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Modelling and Optimization of Natural Gas Sweetening Unit Using Piperazine-Activated Methyldiethanolamine as Solvent

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Abstract
*A kinetic model for prediction and performance optimization of an 80-barg high pressure, high capacity, natural gas sweetening columns using the electrical conductivity properties (in conjunction with other process datasets such as concentration, circulation rate, pH, temperature, pressure, and CO_2 content) has been developed. Findings reveal a strong negative correlation coefficient (-0.9742759) between piperazine-activated methyldiethanolamine (PZ-Activated MDEA) concentration and electrical conductivity. A predictive model expressed as (**y**=54.8848602+(-0.017323229)**x**) determines and enhances the optimal operating conditions, enabling real-time monitoring and automatic intervention. The post-optimization results suggest a significant improvement in CO_2 absorption efficiency which is exemplified in the characteristic reduction in the lean gas average residual CO_2 content from 1,368.74 ppm to 248.06 ppm commercial quality. Other key improvements include an increase in the PZ+MDEA stream average concentration from 36.47 g/100ml to 42.66 g/100ml and a notable amine outlet stream temperature rise (+6°C) alongside a pH reduction of 2.37 due to enhanced absorption. These adjustments led to a leap in CO_2 removal efficiency from 93.06% to 98.75% within a 14-day interval, effectively minimizing the production of lean natural gas with high CO_2 levels.*

Keywords: *Natural gas sweetening; kinetic modelling; electrical conductivity effect; Piperazine-Activated Methyldiethanolamine.*

1.0 Introduction

Gas sweetening plays a crucial role in the removal of acid gases (H_2S and CO_2) from natural gas streams, enhancing its quality and marketability. Among the various amine-based processes, the Piperazine-Activated Methyldiethanolamine (PZ+MDEA) system has gained significant attention due to its high CO_2 absorption capacity, excellent H_2S selectivity, and reduced corrosion potential (Berchiche, *et al.,* 2023). The optimization of PZ-Activated MDEA absorption units is essential to improve process efficiency, reduce operating costs, and meet environmental regulations. This paper presents a detailed kinetic model for the lean PZ+MDEA inlet system, which accurately captures the complex chemical reactions and mass transfer processes involved in the gas sweetening unit. The model is validated against experimental data from industrial-scale PZ+MDEA packed columns, demonstrating its high predictive capabilities. (Wehrung *et al.*, 2023;

Zhan *et al.*, 2023). This work presents results of a predictive model and optimization for the absorption of CO_2 into PZ activated MDEA solvent.

2.0 Methodology

From the bottom tray of the absorption column, and assuming a binary component, the rich natural gas stream is fed and flows upward counter-currently to the lean Piperazine-AQctivated Methyldiethanolamine solution, and when carbon dioxide (CO_2) is absorbed into the mixture of the down-flowing Piperazine ($C_4H_{10}N_2$), Methane based tertiary alkanol amine R1 R2 R3 N and demineralized water blend or PZ+MDEA solution, several reversible proton transfer exothermic reactions take place and MDEA, water, carbamate or bicarbamate products with water are formed. (Valluri, and Kawatra, 2021). Typical chemistry of this reaction is shown below (see reactions 1 to 11).

$$CO_2 + R_1R_2R_3N + H_2O \xleftrightarrow{K_1.K_{21}} R_1R_2R_3NH^+ + HCO_3^- \quad (1)$$
$$CO_2 + PZ + H_2O \xleftrightarrow{K_2.K_{22}} PZCOO^- + H_3O^+ \quad (2)$$
$$CO_2 + R_1R_2R_3N + PZ \xleftrightarrow{K_3.K_{23}} PZCOO^- + R_1R_2R_3NH^+ \quad (3)$$
$$CO_2 + PZCOO^- + H_2O \xleftrightarrow{K_4.K_{24}} PZ(COO^-)_2 + H_3O^+ \quad (4)$$
$$CO_2 + R_1R_2R_3N + PZCOO^- \xleftrightarrow{K_5.K_{25}} PZ(COO^-)_2 + R_1R_2R_3NH^+ \quad (5)$$
$$CO_2 + OH^- \xleftrightarrow{K_6.K_{26}} HCO_3^- \quad (6)$$
$$HCO_3^- + H_2O \overset{K_7}{\leftrightarrow} CO_3^{2-} + H_3O^+ \quad (7)$$
$$PZ + H_3O^+ \overset{K_8}{\leftrightarrow} PZH^+ + H_2O \quad (8)$$
$$PZCOO^- + H_3O^+ \overset{K_9}{\leftrightarrow} PZH^+COO^- + H_2O \quad (9)$$
$$R_1R_2R_3N + H_3O^+ \overset{K_{10}}{\leftrightarrow} R_1R_2R_3NH^+ + H_2O \quad (10)$$
$$2H_2O \overset{K_{11}}{\leftrightarrow} H_3O^+ + OH^- \quad (11)$$

2.1 Correlation Coefficient, *r*

Correlation Coefficient, r:

$$r = \frac{(n(\sum xy)) - ((\sum x)(\sum y))}{\sqrt{\left((n(\sum x^2)) - ((\sum x)^2)\right)(n(\sum y^2) - (\sum y)^2)}} \quad (12)$$

where:

n = number of observations

x = Independent continuous level variable (Activated Methyl-di-ethanolamine) a-MDEA concentration.

y = Dependent continuous level variable (Activated Methyl-di-ethanolamine) a-MDEA electrical conductivity.

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{\left((n(\sum x^2))-((\sum x)^2)\right)(n(\sum y^2)-(\sum y)^2)}} \tag{13}$$

$$= \frac{15(586{,}363.06)-(526.73)(17{,}132)}{\sqrt{(15(18{,}774.3)-(526.73)^2)(15(20{,}446{,}358)-(17{,}132.0)^2}} \tag{14}$$

$$= \frac{8{,}795{,}445.9-9{,}023{,}938.36}{\sqrt{(281{,}614.5-277{,}444.493)(306{,}695{,}370-293{,}505{,}424)}} \tag{15}$$

$$= \frac{-228{,}492.46}{\sqrt{(4{,}170.007)(13{,}189{,}946)}} = \frac{-228{,}492.46}{\sqrt{55{,}002{,}167{,}149.622}} = \frac{-228{,}492.46}{234{,}525.4083} \tag{16}$$

$\boldsymbol{r = -0.9742759}$ (Very strong negative correlation coefficient) (17)

The test statistics are in the critical region at the left-hand end of the correlation coefficient scale range. The test result of $\boldsymbol{-0.9742759}$ is greater than the critical value, thus there is significant evidence:

$$\boldsymbol{r^2} = 0.949213585 \tag{18}$$

$$\boldsymbol{r^2} = \boldsymbol{95.}\% \tag{19}$$

$$y = a + bx \tag{20}$$

where:

y = Line of Regression (Least Squares Line)

a = The y Intercept *(the value of y or a-MDEA concentration, when x or a-MDEA conductivity is/equals zero).*

b = Slope of the Line *(the increase in y or a-MDEA concentration, for every 1 unit increase in x or a-MDEA conductivity).*

y = Activated Methyl-di-ethanolamine (a-MDEA) *concentration* (Dependent variable)

x = Activated Methyl-di-ethanolamine (a-MDEA) *conductivity* (Independent variable).

