

# Investigating the Performance of Microfluidic-Based Chemical Absorption Technology for Carbon-Dioxide Capture

Dr. Hayat Abdulla Yusuf Yousuf  
Department of Chemical Engineering  
University of Bahrain  
Isa Town, Bahrain  
<https://orcid.org/0000-0003-4072-3361>

Dr. Zainab Mohammad Redha  
Department of Chemical Engineering  
University of Bahrain  
Isa Town, Bahrain  
<https://orcid.org/0000-0001-8263-9809>

Amir Hussain Nasiri  
Department of Chemical Engineering  
University of Bahrain  
Isa Town, Bahrain  
[ahnasiri@outlook.com](mailto:ahnasiri@outlook.com)

Mohammed Shafeeq  
Department of Chemical Engineering  
University of Bahrain  
Isa Town, Bahrain  
[MohamedShafeeq2001@gmail.com](mailto:MohamedShafeeq2001@gmail.com)

Talal Alkulaqi  
Department of Chemical Engineering  
University of Bahrain  
Isa Town, Bahrain  
[talal7alkhulaqi@gmail.com](mailto:talal7alkhulaqi@gmail.com)

**Abstract**—As atmospheric CO<sub>2</sub> levels rise, traditional capture methods face challenges, prompting interest in microfluidic systems for improved mass transfer efficiency. This study explores the removal of carbon dioxide using a diethanolamine (DEA) solvent and a combination of methyl diethanolamine (MDEA) with DEA in a specially designed T-shaped microchannel. Employing the central composite design method with Design Expert 13 software free version, the research investigates the effects of operational variables such as temperature, amine concentration, volume percentage of amines, gas flow rate, and liquid flow rate on carbon capture efficiency in the designed microreactor. The results indicate that all parameters, except temperature, significantly impact absorption efficiency. While increasing amine concentrations initially enhances CO<sub>2</sub> removal efficiency, higher concentrations eventually lead to diminishing returns, negatively affecting overall absorption performance. Similarly, increasing the liquid flow rate improves removal efficiency up to an optimum point; beyond this point, further increases in liquid flow rate result in decreased efficiency. Higher gas flow rates are shown to negatively affect CO<sub>2</sub> absorption. Under optimal conditions, CO<sub>2</sub> removal efficiency exceeded 99.99%, with remarkable mass transfer coefficients of 283.2 and 253.7 (kmol/(m<sup>3</sup> h kPa)) for DEA and MDEA + DEA, respectively. These findings highlight the transformative potential of microchannels, particularly the T-shaped serpentine microreactor design, in significantly improving the volumetric overall gas-phase mass transfer coefficient compared to traditional mass transfer devices, providing an innovative approach for efficient CO<sub>2</sub> capture.

**Keywords**—Microreactor, CO<sub>2</sub> Capture, Amine solvents.

## I. INTRODUCTION

Global warming refers to the long-term rise in Earth's average surface temperature, primarily driven by greenhouse gas accumulation in the atmosphere. Key gases include carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), with CO<sub>2</sub> being the most significant, contributing about 76% of warming effects [1,2]. While natural processes release CO<sub>2</sub>,

human activities, especially fossil fuel combustion, are the main contributors to rising atmospheric levels [1]. Effective strategies to combat climate change must focus on reducing CO<sub>2</sub> emissions from these sources.

Carbon capture, utilization, and storage (CCUS) technologies are vital for mitigating CO<sub>2</sub> emissions. Various separation techniques exist, such as cryogenic distillation, physical adsorption, and membrane separation, each with its advantages and limitations. Chemical absorption is widely utilized, employing solvents like alkanolamines, which are favoured for their stability and reactivity [3]. However, conventional chemical absorption units for CO<sub>2</sub> capture face significant challenges that hinder their adoption. High costs related to capital investment, maintenance, and operation are major barriers. Additionally, large quantities of solvents, like alkanolamines, are needed, increasing expenses and logistical issues. The energy required for solvent regeneration and heat integration also impacts efficiency and economics. Furthermore, these systems' physical footprint, along with safety and security requirements, complicates site selection and integration with existing infrastructure, limiting their market development [4].

In contrast, microfluidics—a technique that miniaturizes chemical processes—offers a promising alternative. By using small-scale absorbers or reactors with micro or millimeter-sized channels, CO<sub>2</sub> absorption can be more effectively controlled. Several studies demonstrate that gas-liquid two-phase flow in microchannel reactors enhances mass transfer due to a larger interfacial surface area, improves stability and safety, and allows for easier scalability [5]. Furthermore, microfluidic technology has been successfully applied in various absorption processes, such as the capture of CO<sub>2</sub> using specific solvents in microreactors, showcasing its versatility and efficiency. This sets the stage for a comprehensive study investigating the effects of microreactor dimensions on the absorption process. Key factors, including the hydraulic diameter, cross-sectional geometry, junction design of the microchannels, as well as the length and configuration of the microchannels—whether straight or curved—have shown to significantly impact the efficiency of the absorption process.

