of ΔX_O and ΔX_U can be calculated by using the equation (19):

$$\Delta X_O = 0{,}0295 - \frac{1}{m_{YX}} 1{,}15 \quad (19)$$

$$\Delta X_U = 0{,}0008507 - \frac{1}{m_{YX}} 0{,}00987$$

The value of NTU_{OL} and HTU_{OL} is as follows:

$$NTU_{OL} = \frac{0{,}0295 - 0{,}00085}{\left(0{,}0295 - \frac{1}{m_{YX}}1{,}15\right) - \left(0{,}0008507 - \frac{1}{m_{YX}}0{,}00987\right)} \ln \frac{0{,}0295 - \frac{1}{m_{YX}}1{,}15}{0{,}0008507 - \frac{1}{m_{YX}}00987}$$

$$\gamma = m_{YX} \frac{1}{335996{,}3/26459{,}7} = 0{,}0787 m_{YX}$$

$$HTU_{OL} = 0{,}537 + \frac{1}{0{,}0787 m_{YX}} 0{,}714 = 0{,}537 + \frac{9{,}07}{m_{YX}}$$

A connection is apparent between the packing height values NTU_{OL} and HTU_{OL}. The height from the mechanical data sheet for the amine still is calculated as 12 m and the m_{YX} value can be determined by performing a goal-seek analysis. The analysis generates an m_{YX} value of 45. This value indicates that the gas phase transfer load component (Y) is higher than that of the liquid phase transfer load component (X) in both the overhead and bottom sides of the still. The transfer load component is a function of the mole fraction, which explains its greater magnitude in comparison to the liquid mole fraction. The amine still desorption process is the mass transfer of the CO_2 component from the liquid phase to the gas phase. Mass transfer occurs to achieve equilibrium both in the gas phase and liquid phase.

The slope value is a fixed variable used in high packing calculation design. Since the packing height serves as the design data, this slope will be used as a fixed variable of variation for the increase in concentration and the flow rate.

The following numbers are the value of NTU_{OL} and HTU_{OL} after determining the m_{YX} value:

ΔX_O = 0.0042
ΔX_U = 0.00063
γ = 2.786
NTU_{OL} = 15.13
HTU_{OL} = 0.79 m

Table 1. Results of equilibrium curve calculations

Parameter	Value
D_G	4.12 x 10^{-6} m^2/s
D_L	2.5457 x 10^{-9} m^2/s
a_w	91.75 m^2/m^3
k_G	1.08 kmol/h.m^2.bar
k_L	1.08 m/h
HTU_L	0.537 m
HTU_V	0.71 m
m_{YX}	45
NTU_{OL}	15.13
HTU_{OL}	0.79 m

3.6 Amine still design conditions for CO2 concentration in the amine still (xo)

We utilized the above design equations and results of equilibrium curve calculations to create differentiation for the liquid phase of CO_2 composition in the amine still (x_o) feed (rich amine). To ensure that the amine still fulfils the design conditions (12 m), a goal-seek analysis is performed for the liquid phase of CO_2 composition out of the amine still (x_u) (lean amine). The slope of the equilibrium curve in the desorption process can be considered constant at all concentrations from top to bottom of the amine still, hence the m_{yx} values can be used. The results of the x_o to x_u variations are as follows:

Table 2. Variation of x_o towards x_u

x_o	y_o	x_u	y_u
0.02870	0.5347	0.00085	0.0098
0.02899	0.5383	0.00090	0.0103
0.02927	0.5420	0.00095	0.0109
0.02956	0.5456	0.00101	0.0116
0.02985	0.5493	0.00107	0.0123
0.03014	0.5529	0.00114	0.0131
0.03042	0.5566	0.00121	0.0139
0.03071	0.5602	0.00129	0.0149
0.03100	0.5639	0.00138	0.0159

The x_o towards x_u graph obtained is presented in Figure 1. As depicted, an increase in x_o will lead to an increase in x_u. Mass transfer in the liquid phase uses concentration, which is not in an equilibrium state, as the driving force. Hence, a voltage gradient exists in the contact surface. This situation is also known as the Marangoni effect. Consequently, the voltage gradient increases the mass transfer rate.