$\bar{x}$ = Activated Methyl-di-ethanolamine *conductivity* or mean of Independent variable.

$\bar{y}$ = Activated Methyl-di-ethanolamine *concentration* or mean of Dependent variable.

n = number of sets of observations.

$$b = \frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2} \quad (21)$$

$$b = \frac{15(586{,}363.06) - (17{,}132.0)(526.73)}{15(20{,}446{,}358.0) - (17{,}132.0)^2} \quad (22)$$

$$b = \frac{8{,}795{,}445.9 - 9{,}023{,}938.36}{306{,}695{,}370 - 293{,}505{,}424} = \frac{-228{,}492.46}{13{,}189{,}946} \quad (23)$$

$$\boldsymbol{b = -0.017323229} \quad (24)$$

$$a = \bar{y} - b\bar{x} \quad (25)$$

$$a = 35.1 - (-0.017323229) * 1{,}142.1 \quad (26)$$

$$a = 35.1 - (-19.784860269) = 54.8848602 \quad (27)$$

$$\boldsymbol{a = 54.8848602} \quad (28)$$

Regression (y)

$$y = a + bx \quad (29)$$

Regression $\boldsymbol{y} = 54.8848602 + (\boldsymbol{-0.017323229})\boldsymbol{x}$ (30)

The equation above can predict with 95% accuracy (5% margin of error) the a-MDEA concentrations (lean or rich) from the amine electrical conductivity or vice-versa.

Where:

(y) = Piperazine activated Methyl-di-ethanolamine (a-MDEA) concentration in (g/100ml).

(x) = Piperazine-activated Methyl-di-ethanolamine (a-MDEA) conductivity micro S/cm

The a-MDEA **concentration value or y when x (conductivity) is 694?**

$$y = 54.8848602 + (\mathbf{-0.017323229})x \quad (31)$$

$$y = 54.8848602 + (\mathbf{-0.017323229})(\mathbf{694}) \quad (32)$$

$$y = 54.8848602 + (-12.022321) \quad (33)$$

Regression (y) = **42.86254 (g/100ml)** (34)

Therefore, **694 micro S/cm** increase in the Piperazine-Activated Methyldiethanolamine (MDEA) electrical conductivity will result in **42.86254 g/100ml** change in the activated Piperazine-Activated Methyldiethanolamine sample concentration.

Conversely to solve for (x) = Piperazine-activated Methyl-di-ethanolamine (a-MDEA) conductivity in micro S/cm:

$$42.86254 = 54.8848602 + (-0.017323229)x \quad (35)$$

$$42.86254 = 54.8848602 - 0.017323229x \quad (36)$$

$$42.86254 = -0.017323229x + 54.8848602 \quad (37)$$

$$42.86254 + (-54.8848602) = (-0.017323229x + 54.8848602) + (-54.8848602) \quad (38)$$

$$42.86254 - 54.8848602 = -0.017323229x + 54.8848602 - 54.8848602 \quad (39)$$

$$-12.0223202 = 0.017323229x \quad (40)$$

$$-0.017323229x = -12.0223202 \quad (41)$$

$$\frac{0.017323229x}{0.017323229} = \frac{12.0223202}{0.017323229} \quad (42)$$

$$x = \frac{12.0223202}{0.017323229} \quad (43)$$

$$x = 693.999958 \quad (44)$$

Piperazine-Activated Methyl-di-ethanolamine (MDEA) conductivity = 694.0 micro S/cm

3.0 Results

1. **CO_2 Absorption Column-A Pre-optimization PZ+MDEA Inlet and Outlet Conductivity and Concentration Difference:**

The CO_2 Absorption Unit consist of parallel operating column-A/B/C with separate natural gas, and amine inlet and outlet spools from the main Header, while unit-C was on stand-by, the CO_2 Absorption Column-A, pre-optimization Piperazine-activated Methyldiethanolamine inlet stream analyzed average electrical conductivity at 25^{o}C 1,112.14 micro S/cm and outlet 11,767.6 micro S/cm at 36.40 g/100ml inlet and 35.01 g/100ml outlet solution concentration within the initial 14 days observational period.

2. **CO_2 Absorption Column-A Pre-optimization PZ+MDEA Inlet and Outlet pH and Temperature Difference:**
   The Absorption Column-A, pre-optimization Piperazine-activated Methyl-di-ethanolamine inlet and outlet stream analysed pH and temperature difference, there was an average 6^{o}C gain on the outlet stream with a corresponding decrease of 2 on the pH scale within the 14-day observational period.

3. **CO_2 Absorption Column-A Post-optimization PZ+MDEA Inlet and Outlet pH and Temperature Difference:**
   The Absorption Column-A, post-optimization Piperazine-activated Methyl-di-ethanolamine inlet and outlet stream analysed pH and temperature difference, there was an average 6.8^{o}C gain on the outlet stream with a corresponding decrease of 2.2 on the pH scale within the final 14-day observational period.

4. **CO_2 Absorption Column-B Pre-optimization PZ+MDEA Inlet and Outlet Conductivity and Concentration Difference:**
   The Absorption Column-B, pre-optimization Piperazine-activated Methyl-di-ethanolamine inlet stream analyzed average electrical conductivity at 25^{o}C of 1,023.40 micro S/cm and outlet stream conductivity of 9,074.29 micro S/cm at 36.37 g/100ml amine inlet strength, and corresponding 35.16 g/100ml outlet solution concentration within the initial assessment period.

5. **CO_2 Absorption Column-B Pre-optimization PZ+MDEA Inlet and Outlet pH and Temperature Difference:**
   The Absorption Column-B, pre-optimization Piperazine-activated Methyl-di-ethanolamine inlet and outlet stream analysed pH and temperature profiles relationship, there was an average 6^{o}C increase on the outlet stream with a corresponding decrease of 1.9 on the pH scale within the initial 14-day period.

6. **CO_2 Absorption Column-B Post-optimization PZ+MDEA Inlet and Outlet pH and Temperature Difference:**
   The Absorption Column-B, post-optimization Piperazine-activated Methyl-di-ethanolamine inlet and outlet stream analysed pH and temperature assessment, there was an average 6.1^{o}C improvement on the outlet stream with a corresponding decrease of 2.23 on the pH scale within the final 14-day period.

7. **CO_2 Absorption Column-A/B Pre and Post-optimization PZ-MDEA Inlet Conductivity Average Difference:**
   The Absorption Column-A/B, pre-optimization Piperazine-activated Methyl-di-ethanolamine inlet stream electrical conductivity variable analyzed at 25^{o}C of 1,069.1 and 1,142.1 micro S/cm relationship, with an analyzed average amine concentration inlet stream of 36.47 g/100ml declining in the opposite directions, occasionally crossing path near the optimal values and drifting wider apart from the mean.