Cantu-Perez et al., numerically investigated the effect of different cross-sectional shapes on CO<sub>2</sub> absorption and demonstrated a more stable flow pattern in flat rectangular microchannels due to the thin, spatially uniform, and stable

liquid film caused by the corner capillary effect [6]. Ganapathy et al., showed that decreasing the microchannel size increased the liquid side volume mass transfer coefficient ( $k_{La}$ ) for CO<sub>2</sub> absorption by 2.6 times [7]. Tan et al., tested the mass transfer rate of different gas-liquid inlet angles in a rectangular microchannel and found that the T-junction rendered better mass transfer performance due to the highest shear force [8]. Yang et al., demonstrated significantly increased mass transfer rates in curved microchannels due to enhanced liquid mixing [9]. Zhou et al., designed and experimentally tested a serpentine rectangular microchannel for CO<sub>2</sub> absorption, showing a 40% increase in the gas-side mass transfer coefficient ( $K_{Ga}$ ) compared to a straight channel [10].

This study aims to bridge a research gap by investigating the absorption of CO<sub>2</sub> using an aqueous alkanolamine solution within an in-house fabricated microreactor designed with optimal dimensions. Previous research has predominantly focused on larger-scale absorption systems, often overlooking the potential benefits of miniaturization in enhancing mass transfer efficiency. This work contributes to the existing literature by demonstrating how microreactor technology can improve CO<sub>2</sub> capture through better control of reaction conditions and mass transfer dynamics. Specifically, the focus is on utilizing diethanolamine (DEA) solvent, as well as a mixture of methyl diethanolamine (MDEA) and DEA, in this unique microreactor design. By leveraging the Central Composite Design (CCD) method, the impact of key parameters such as operating temperature, liquid flow rate, gas flow rate, and amine concentration on CO<sub>2</sub> absorption efficiency was investigated. The experiments are conducted with a CO<sub>2</sub>-N<sub>2</sub> gas blend under a pressure of 0.1 bar. Ultimately, the goal is to compare the effectiveness of the optimized gas-based volumetric mass transfer coefficient with values derived from alternative microreactor configurations and mass transfer devices. Additionally, the effectiveness of the microreactor was verified at optimized conditions by comparing the obtained volumetric mass transfer coefficient with that of other published microreactor configurations.

## II. MATERIALS AND METHODS

### A. Materials

DEA and MDEA with a purity of 99.9% were obtained from The Dow Chemical Company (Midland, Michigan, USA). Synthetic gas mixture comprising 10 vol% CO<sub>2</sub> and 90 vol% N<sub>2</sub> was purchased from Yateem Oxygen Company, (Manama, Bahrain).

### B. Experimental Set-up

A microreactor with a square cross-section was utilized for carbon dioxide (CO<sub>2</sub>) absorption. This in-house fabricated microreactor was constructed using polymethyl methacrylate (PMMA) acrylic and manufactured with a computer numerical control (CNC) machine, allowing for precise control of dimensions and flow characteristics. The gas and liquid phases were introduced at a collision angle of 180° in a T-shaped configuration. Detailed dimensions of the microreactor are provided in Table 1.

Table 1: Microreactor Dimensions.

| Specifications        | Characteristics           |
|-----------------------|---------------------------|
| Cross-sectional shape | Square                    |
| Cross-sectional area  | 800 × 800 μm <sup>2</sup> |

|                          |                     |
|--------------------------|---------------------|
| Microchannel Junction    | T- shaped (180°)    |
| Microchannel length      | 260 mm (Serpentine) |
| Material of Construction | PMMA                |

To analyze the gas flow at the inlet and outlet, a 20% CO<sub>2</sub> sensor (model CM-0123) from Cozir Company was employed. A Cole-Palmer variable-flow pump (Model 77390-00) regulated the desired solvent flow rates. The operating temperature was maintained using a Cole-Palmer water bath (Model E21017478-01n). Gas flow was controlled with a flow meter supplied by Gulf Petrochemical Industries Company (GPIC).

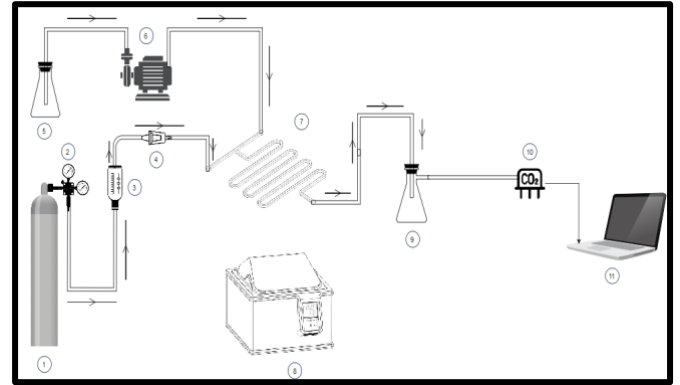


Figure 1: Experimental Setup Schematic Diagram.

1. Gas cylinder, 2. Gas pressure regulator, 3. Gas flow meter, 4. One way check valve, 5. Amine solvent container, 6. Centrifugal pump, 7. Microreactor, 8. Water Bath, 9. Gas-liquid separator, 10. CO<sub>2</sub> sensor, 11. Computer

### C. Design of experiment

One of the key parameters used to evaluate the efficiency of the process is the removal percentage of CO<sub>2</sub>. This metric gauges the degree to which CO<sub>2</sub> is absorbed by a solution, offering valuable insights into absorption process effectiveness. The CO<sub>2</sub> removal rate has been computed as follows:

$$CO_2 \text{ Removal (\%)} = \frac{y_{CO_2,in} - y_{CO_2,out}}{y_{CO_2,in}} \times 100\%$$

Where  $y_{CO_2,in}$  and  $y_{CO_2,out}$  are the mole fraction of CO<sub>2</sub> at the inlet and outlet, respectively.