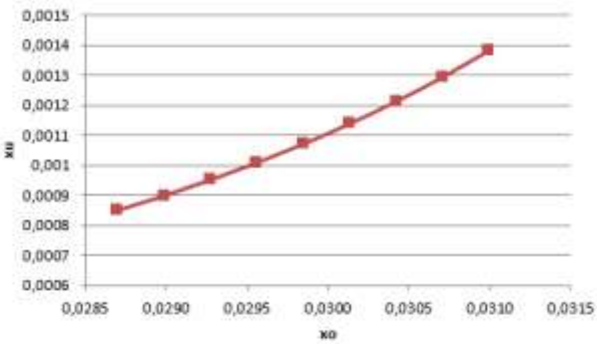

Fig. 1. Variation of x_o towards x_u

As shown in Figure 1, an increase in x_o will cause an increase in x_u, where the x_u result is still within the design boundary. The x_u result will exceed the design boundary (0.0013) at x_o value of above 0.0307. To sum up, with the flow rate of L and V equal to the design flow rate, the maximum of CO_2 composition in rich amine which can be treated by the amine still to produce the CO_2 composition of lean amine which is still in conformity with the design is 0.0307.

Table 3. Variation of flow rate to x_u (x_o = 0.029)

L (kg/h)	V (kg/h)	Total flow rate (kg/h)	x_u	y_u
335,996.3	26,459.7	362,456.0	0.00090	0.0104
369,595.9	29.105.7	398,701.6	0.00094	0.0109
403,195.5	31,751.6	434,947.2	0.00099	0.0113
436,795.2	34,397.6	471,192.8	0.00103	0.0118
470,394.8	37,043.6	507,438.4	0.00106	0.0122
503,994.4	39,689.6	543,684.0	0.00110	0.0127
537,594.0	42,335.5	579,929.6	0.00114	0.0131
571,193.7	44,981.5	616,175.2	0.00117	0.0135
604,793.3	47,627.5	652,420.8	0.00121	0.0139
638,392.9	50,273.4	688,666.4	0.00124	0.0143
671,992.6	52,919.4	724,912.0	0.00128	0.0147
705,592.2	55,565.4	761,157.6	0.00131	0.0150
739,191.8	58,211.4	797,403.2	0.00134	0.0154
772,791.4	60,857.3	833,648.8	0.00137	0.0157
806,391.1	63,503.3	869,894.4	0.00140	0.0161

3.7 Amine still design condition towards flow rate

The variation of the amine still design to the flow rate serves as a way to obtain the x_u value of 0.0013 mole fraction, which happens to be the maximum value of CO_2 allowed in lean amine. The value of the CO_2 composition in the liquid phase at the bottom of the packing (x_u) with a maximum limit value of 0.0013 in each variation.

Table 4. Variation of flow rate to x_u ($x_o = 0.0295$)

L (kg/h)	V (kg/h)	Total flow rate (kg/h)	x_u	y_u
335,996.3	26,459.7	362,456.0	0.00100	0.0114
369,595.9	29,105.7	398,701.6	0.00104	0.0120
403,195.5	31,751.6	434,947.2	0.00109	0.0125
436,795.2	34,397.6	471,192.8	0.00113	0.0130
470,394.8	37,043.6	507,438.4	0.00117	0.0135
503,994.4	39,689.6	543,684.0	0.00121	0.0139
537,594.0	42,335.5	579,929.6	0.00125	0.0144
571,193.7	44,981.5	616,175.2	0.00129	0.0148
582,953.5	45,907.6	628,861.1	0.00130	0.0150
604,793.3	47,627.5	652,420.8	0.00132	0.0152
638,392.9	50,273.4	688,666.4	0.00136	0.0156
671,992.6	52,919.4	724,912.0	0.00139	0.0160

Table 5. Variation of flow rate to x_u ($x_o = 0.03$)

L (kg/h)	V (kg/h)	Total flow rate (kg/h)	x_u	y_u
335,996.3	26,459.7	362,456.0	0.00111	0.0127
369,595.9	29,105.7	398,701.6	0.00116	0.0133
403,195.5	31,751.6	434,947.2	0.00120	0.0138
436,795.2	34,397.6	471,192.8	0.00125	0.0144
470,394.8	37,043.6	507,438.4	0.00129	0.0149
476,442.7	37,519.9	513,962.6	0.00130	0.0150
503,994.4	39,689.6	543,684.0	0.00134	0.0154
537,594.0	42,335.5	579,929.6	0.00138	0.0158
571,193.7	44,981.5	616,175.2	0.00142	0.0163

Table 6. Variation of flow rate to x_u ($x_o = 0.0305$)