8. **CO_2 Absorption Column-A/B Pre and Post-optimization PZ-MDEA Inlet Concentration Average Difference:**
   The Absorption Column-A/B, average pre-optimization Piperazine-activated Methyl-di-ethanolamine intlet stream analyzed concentration of 36.47 g/100ml is relatively lower than the post-optimization 42.66 g/100ml outlet stream average, figure-1.

9. **CO_2 Absorption Column-A/B Pre and Post-optimization PZ-MDEA Inlet Conductivity Average Response:**
   Absorption Column-A/B, Pre-optimization Piperazine-activated Methyl-di-ethanolamine inlet stream analysed average electrical conductivity at 25^{o}C of 697.85 micro S/cm relationship with the post-optimization PZ+MDEA inlet stream average concentration of 42.66 g/100ml converges more at the optimal values near the centre, same response holds for the PZ+MDEA outlet average electrical conductivity of 1,293.5 micro S/cm at 41.0 g/100ml strength.

10. **CO_2 Absorption Column-A/B Pre-optimization PZ-MDEA Inlet Conductivity and Concentration, Correlation, Regression and Mathematical Model:**
    Absorption Column-A/B pre-optimization Piperazine-activated Methyl-di-ethanolamine inlet stream analyzed electrical conductivity and concentration average data analysis resulted in a very strong negative correlation coefficient of -0.9742, a regression linear relationship of 0.9491 and a mathematical model expressed as $y = 54.8848602 - 0.017323229x$.

11. **CO_2 Absorption Column-A/B Post-optimization PZ-MDEA Inlet Conductivity and Concentration, Correlation and Regression:**
    Absorption Column-A/B post-optimization Piperazine-activated Methyl-di-ethanolamine inlet stream analyzed electrical conductivity and concentration average results data analysis reported an improved very strong negative correlation coefficient of -0.992447762 and a linear regression relationship of 0.985.

12. CO_2 Absorption Column-A/B Post-optimization PZ-MDEA Inlet Conductivity Model Data Validation Differential:

Absorption Column-A/B post-optimization Piperazine-activated Methyl-di-ethanolamine inlet stream average electrical conductivity model data was validated against analyzed data and closely matched the laboratory observed values at an average differential of 7.843 micro S/cm.

Table 1.0: Absorption Column-A/B PZ-Activated MDEA Conductivity Vs Concentration Inlet ***(equation 14)***

Date	n (Observations)	PZ+MDEA (Inlet) Conductivity Analyzed (micro S/cm) x	PZ+MDEA (Inlet) Concentration Analyzed (g/100ml) y	y_i^2	x_i^2	$(x_i * y_i)$
Day-1	1	1,460.0	28.82	2,131,600.0	830.6	42,077.20
Day-2	2	1,425.0	29.52	2,030,625.0	871.4	42,066.00
Day-3	3	1,414.0	30.23	1,999,396.0	913.9	42,745.22
Day-4	4	1,383.0	30.69	1,912,689.0	941.9	42,444.27
Day-5	5	1,351.0	31.86	1,825,201.0	1,015.1	43,042.86
Day-6	6	1,320.0	33.04	1,742,400.0	1,091.6	43,612.80
Day-7	7	1,289.0	34.21	1,661,521.0	1,170.3	44,096.69
Day-8	8	1135.00	34.96	1,288,225.0	1,222.2	39,679.60
Day-9	9	1,048.0	35.38	1,098,304.0	1,251.7	37,078.24
Day-10	10	994.00	35.85	988,036.0	1,285.2	35,634.90
Day-11	11	961.0	39.34	923,521.0	1,547.6	37,805.74
Day-12	12	924.0	39.58	853,776.0	1,566.6	36,571.92
Day-13	13	922.0	40.30	850,084.0	1,624.1	37,156.60
Day-14	14	812.0	40.54	659,344.0	1,643.5	32,918.48
Day-15	15	694.00	42.41	481,636.0	1,798.6	29,432.54
TOTAL: ∑		17,132.0	526.73	20,446,358.0	18,774.3	586,363.06
Mean (μ):		1,142.1	35.1			

The study found that Piperazine-Activated Methyldiethanolamine (PZ+MDEA) exhibits a strong negative correlation (-0.9742) between electrical conductivity and concentration, which shifts to a highly negative correlation (-0.992447762) after optimization (figure-7), as validated by comprehensive experiments including linear regression and sensitivity analysis of process variables (Abdulkhaleq, 2016). Absorption Column-A pre-optimization showed an inlet and outlet electrical conductivities of 1,112.14 and 11,777.86 micro S/cm (figure-6), respectively, with slight decreases in solution concentration from inlet to outlet and a notable 6°C temperature increase in the outlet stream, alongside a 2-point pH decrease (figure-2&3). These findings relationship pattern were consistent with unit-B response over the 28-day investigation period, and highlight the significant impact of PZ+MDEA on the post- optimization.