Another important criterion for assessing absorption efficiency is the overall gas-phase volumetric mass transfer coefficient. This total mass transfer rate in the gas phase serves as a comprehensive and specific metric for evaluating absorption efficiency in microreactors, allowing for effective comparisons with other mass transfer devices. The total mass transfer coefficient in the gas phase is defined as follows [11]:

$$K_G \alpha_v = \frac{G}{PV} \left( \ln \left( \frac{y_{CO_2,in}}{y_{CO_2,out}} \right) + (y_{CO_2,in} - y_{CO_2,out}) \right)$$

Where G, P and V, respectively, represent the molar flow rate introduced to the microreactor (kmol/h), the system pressure (kPa), and the volume of the microreactor (m<sup>3</sup>).

In this research, DEA and MDEA+DEA mixture were used as solvents. All tests are conducted at a pressure of 0.1 bar with an inlet gas containing 10 vol% CO<sub>2</sub>. To thoroughly

explore various factors while keeping the number of trials low, the study employs the Central Composite Design (CCD) technique using Design Expert 13 software free version. The operational parameters and their corresponding values are

presented in Table 2. The ranges of input variables have been determined based on the methodologies adopted in prior studies by notable researchers in the field [11, 12, 13].

**Table 2: Operational variables and ranges.**

| Solvent    | Variables                                                | Unit     | Levels       |              |              |              |              |
|------------|----------------------------------------------------------|----------|--------------|--------------|--------------|--------------|--------------|
|            |                                                          |          | - $\alpha$   | -1           | 0            | +1           | + $\alpha$   |
| DEA        | Operating Temperature                                    | °C       | 20           | 25           | 30           | 35           | 40           |
|            | Gas Flow Rate                                            | L/min    | 0.06         | 0.12         | 0.18         | 0.24         | 0.30         |
|            | Liquid Flow Rate                                         | L/min    | 0.002        | 0.004        | 0.006        | 0.008        | 0.01         |
|            | Amine Concentration                                      | wt. %    | 2.5          | 10           | 17.5         | 25           | 32.5         |
| MDEA + DEA | Operating Temperature                                    | °C       | 20           | 25           | 30           | 35           | 40           |
|            | Gas Flow Rate                                            | L/min    | 0.06         | 0.12         | 0.18         | 0.24         | 0.30         |
|            | Liquid Flow Rate                                         | L/min    | 0.002        | 0.004        | 0.006        | 0.008        | 0.01         |
|            | Amine Concentration                                      | wt. %    | 2.5          | 10           | 17.5         | 25           | 32.5         |
|            | Vol% of Amine DEA: MDEA<br>(coded from 1-5 for mixtures) | vol/vol% | 10:90<br>(1) | 20:80<br>(2) | 30:70<br>(3) | 40:60<br>(4) | 50:50<br>(5) |

### III. RESULTS AND DISCUSSION

The experimental procedure tracked CO<sub>2</sub> levels throughout the absorption process, with measurements taken at regular intervals. CO<sub>2</sub> concentrations consistently decreased until reaching equilibrium, confirmed by averaging the last 50 readings after 3-4 minutes. A Central Composite Design (CCD) approach optimized conditions for CO<sub>2</sub> absorption, revealing that diethanolamine (DEA) achieved a maximum removal efficiency of 100% and a minimum of 45.03%. In comparison, the MDEA+DEA mixture demonstrated a maximum removal of 98.4% and a minimum of 19.2%. These findings highlight the effectiveness of both solvents in carbon capture applications, particularly emphasizing the potential of the T-shaped serpentine microfluidic design to enhance absorption efficiency.

#### A. Statistical Analysis of the Results

The statistical analysis, including analysis of variance (ANOVA), assessed the significance of various parameters and validated model predictions for both DEA and MDEA+DEA. P-values indicated that temperature had no significant effect on CO<sub>2</sub> absorption for either solvent, while factors such as amine concentration, gas flow rate, liquid flow rate, and the concentration ratio for the mixture were highly significant ( $p < 0.0001$ ). Notable interaction effects for DEA included temperature and gas flow rate ( $p = 0.0166$ ) and concentration and temperature ( $p = 0.0008$ ). For the MDEA+DEA mixture, the only significant interaction was between concentration and the concentration ratio ( $p = 0.016$ ).

Interpreting and reporting both main and interaction effects, even when not significant, provides a comprehensive understanding of variable relationships in the study [14]. Notably, the p-values for each model were highly significant, falling below the 0.0001 threshold, indicating strong statistical relevance. Furthermore, the lack of fit terms were insignificant, suggesting that any experimental errors were either negligible or not critical to the analysis.

#### B. Model Validation Results

In addition to ANOVA analysis, model validation is essential for assessing the quality of the proposed model. In this study, we validated the model by calculating errors and examining key statistical metrics such as adjusted R<sup>2</sup>, predicted R<sup>2</sup>, and

R<sup>2</sup> values. The R<sup>2</sup> value reflects the relationship between measured and predicted values, indicating how effectively the model describes the reaction response. The adjusted R<sup>2</sup> accounts for the model's efficiency when additional terms are included, while the predicted R<sup>2</sup> evaluates the model's ability to forecast values for new observations [15].