L (kg/h)	V (kg/h)	Total flow rate (kg/h)	x_u	y_u
335,996.3	26,459.7	362,456.0	0.00123	0.0142
342,716.2	26,988.9	369,705.1	0.00124	0.0143
349,436.1	27,518.1	376,954.2	0.00126	0.0144
356,156.1	28,047.3	384,203.3	0.00127	0.0146
362,876.0	28,576.5	391,452.5	0.00128	0.0147
369,595.9	29,105.7	398,701.6	0.00129	0.0148
376,315.8	30,428.7	406,744.5	0.00130	0.0149
379,675.8	29,899.5	409,575.3	0.00130	0.0150
383,035.8	30,164.1	413,199.8	0.00131	0.0150
403,195.5	31,751.6	434,947.2	0.00134	0.0154
436,795.2	34,397.6	471,192.8	0.00139	0.0160

Using the above equations and m_{yx} results, variations in flow rates (L and V) are performed for the amine still with different x_o values. The slope of the equilibrium curve in the desorption process can be considered constant at all concentrations from top to bottom of the amine still so that the m_{yx} values of the calculations can be used.

The x_o value used is between the design value (0.0287) and the maximum value (0.0307). Table 3 shows the variation at x_o of 0.029. Table 4 shows the variation at x_o of 0.0295. Table 5 presents the variation at x_o of 0.03. Table 6 demonstrates the variation at x_o of 0.0305. A goal-seek analysis was then performed on the liquid phase CO_2 composition out of the amine still (x_u) (lean amine) so that the high amine still remained in accordance with the design (12 m).

The total flow rates of x_u obtained are as presented in Figure 2. As demonstrated, the increase in flow rate will cause an increase in x_u. This occurs because the increase in flow rate causes fluid turbulence inside the column to increase. In turbulent flow, the molecules in the fluid will move in any direction, increasing the rate of collision between them and these collisions form gaps where the gas will be trapped. This causes increased mass transfer from one phase to another.

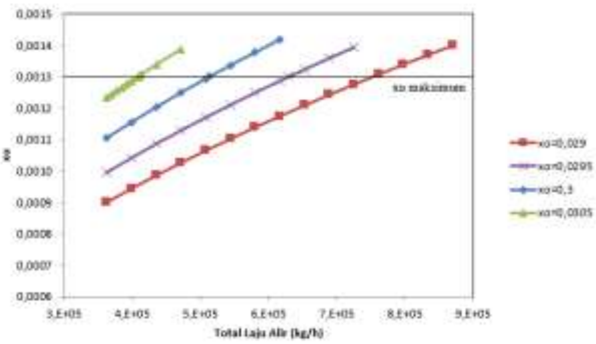

Fig. 2. Variation of flow rate of x_u for several x_o values

Table 7 presents the maximum total flow rate that can be separated by the amine still with CO_2 feed composition in liquid phase (x_o). The value of CO_2 composition in the liquid phase at the bottom part of the packing (x_u) exceeds the maximum limit value of 0.0013 in each variation. The higher the value of x_o, the lower the maximum flow rate. The assorted CO_2 feed (x_o) composition contributes to the maximum total flow rate that can be separated, so as to produce lean amine as per specifications which will be lower for large x_o values.

Table 7. Maximum total flow rate value based on the x_o value

x_o	Maximum flow rate (kg/h)
0.029	761,157.6
0.0295	628,861.1
0.03	513,962.6
0.0305	409,575.3

At the value of CO_2 of rich amine of x_o = 0.029, the total flow rate value is 761.157.6 kg/hour. At the value of CO_2 rich amine of x_o = 0.0295, the total flow rate value is

628.861.1 kg/hour. At the value of CO_2 rich amine of x_o = 0.03, the total flow rate value is 513.962.6 kg/hour. At the value of CO_2 rich amine of x_o = 0.0305, the total flow rate value is 409.575.3 kg/hour.

4 Conclusion

This study attempts to analyze the correlation between amine still design in Field X and increase in CO_2. Utilizing HTU and NTU designs, the findings suggest that an equilibrium curve slope (m_{yx}) in the amine still desorption process of 45 is acquired from the data and design equation. The maximum liquid CO_2 composition of the amine still (x_o) feedstock which can be separated to produce lean amine according to the specification (maximum x_u 0.01 mol/mol MDEA of 0.0013 mole fraction) for the design flow rate is 0.0307. The total flow rate of CO_2 rich amine at x_o = 0.029 is 761,157.6 kg/hour. The total flow rate of CO_2 rich amine (x_o = 0.0295) is 628,861.1 kg/hour. The total flow rate of CO_2 rich amine (x_o = 0.03) is 513,962.6 kg/hour. The total flow rate of CO_2 rich amine (x_o = 0.0305) is 409,575.3 kg/hour.

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