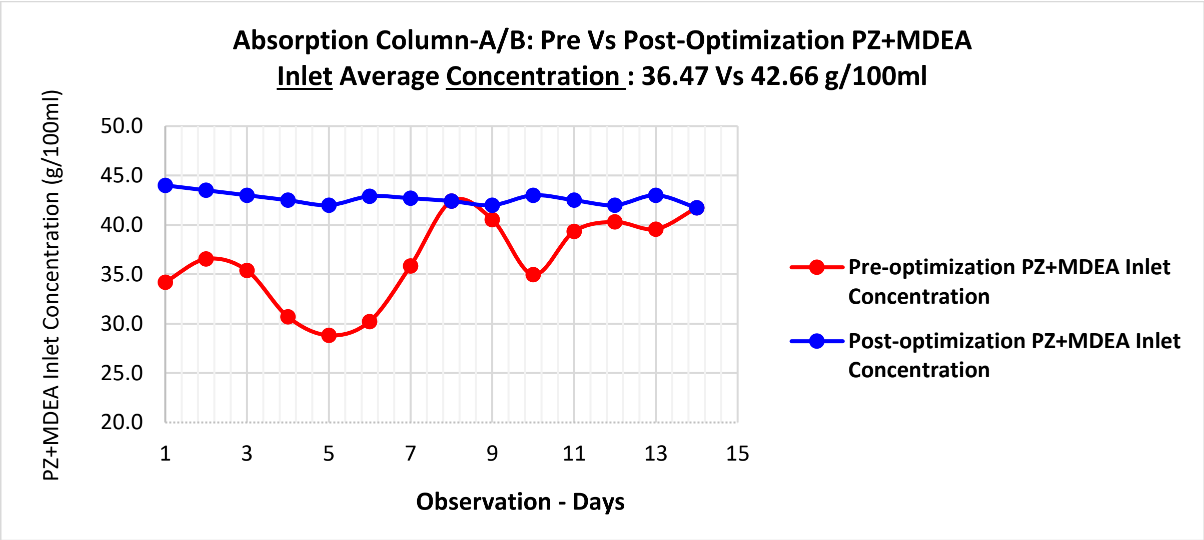

Figure 1.0: Column-A/B: Pre-Post-Optimization PZ+MDEA Inlet Concentration

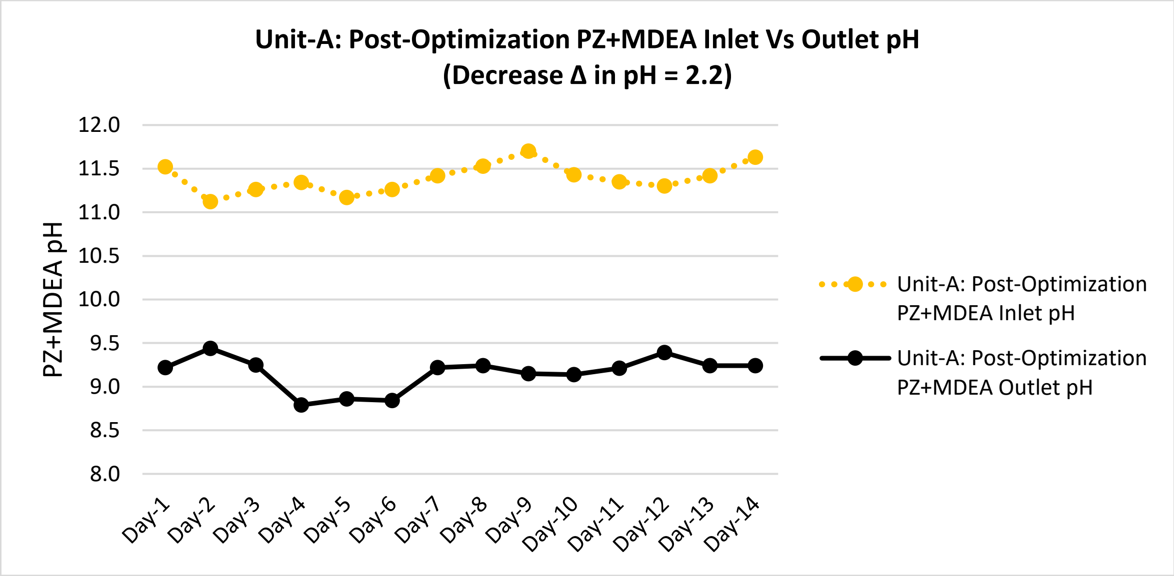

Figure 2.0: Column-A: Post-Optimization PZ+MDEA Inlet/Outlet pH

The observed elevation in Absorption Column-A/B pre-optimization PZ+MDEA outlet electrical conductivity average from 1,112.14 micro S/cm at the inlet to 11,777.86 micro S/cm at the outlet (figure-6), alongside the decline in lean amine inlet concentration from 36.47 g/100ml to 35.04 g/100ml (figure-1&5), a decrease in pH (figure-2&3), and a rise in outlet temperature, can be attributed to the CO_2 absorption by the PZ+MDEA solution through a base-hydration mechanism. This process, an exothermic reaction, not only strips the CO_2 from the incoming rich natural gas but also increases PZ+MDEA outlet acidity, as evidenced by the lower pH values observed (Ullah, 2022).