Model validation metrics are summarized Table 3 below, demonstrating excellent accuracy for predicting CO<sub>2</sub> absorption:

**Table 3: Model validation results.**

| Amine Solvent | R <sup>2</sup> | Adjusted R <sup>2</sup> | Predicted R <sup>2</sup> |
|---------------|----------------|-------------------------|--------------------------|
| DEA           | 98.95%         | 97.73%                  | 94.10%                   |
| MDEA+DEA      | 99.45%         | 99%                     | 97.9%                    |

The high R<sup>2</sup> values indicate that both models robustly explain the variance in CO<sub>2</sub> absorption. Empirical equations derived for both solvents are as follows:

##### a. DEA:

$$E (\%) = 87.35 + 0.385 A + 9.774 B - 9.635 C + 2.357 D + 1.310 A^2 - 4.758 B^2 - 1.042 C^2 - 0.326 D^2 + 0.284 AB + 1.557 AC + 0.328 AD + 3.386 BC - 2.494 BD - 0.872 CD$$

##### b. MDEA + DEA:

$$E (\%) = 62 - 0.025 A + 9.792 B - 17.988 C + 1.957 D + 6.157 E + 1.487 A^2 - 3.667 B^2 + 0.107 C^2 - 2.004 D^2 - 0.006 E^2 + 0.418 AB - 0.167 AC - 0.124 AD + 0.736 AE + 0.641 BC - 0.427 BD + 0.956 BE - 0.276 CD + 0.549 CE - 0.319 DE$$

Where A is temperature (°C), B is concentration (wt.%), C is gas flow rate (l/min), D is liquid flow rate (l/min), and E is concentration (vol/vol%).

Residual analysis indicated normal distribution patterns, supporting the reliability of the data. Overall, this analysis provided valuable insights into the significance of various parameters and the validity of the models, enhancing our understanding of CO<sub>2</sub> absorption efficiency.

### C. Effect of Main Process Variables on CO<sub>2</sub> Absorption

This section presents a detailed examination of how various operating conditions affect the efficiency of CO<sub>2</sub> absorption in microchannel reactor. The study analyzes five key factors: temperature, amine concentration, liquid and gas flow rates. The goal is to understand how each of these factors individually influences CO<sub>2</sub> removal efficiency while keeping all other parameters constant. While the primary focus of this report is on the main effects of these independent variables, the complexities of their interactions are acknowledged.

### D. Effect of Temperature

The relationship between temperature and CO<sub>2</sub> absorption within the range of 20–40 °C is illustrated in Fig. 2. The graph shows that both solvents responded similarly to temperature changes. Initially, from 20 to 30 °C, CO<sub>2</sub> removal efficiency declines because CO<sub>2</sub> is more soluble in liquids at lower temperatures, leading to higher physical absorption. As temperature rises, CO<sub>2</sub> solubility decreases, although the reaction rate constant, and chemical absorption increases [11]. At this stage, physical absorption dominates, resulting in reduced CO<sub>2</sub> efficiency. However, from 30 to 40 °C, the influence of reaction rates becomes more pronounced. Increased rate constants accelerate the forward reaction, enhancing CO<sub>2</sub> removal efficiency. Additionally, higher temperatures reduce solution viscosity, allowing for thinner liquid film layers and decreased flow resistance, which further improves mass transfer and CO<sub>2</sub> absorption [11].

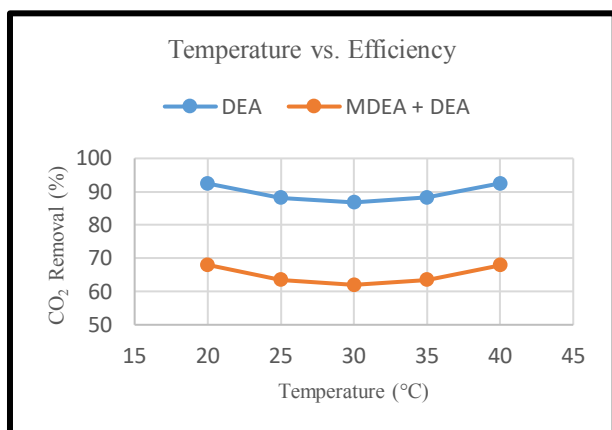


Figure 2: The effect of temperature on CO<sub>2</sub> removal.

### E. Effect of Amine Concentration

The concentration of amine sorbents significantly impacts CO<sub>2</sub> removal efficiency, as shown in Fig. 3. Both diethanolamine (DEA) and methyl diethanolamine (MDEA) + DEA mixtures exhibit enhanced CO<sub>2</sub> removal efficiency with increasing amine concentrations from 2.5 to 25.5 wt.%. This trend indicates that a higher concentration of amine provides more active sites for CO<sub>2</sub> molecules, facilitating more effective chemical reactions and enhancing the overall absorption process [11]. However, beyond 25.5 wt.%, the relationship between amine concentration and CO<sub>2</sub> removal efficiency becomes non-linear. While higher amine concentrations initially provide more active sites for CO<sub>2</sub> absorption, facilitating improved chemical reactions and absorption, exceeding 25.5 wt.% results in increased solvent viscosity. This rise in viscosity elevates mass transfer resistance at the gas-liquid interface, which ultimately hinders mass transfer rates and diminishes CO<sub>2</sub> removal efficiency [16].

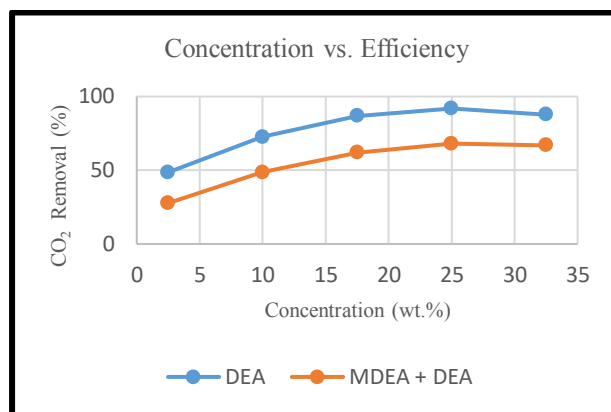


Figure 3: The effect of Solvent's concentration on CO<sub>2</sub> removal.

### F. Effect of Gas Flow Rate

The impact of gas flow rate on the removal of CO<sub>2</sub> is demonstrated in Fig. 4. In both scenarios involving DEA and MDEA+DEA amines, it was observed that the efficiency of CO<sub>2</sub> removal decreases as the gas flow rate increases. This can be explained by the reduction in gas-liquid residence contact time caused by the accelerated movement of gas within the microreactor at higher flow rates. Consequently, there is insufficient time for the effective absorption of CO<sub>2</sub> to occur due to the limited interaction time between the gas and liquid phases [17]. However, the MDEA + DEA mixture is particularly affected by this phenomenon, as the slower reaction kinetics of MDEA compared to DEA lead to a more pronounced decline in CO<sub>2</sub> removal efficiency at elevated gas flow rates [18].

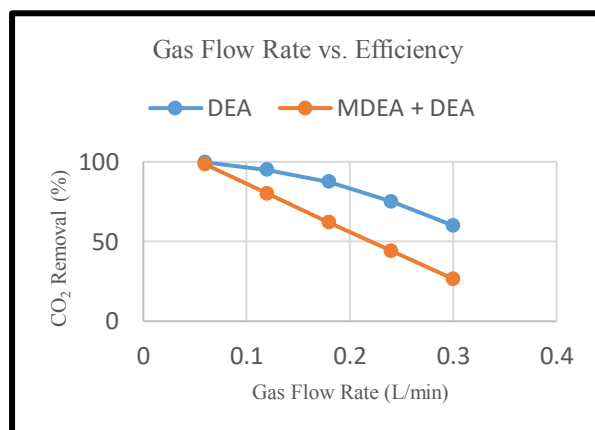


Figure 4: The effect of gas flow rate on CO<sub>2</sub> removal.

### G. Effect of Liquid Flow Rate

The effect of liquid flow rate on CO<sub>2</sub> removal efficiency is shown in Fig. 5. Initially, increasing the flow rate enhances absorption for both solvents due to the increased availability of active sites in the solution, leading to greater CO<sub>2</sub> - absorbent reactions [17]. This also promotes turbulent flow, thereby enhancing mass transfer and absorption rates [19]. However, for the MDEA + DEA mixture, the plateau pattern observed at higher flow rates can be attributed to MDEA's slower reaction kinetics compared to DEA. As flow rates increase, the residence time of the solvent in the microreactor decreases, limiting the time available for CO<sub>2</sub> to react with MDEA. Research has shown that MDEA has a lower reaction rate with CO<sub>2</sub>, which can lead to diminished effectiveness in capturing CO<sub>2</sub> under conditions of rapid flow [18]. Consequently, this reduction in residence time inhibits the full

utilization of MDEA's absorption capacity, ultimately resulting in a lower CO<sub>2</sub> removal efficiency as indicated by the plateau in the performance curve.

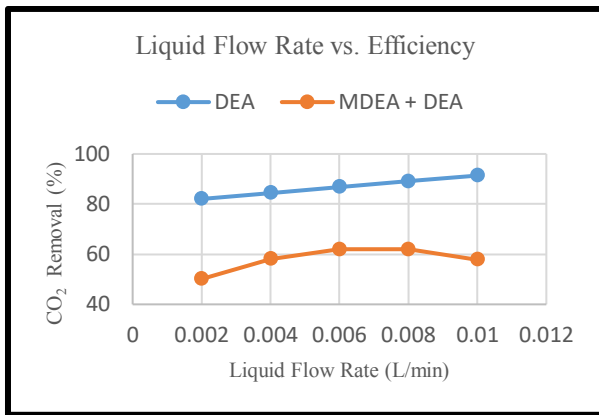


Figure 5: The effect of liquid flow rate on CO<sub>2</sub> removal.

#### H. Effect of Concentration Ratio (MDEA: DEA)

Figure 6 shows a distinct linear relationship between the volume percentage of amine and the effectiveness of CO<sub>2</sub> removal. As the volume percentage of DEA in the solution rises, the efficiency of CO<sub>2</sub> removal also increases. This improvement is due to DEA's higher reaction rates, which enhance the chemical absorption of CO<sub>2</sub> molecules. As a result, the greater absorption capacity of DEA contributes to more effective CO<sub>2</sub> removal from the system [20].

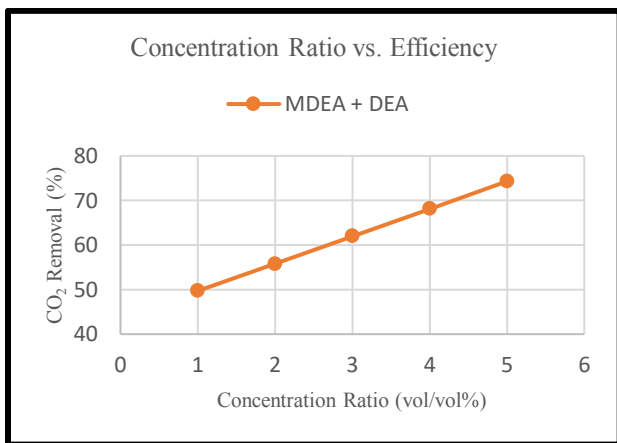


Figure 6: The effect of concentration ratio on CO<sub>2</sub> removal.