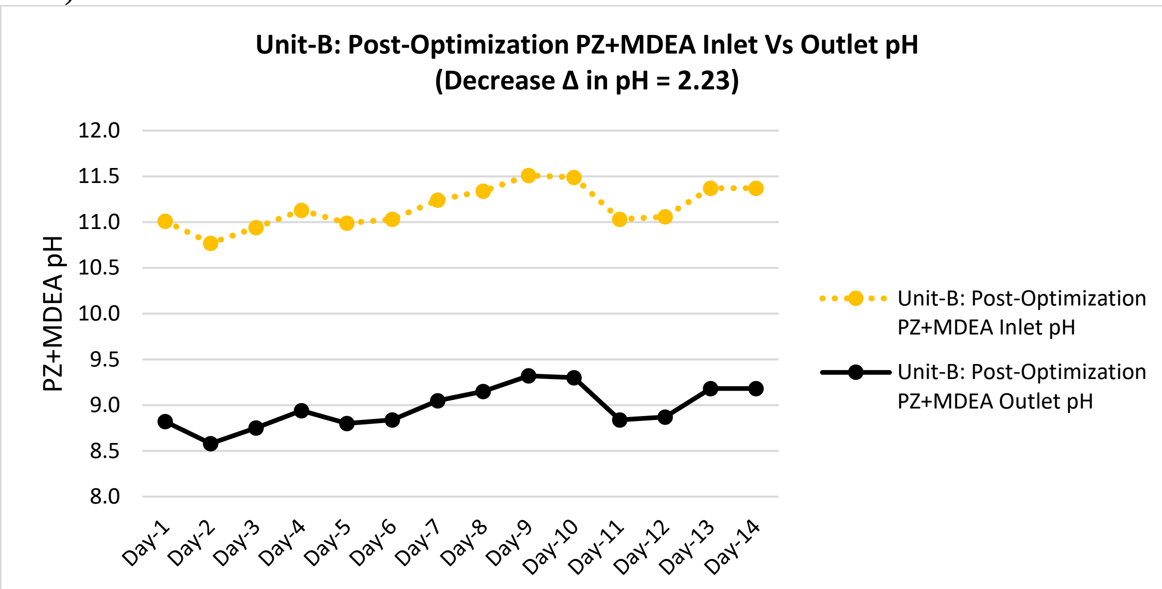

Figure 3.0: Column-B: Post-Optimization PZ+MDEA Inlet/Outlet pH

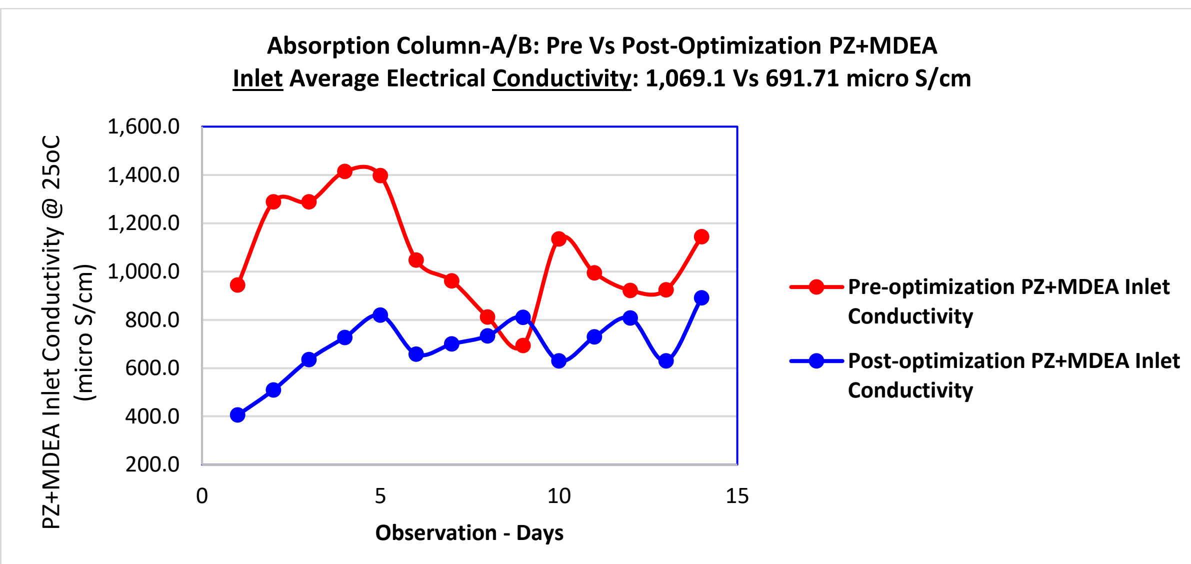

Figure 4.0: Column-A/B: Pre-Post-Optimization PZ+MDEA Inlet Conductivity

An analysis of the Piperazine-activated Methyl-di-ethanolamine (PZ-MDEA) mixture in an absorption column pre-optimization study revealed a strong negative correlation (-0.9742) between electrical conductivity and concentration (figure-7). Utilizing a regression model (Famoye & Singh, 2021) and a mathematical formula (Peng *et al.*, 2021), the optimal concentration range for PZ-MDEA was identified as 40 – 45 g/100ml. This concentration ensures optimal CO_2 removal efficiency, monitored and regulated via inline sensors (Steinhauser *et al.*, 2020) and a feedback control system (Chen *et al.*, 2021). The PZ+MDEA inlet stream average electrical conductivity model predicted data was validated against the analyzed data, and showed a very close match at an average differential of 7.843 micro S/cm thus highlighting (figure-8) the reliability and significance of the model and inline monitoring automated system. (Pan *et al.*, 2022).

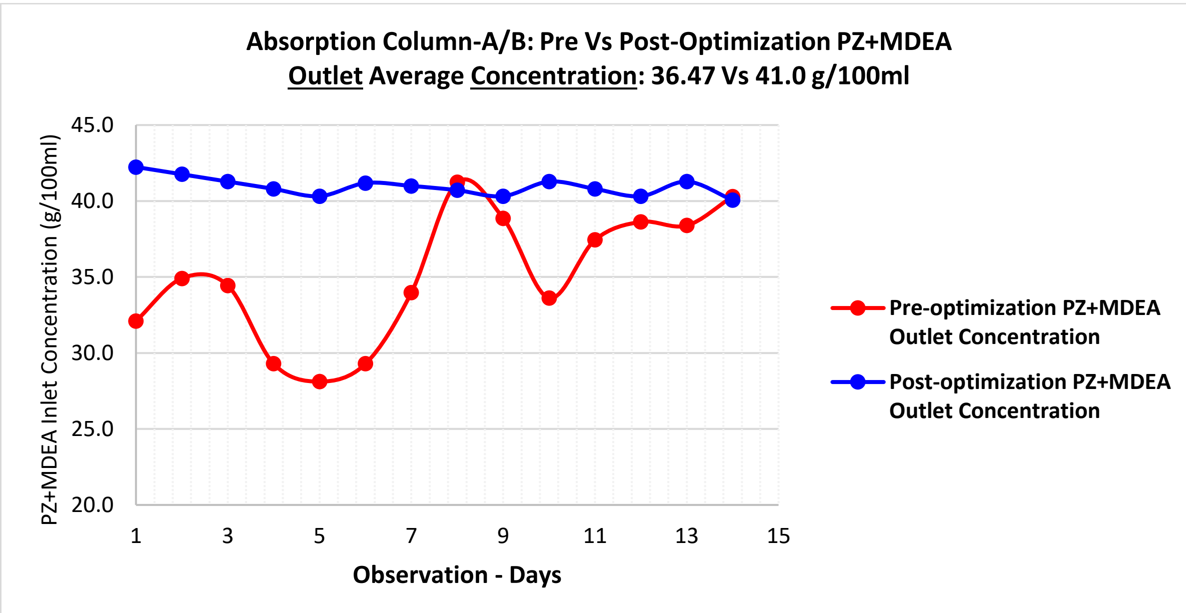

Figure 5.0: Column-A/B: Pre-Post-Optimization PZ+MDEA Outlet Concentration

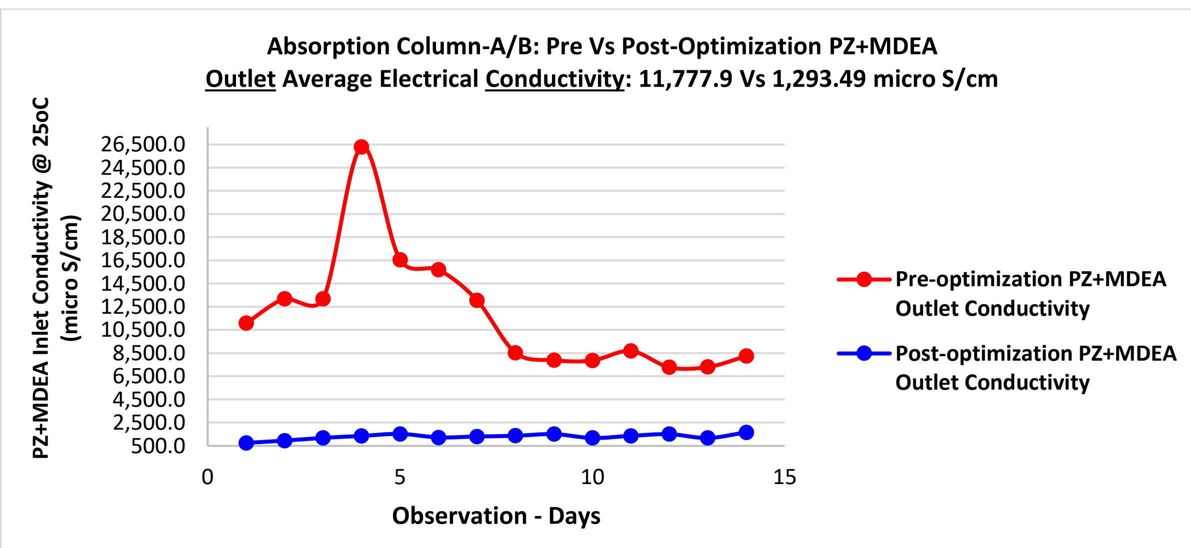

Figure 6.0: Column-A/B: Pre-Post-Optimization PZ+MDEA Outlet Conductivity -Average

After optimizing the absorption column-A/B, the rich natural gas inlet flow-rate average was maintained at 155,000.0 std m3/hr, with a CO_2 concentration of 19,675.01ppm threshold limit (Shankar *et al.*, 2022). Post-optimization, the average concentration of the PZ+MDEA solution inlet stream increased from 36.47 g/100ml to 42.66 g/100ml, improving its efficiency (Khan *et al.*, 2017). Additionally, there was a notable increase in the amine outlet stream's temperature by +6°C and a decrease in pH by 2.37, facilitated by an automatic inline monitoring system (Huang *et al.*, 2017; Penn & Camberato, 2019). These adjustments helped reduce the CO_2 content in the produced gas from 1,368.74ppm to 248.06ppm average (figure-9&10), effectively preventing the production of off-specification sweet natural gas with high CO_2 levels (Sahl *et al.*, 2021). As a result, the unit's performance was optimized from 93.06% to 98.75%, marking a 5.69% improvement within a 14-days post-optimization period (Zhang *et al.*, 2023).