#### I. Optimization and comparison

This section focuses on developing a robust objective function to create an effective quantification model. The primary aim is to identify key parameters that maximize CO<sub>2</sub> removal efficiency. To achieve this purpose, Response Surface Methodology (RSM) Design was employed to systematically explore the parameter space and optimize the response for maximum CO<sub>2</sub> removal efficiency.

Using the Design Expert numerical optimizer tool, the ideal combination of input variables was optimised for both DEA and MDEA + DEA amines, as detailed in Table 4. It is important to note that this section does not include an economic analysis of the optimization results; future work should address the economic implications of the identified optimal conditions.

Table 4: Optimization Results.

| Operational Parameters         | Solvent |          |
|--------------------------------|---------|----------|
|                                | DEA     | MDEA+DEA |
| Temperature (°C)               | 40      | 40       |
| Concentration (wt.%)           | 21.5    | 30.5     |
| Gas Flow Rate (L/min)          | 0.18    | 0.16     |
| Liquid Flow Rate (L/min)       | 0.009   | 0.005    |
| Concentration Ratio (MDEA/DEA) | -       | 50:50    |
| CO <sub>2</sub> Removal (%)    | 100     | 100      |

One way to evaluate the performance of microchannels compared to other mass transfer units is by examining the total mass transfer coefficient of the gas phase. This coefficient serves as a comprehensive measure for assessing CO<sub>2</sub> removal efficiency. Table 5 illustrates such a comparison, highlighting notable variations in the volumetric overall gas-phase mass transfer coefficient between single or mixed amines and other units. The microchannel configurations in this study demonstrate significant enhancements in mass transfer performance, attributed to their unique design features, such as reduced hydraulic diameters and increased surface area for gas-liquid interaction.

For instance, the current study's microchannel with a diameter of 800  $\mu\text{m}$  achieved a gas-phase mass transfer coefficient of 283.2 and 251.7  $\text{kmol}/(\text{m}^3 \text{ h kPa})$  for the DEA and MDEA + DEA mixture, which is markedly higher than values reported in traditional systems like packed columns and spray towers. Notably, DEA alone exhibited a higher mass transfer coefficient compared to MDEA due to its faster reaction kinetics with CO<sub>2</sub>. Furthermore, the combination of MDEA and DEA outperformed MDEA alone, highlighting the improved kinetics achieved through the synergistic effects of the two solvents. The use of mixed amines not only increases the number of active sites for CO<sub>2</sub> capture but also enhances overall absorption efficiency. Additionally, the small size of the microchannel allows for better control of flow dynamics, leading to reduced residence time while maintaining effective mass transfer rates. This study provides compelling evidence that microchannel technology can significantly outperform conventional mass transfer devices, offering a promising avenue for CO<sub>2</sub> capture applications.

#### IV. CONCLUSION

This study investigated CO<sub>2</sub> absorption in a T-shaped microreactor with a square cross-section of 800  $\mu\text{m} \times 800 \mu\text{m}$  and a length of 26 cm, utilizing DEA and a mixture of MDEA + DEA. Response Surface Methodology with a Central Composite Design (RSM-CCD) was employed to analyze how various factors—including temperature, amine concentration, gas flow rate, liquid flow rate, and the MDEA to DEA concentration ratio—affect CO<sub>2</sub> removal efficiency. Statistical analysis validated the models, which achieved excellent R<sup>2</sup> values and demonstrated a non-significant lack of fit. This indicates that the models can reliably predict and optimize conditions for CO<sub>2</sub> absorption in the microreactor technology. The findings revealed that all parameters, except temperature, significantly influenced absorption efficiency. While higher gas flow rates negatively impacted CO<sub>2</sub> absorption, increasing amine concentrations initially enhanced CO<sub>2</sub> removal before excessive concentrations led to decreased performance. Liquid flow rates generally improved efficiency, although the MDEA + DEA mixture exhibited an optimal point beyond which efficiency declined.

Table 5: Comparison between different mass transfer devices.

| Mass Transfer Device | Amine Solution | Experimental Conditions                                                                                                                                                                                                                                     | $K_G \alpha_v$ (kmol/m <sup>3</sup> h kPa) | Reference     |
|----------------------|----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|---------------|
| Spray Tower          | MEA            | $C_{CO_2} = 5 - 15\%$<br>$T = 300\text{ K}$<br>$Q_g = 764\text{ m}^3/\text{m}^2\text{ h}$<br>$Q_L = 10.3\text{ m}^3/\text{m}^2\text{ h}$<br>$C_{amine} = 3 - 7\text{ kmol/m}^3$<br>$Reactor\ Length = 0.552\text{ m}$<br>$Reactor\ Diameter = 0.1\text{ m}$ | 6                                          | [21]          |
| Packed Column        | DEA            | $C_{CO_2} = 10\%$<br>$Q_g = 48.2\text{ kmol/m}^2\text{ h}$<br>$Q_L = 4.8 - 10\text{ m}^3/\text{m}^2\text{ h}$<br>$C_{amine} = 3\text{ kmol/m}^3$<br>$Reactor\ Length = 2\text{ m}$<br>$Reactor\ Diameter = 0.02\text{ m}$                                   | 1.23                                       | [22]          |
| Microchannel         | MEA + DEA      | $y_{CO_2} = 10.5\%$<br>$T = 293.15 - 313.15$<br>$Q_g = 3 - 15\text{ L/h}$<br>$Q_L = 10 - 30\text{ mL/h}$<br>$C_{amine} = 2.5 - 32.5\text{ wt}\%$<br>$Reactor\ Length = 25\text{ cm}$<br>$Reactor\ Diameter = 0.6\text{ mm}$                                 | 110                                        | [11]          |
|                      | MEA + TEA      | $Reactor\ Diameter = 0.6\text{ mm}$                                                                                                                                                                                                                         | 67.5                                       |               |
| Microchannel         | DEA            | $y_{CO_2} = 10\%$<br>$T = 293.15 - 313.15$<br>$Q_g = 0.06 - 0.3\text{ L/min}$<br>$Q_L = 0.002 - 0.01\text{ L/min}$<br>$C_{amine} = 2.5 - 32.5\text{ wt}\%$<br>$Reactor\ Length = 26\text{ cm}$<br>$Reactor\ Diameter = 800\text{ }\mu\text{m}$              | 283.2                                      | Current Study |
|                      | MDEA + DEA     | $Reactor\ Diameter = 800\text{ }\mu\text{m}$                                                                                                                                                                                                                | 251.7                                      |               |

Notably, the CO<sub>2</sub> removal efficiency of the MDEA + DEA solution improved with a higher proportion of DEA. Under optimal conditions, CO<sub>2</sub> removal exceeded 99.99%, achieving impressive mass transfer coefficients of 283.2 and 251.7 (kmol/m<sup>3</sup> h kPa) for DEA and MDEA + DEA, respectively. The T-shaped serpentine microreactor design significantly enhanced the volumetric overall gas-phase mass transfer coefficient compared to conventional mass transfer devices, presenting a novel approach for efficient CO<sub>2</sub> capture. For future work, we advocate for a "numbering-up" approach in the development of microchannels to facilitate the industrial adoption of this technology. From an implementation perspective, the microreactor's design allows for easy fabrication using CNC machining, ensuring precise control over dimensions critical for optimizing flow characteristics. The use of readily available materials, such as PMMA, supports large-scale production, while the controllability of key operational parameters facilitates effective utilization in various industrial settings. Additionally, the scalability of microfluidic systems enables the integration of multiple microreactors, enhancing throughput while maintaining a compact footprint. Ultimately, further research should focus

on the economic feasibility and potential for widespread use of microreactor technology in the carbon capture landscape. This comprehensive approach will ensure that the benefits of the T-shaped serpentine microreactor can be effectively translated into real-world applications.

#### ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the University of Bahrain (UOB) for its invaluable support and resources throughout this project. We also extend our appreciation to Gulf Petrochemical Industries Company (GPIC) for their financial assistance and to FabLab Bahrain for their steadfast support in fabrication, along with essential resources and expertise. Furthermore, we would like to thank Yateem Oxygen Bahrain for providing the gas mixture that was crucial for our research.