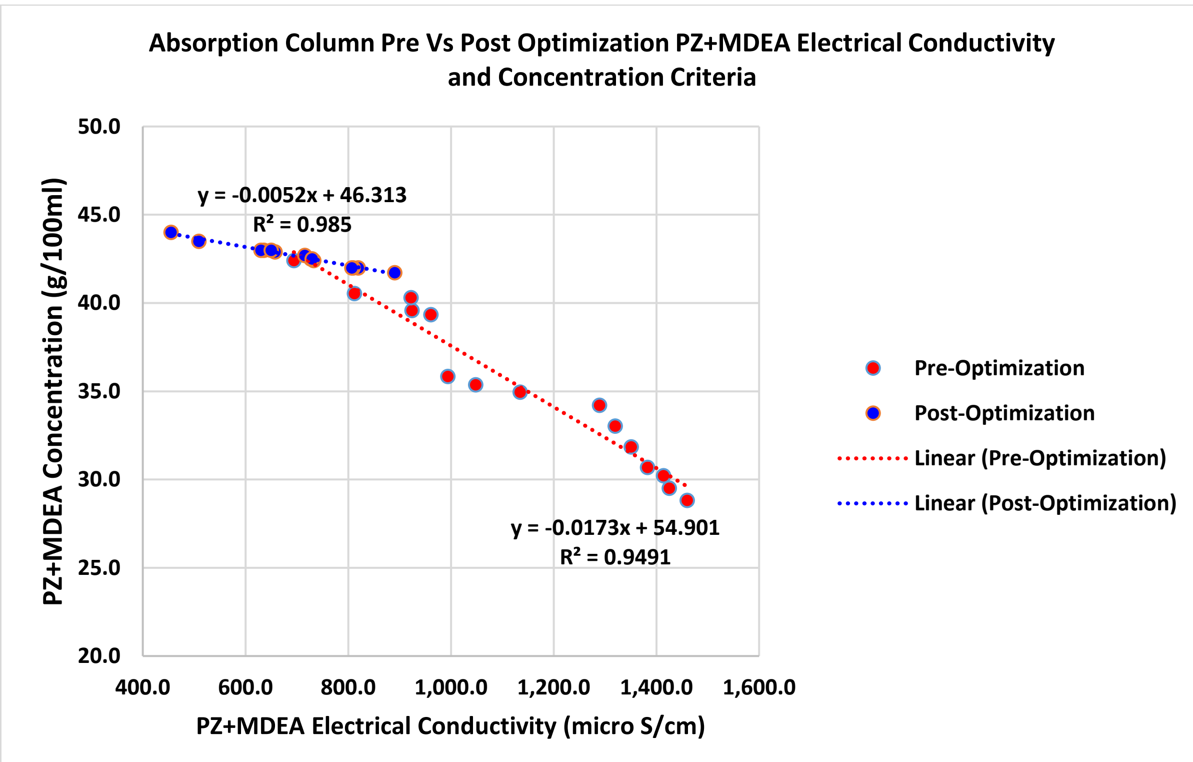

Figure 7.0: Column-A/B: Pre Vs Post-optimization PZ+MDEA Inlet variables scatter plot

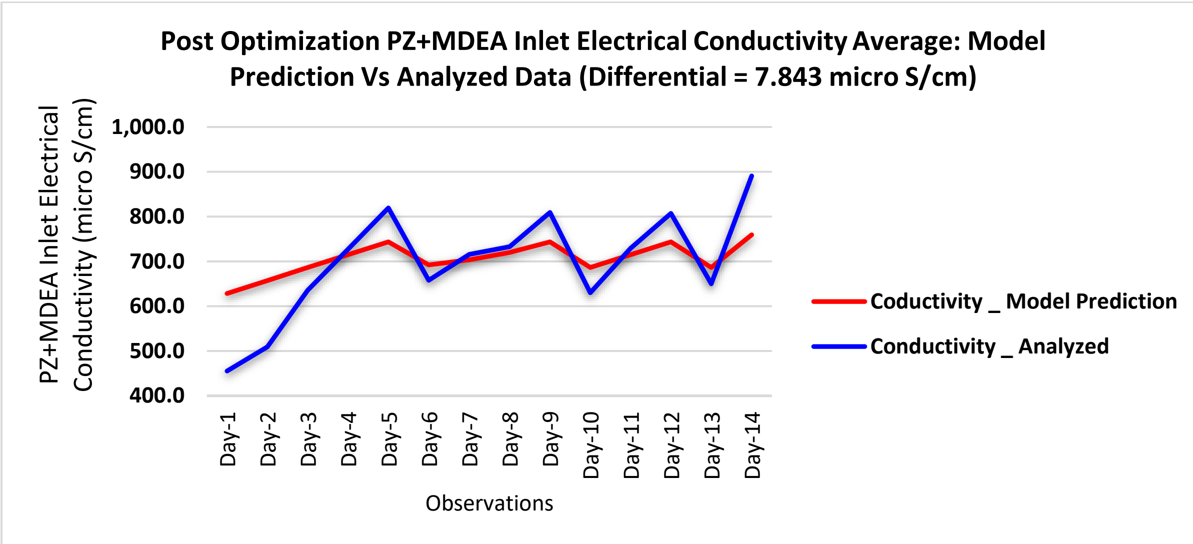

Figure 8.0: Column-A/B: Post-optimization PZ+MDEA inlet conductivity model Vs analyzed data

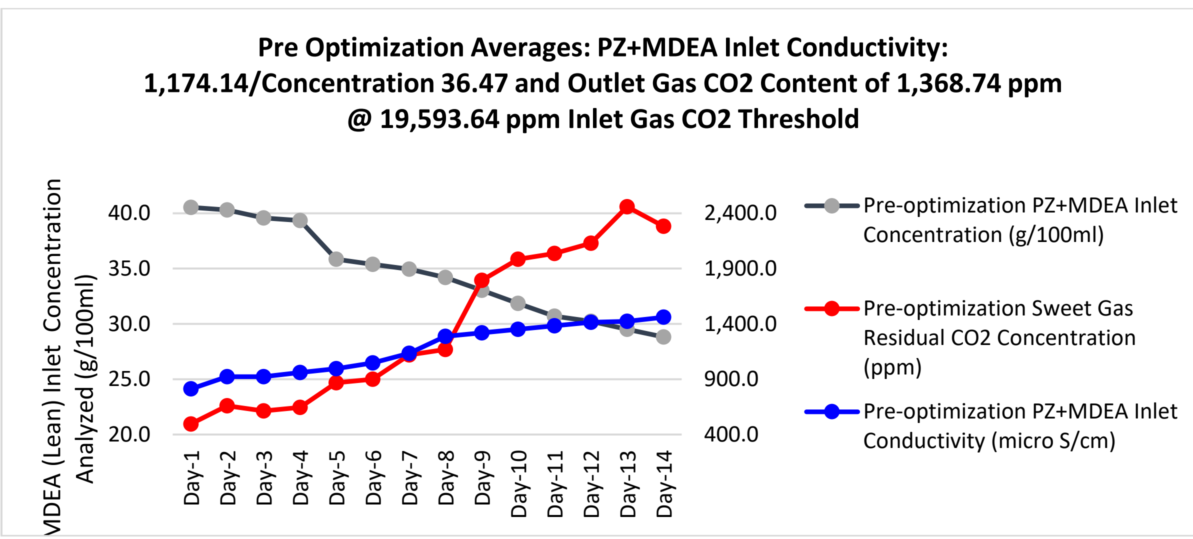

Figure 9.0: Column-A/B Pre-optimization averages: PZ+MDEA inlet conductivity Vs concentration and outlet residual CO_2 content

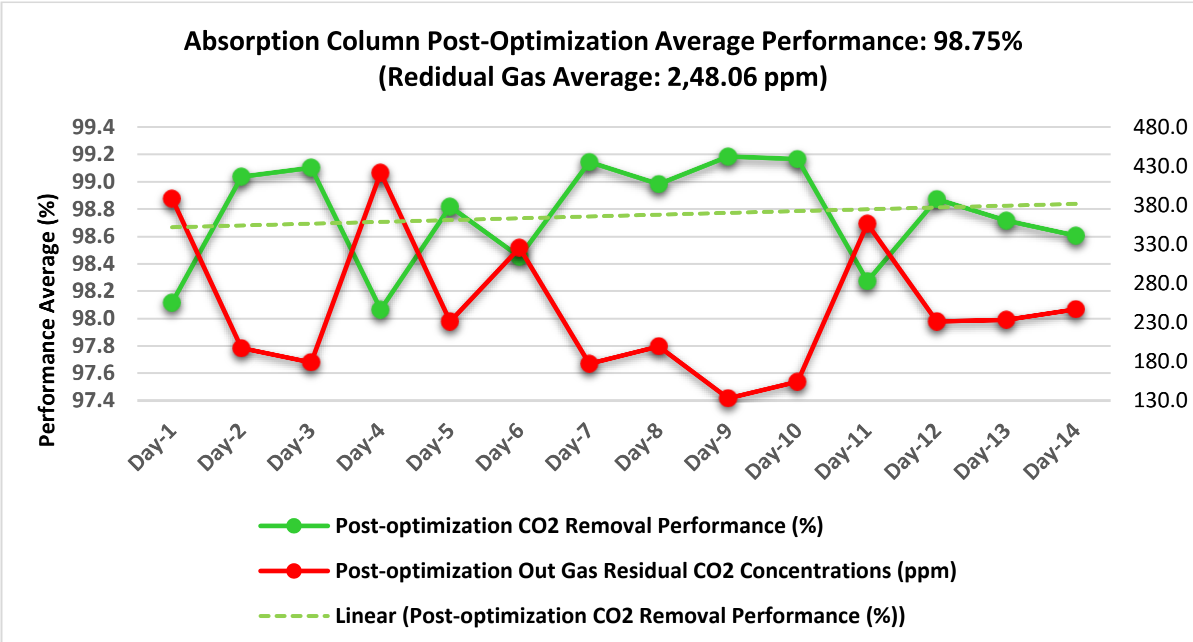

Figure 10.0: Column-A/B: Post-optimization average performance assessment

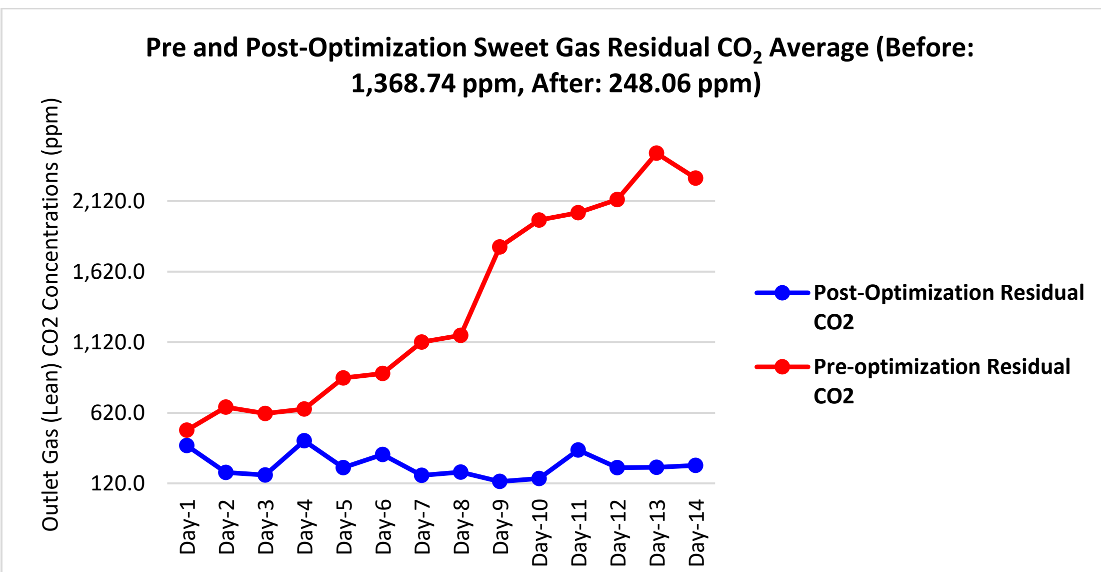

Figure 11.0: Column-A/B Pre and Post-optimization outlet gas residual CO_2 content

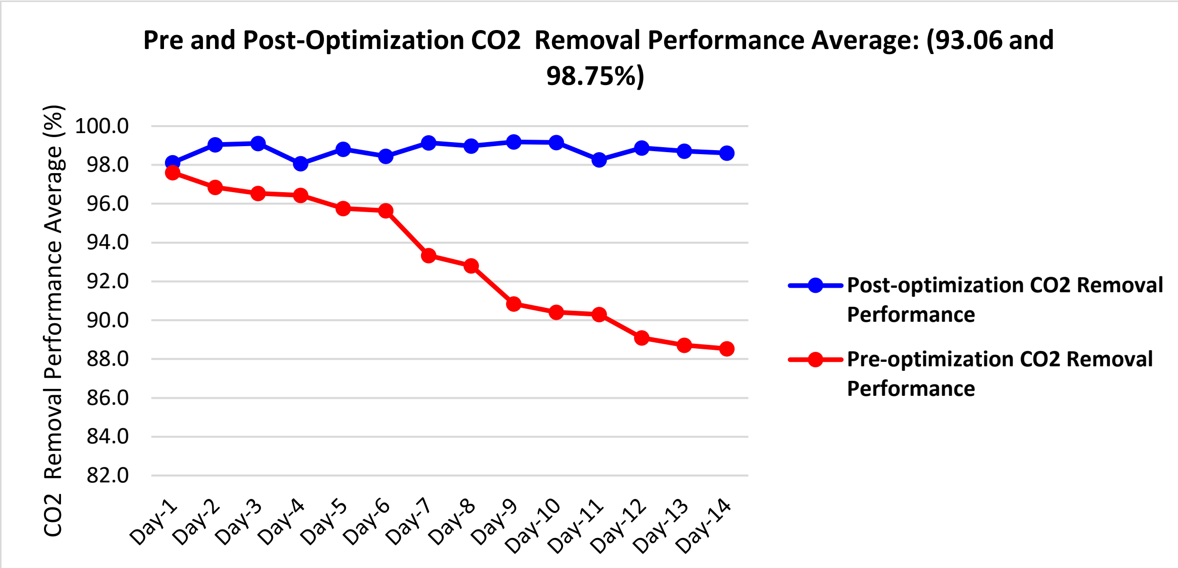

Figure 12.0: Column-A/B Pre and Post-optimization CO_2 removal performance average

4.0 Conclusion

The study demonstrated that Piperazine-Activated Methyldiethanolamine (PZ+MDEA) significantly influences electrical conductivity, CO_2 absorption, and other chemical properties in an absorption column, both before and after optimization processes. Initially, a strong (-0.9742) negative correlation between electrical conductivity and concentration of PZ+MDEA was observed, which further intensified to (-0.992447762) post-optimization. The model predicting the electrical conductivity of the PZ+MDEA inlet stream was validated and found to closely align with analyzed data, with an average difference of just 7.843 micro Siemens per centimetre. This highlights the model and the automated inline monitoring system's reliability and importance. Before optimization, measurements showed a substantial increase in electrical conductivity and temperature alongside a decrease in pH and solution concentration from the column inlet to the outlet, indicating CO_2 absorption by the PZ+MDEA solution. After optimization, the efficiency of the absorption process improved, evidenced by better CO_2 removal and adjusted chemical concentrations, leading to a 5.69% enhancement in unit performance. This process optimization, supported by regression analysis and online monitoring, significantly increases the removal efficiency of CO_2 from natural gas, ensuring the production of gas within the desired 250.0ppm residual CO_2 specifications.

References

Abdulkhaleq, L. G. (2016). A mechanistic model for carbon steel corrosion rate in aqueous carbonated solution of activated MDEA and activated DEA.

Berchiche, A., Guenoune, M., Belaadi, S., & Léonard, G. (2023). Optimal Energy Integration and Off-Design Analysis of an Amine-Based Natural Gas Sweetening Unit. Applied Sciences.

Cao, Y., Rehman, Z., Ghasem, N., Al-Marzouqi, M., Abdullatif, N., Nakhjiri, A. T., ... Shirazian, S. (2021). Intensification of CO_2 absorption using MDEA-based nanofluid in a hollow fibre membrane contactor. Scientific Reports.

Chen, X., Hu, J., Chen, Z., Lin, B., Xiong, N., & Min, G. (2021). A Reinforcement Learning-Empowered Feedback Control System for Industrial Internet of Things. IEEE Transactions on Industrial Informatics.

Deng, Q., Li, X., Gao, R., Wang, J., Zeng, Z., Zou, J.-J., ... Tsang, S. (2021). Hydrogen-Catalyzed Acid Transformation for the Hydration of Alkenes and Epoxy Alkanes over Co-N Frustrated Lewis Pair Surfaces. Journal of the American Chemical Society.

Famoye, F., & Singh, K. P. (2021). Zero-Inflated Generalized Poisson Regression Model with an Application to Domestic Violence Data. Journal of Data Science.

Khan, A. A., Halder, G., & Saha, A. (2017). Experimental investigation on efficient carbon dioxide capture using piperazine (PZ) activated aqueous methyldiethanolamine (MDEA) solution in a packed column. International Journal of Greenhouse Gas Control, 64, 163-173.

Ng, E., Lau, K. K., Chin, S., & Lim, S.-F. (2023). Foam and Antifoam Behavior of PDMS in MDEA-PZ Solution in the Presence of Different Degradation Products for CO_2 Absorption Process. Sustainability.

Oni, A., Anaya, K., Giwa, T., Di Lullo, G., & Kumar, A. M. (2022). Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. Energy Conversion and Management.

Pan, S., Wang, T., Jin, K., & Cai, X. (2022). Understanding and designing metal matrix nanocomposites with high electrical conductivity: a review. Journal of Materials Science, 57, 6487-6523.

Peng, S., Yuan, K., Gao, L., & Tang, Z. (2021). MathBERT: A Pre-Trained Model for Mathematical Formula Understanding. ArXiv.

Penn, C., & Camberato, J. (2019). A Critical Review on Soil Chemical Processes that Control How Soil pH Affects Phosphorus Availability to Plants. Agriculture.

Sahl, A. B., Siyambalapitiya, T., Mahmoud, A., & Sunarso, J. (2021). Towards zero carbon dioxide concentration in sweet natural gas product from amine sweetening plant. IOP Conference Series: Materials Science and Engineering, 1195.

Shankar, V., Velmurugan, G., Kaliappan, S., Sethupathy, S. B., Sekar, S., Patil, P. P., Anitha, G., & Kailo, G. G. (2022). Optimization of CO2 Concentration on Mortality of Various Stages of Callosobruchus maculatus and Development of Controlled Atmosphere Storage Structure for Black Gram Grains. Adsorption Science & Technology, 706-712.

Steinhauser, S., Fattahi, E., Geier, D., & Becker, T. (2020). Entwicklung eines Inline-Sensors zur kontaktlosen Analyse hochviskoser Medien mittels Laser Speckle Rheology. Chemie Ingenieur Technik.

Ullah, I. (2022). Activation energy with exothermic/endothermic reaction and Coriolis force effects on magnetized nanomaterials flow through Darcy–Forchheimer porous space with variable features. Waves in Random and Complex Media.

Wang, J., Li, Q., Li, K., Sun, X., Wang, Y., Zhuang, T., ... Wang, H. (2022). Ultra-High Electrical Conductivity in Filler-Free Polymeric Hydrogels Toward Thermoelectrics and Electromagnetic Interference Shielding. Advanced Materials.

Wang, K., Jiang, M.-l., Zhou, J., Liu, Y., Zong, Q., & Yuan, Y. (2022). Tumor-Acidity and Bioorthogonal Chemistry-Mediated On-Site Size Transformation Clustered Nanosystem to Overcome Hypoxic Resistance and Enhance Chemoimmunotherapy. ACS nano.

Wehrung, Q., Destefanis, E., Caviglia, C., Bernasconi, D., Pastero, L., Bruno, M., Bernasconi, A., Vernai, A. M., Rienzo, A. D., & Pavese, A. (2023). Experimental Modeling of CO2 Sorption/Desorption Cycle with MDEA/PZ Blend: Kinetics and Regeneration Temperature. Sustainability.

Zhan, C., Yi, J., Hu, S.-Q., Zhang, X.-G., Wu, D.-Y., & Tian, Z. (2023). Plasmon-mediated chemical reactions. Nature Reviews Methods Primers, 3.

Zhang, H., Jing, Y., & Zhou, P. (2023). Machine Learning-Based Device Modeling and Performance Optimization for FinFETs. IEEE Transactions on Circuits and Systems II: Express Briefs, 70.

Valluri, S., & Kawatra, S. (2021). Simultaneous removal of CO_2, NOx and SOx using single stage absorption column. Journal of environmental sciences, 103, 279-287.