## REFERENCES

- [1] "Overview of greenhouse gases | US EPA," *US EPA*, Apr. 11, 2024. Available: <https://www.epa.gov/ghgemissions/overview-greenhouse-gases>
- [2] Center for Climate and Energy Solutions, "Global Emissions - Center for Climate and Energy Solutions," *Center for Climate and Energy Solutions*, Dec. 01, 2022. Available: <https://www.c2es.org/content/international-emissions/>
- [3] "Gas Purification by Arthur L Kohl, 5th edition | 9780884152200, 9780080507200," Aug. 28, 1997. Available: <https://www.perlego.com/book/1813861/gas-purification-pdf>
- [4] C. Ye, M. Dang, C. Yao, G. Chen, and Q. Yuan, "Process analysis on CO<sub>2</sub> absorption by monoethanolamine solutions in microchannel reactors," *Chemical Engineering Journal*, vol. 225, pp. 120–127, Mar. 2013, doi: 10.1016/j.cej.2013.03.053. Available: <https://www.sciencedirect.com/science/article/abs/pii/S1385894713003781>
- [5] Y. Zhang, C. Zhu, C. Chu, T. Fu, and Y. Ma, "Mass transfer and capture of carbon dioxide using amino acids sodium aqueous solution in microchannel," *Chemical Engineering and Processing - Process Intensification*, vol. 173, p. 108831, Feb. 2022, doi: 10.1016/j.cep.2022.108831. Available: <https://www.sciencedirect.com/science/article/abs/pii/S0255270122000526>
- [6] M. Al-Rawashdeh *et al.*, "Microstructure-based intensification of a falling film microreactor through optimal film setting with realistic profiles and in-channel induced mixing," *Chemical Engineering Journal*, vol. 179, pp. 318–329, Nov. 2011, doi: 10.1016/j.cej.2011.11.014. Available: <https://www.sciencedirect.com/science/article/abs/pii/S1385894711013933>
- [7] H. Ganapathy, A. Shooshtari, S. Dessiatoun, M. M. Ohadi, and M. Alshehhi, "Hydrodynamics and mass transfer performance of a microreactor for enhanced gas separation processes," *Chemical Engineering Journal*, vol. 266, pp. 258–270, Dec. 2014, doi: 10.1016/j.cej.2014.12.028. Available: <https://www.sciencedirect.com/science/article/abs/pii/S1385894714016386>
- [8] J. Tan, Y. C. Lu, J. H. Xu, and G. S. Luo, "Mass transfer characteristic in the formation stage of gas–liquid segmented flow in microchannel," *Chemical Engineering Journal*, vol. 185–186, pp. 314–320, Jan. 2012, doi: 10.1016/j.cej.2012.01.054. Available: <https://www.sciencedirect.com/science/article/abs/pii/S1385894712000575>
- [9] L. Yang, K. Loubiere, N. Dietrich, C. L. Men, C. Gourdon, and G. Hébrard, "Local investigations on the gas-liquid mass transfer around Taylor bubbles flowing in a meandering millimetric square channel," *Chemical Engineering Science*, vol. 165, pp. 192–203, Mar. 2017, doi: 10.1016/j.ces.2017.03.007. Available: <https://www.sciencedirect.com/science/article/abs/pii/S000925091730177X>
- [10] Y. Zhou, C. Yao, P. Zhang, X. Zhang, H. Lü, and Y. Zhao, "Dynamic Coupling of Mass Transfer and Chemical Reaction for Taylor Flow along a Serpentine Microchannel," *Industrial & Engineering Chemistry Research*, vol. 59, no. 19, pp. 9279–9292, Apr. 2020, doi: 10.1021/acs.iecr.0c00014. Available: <https://pubs.acs.org/doi/10.1021/acs.iecr.0c00014>
- [11] S. Janati, B. Aghel, and M. S. Shadloo, "The effect of alkanolamine mixtures on CO<sub>2</sub> absorption efficiency in T-Shaped microchannel," *Environmental Technology & Innovation*, vol. 24, p. 102006, Oct. 2021, doi: 10.1016/j.eti.2021.102006. Available: <https://www.sciencedirect.com/science/article/pii/S2352186421006544>
- [12] C. Y. Chuah, K. Kim, J. Lee, D.-Y. Koh, and T.-H. Bae, "CO<sub>2</sub> absorption using membrane contactors: recent progress and future perspective," *Industrial & Engineering Chemistry Research*, vol. 59, no. 15, pp. 6773–6794, Dec. 2019, doi: 10.1021/acs.iecr.9b05439. Available: <https://pubs.acs.org/doi/10.1021/acs.iecr.9b05439>
- [13] B. Aghel, S. Sahraie, E. Heidaryan, and K. Varmira, "Experimental study of carbon dioxide absorption by mixed aqueous solutions of methyl diethanolamine (MDEA) and piperazine (PZ) in a microreactor," *Process Safety and Environmental Protection*, vol. 131, pp. 152–159, Sep. 2019, doi: 10.1016/j.psep.2019.09.008. Available: <https://www.sciencedirect.com/science/article/abs/pii/S0957582019315265>
- [14] D. C. Montgomery, *Design and analysis of experiments*. Wiley, 2012.
- [15] C. P. Doncaster and A. J. H. Davey, *Analysis of variance and covariance*. 2007. doi: 10.1017/cbo9780511611377.
- [16] C. Nwaoha *et al.*, "Advancement and new perspectives of using formulated reactive amine blends for post-combustion carbon dioxide (CO<sub>2</sub>) capture technologies," *Petroleum*, vol. 3, no. 1, pp. 10–36, Dec. 2016, doi: 10.1016/j.petlm.2016.11.002. Available: <https://www.sciencedirect.com/science/article/pii/S2405656116301808>
- [17] F. Karimi and P. Valeh-E-Sheyda, "A green amino acid-based solvent blended with diethanolamine solution for CO<sub>2</sub> capture using micro-reactor," *Brazilian Journal of Chemical Engineering*, vol. 41, no. 1, pp. 221–233, May 2023, doi: 10.1007/s43153-023-00348-5. Available: <https://link.springer.com/article/10.1007/s43153-023-00348-5>
- [18] S. Mokhtab, W. A. Poe, and J. Mak, *Handbook of Natural Gas Transmission and Processing: Principles and Practices*. Gulf Professional Publishing, 2018.
- [19] Libretexts, "Le Chatelier's Principle Fundamentals," *Chemistry LibreTexts*, Jan. 30, 2023. Available: [https://chem.libretexts.org/Bookshelves/Physical\\_and\\_Theoretical\\_Chemistry\\_Textbook\\_Maps/Supplemental\\_Modules\\_\(Physical\\_and\\_Theoretical\\_Chemistry\)/Equilibria/Le\\_Chateliers\\_Principle/Le\\_Chatelier's\\_Principle\\_Fundamentals](https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Equilibria/Le_Chateliers_Principle/Le_Chatelier's_Principle_Fundamentals)
- [20] G. Lin, S. Jiang, C. Zhu, T. Fu, and Y. Ma, "Mass-Transfer Characteristics of CO<sub>2</sub> Absorption into Aqueous Solutions of N-Methyldiethanolamine + Diethanolamine in a T-Junction Microchannel," *ACS Sustainable Chemistry & Engineering*, vol. 7, no. 4, pp. 4368–4375, Jan. 2019, doi: 10.1021/acssuschemeng.8b06231. Available: <https://pubs.acs.org/doi/10.1021/acssuschemeng.8b06231>
- [21] J. Kuntz and A. Aroonwilas, "Mass Transfer in a Spray Column for CO<sub>2</sub> Removal," *ResearchGate*, vol. 22, pp. 1–6, May 2006, doi: 10.1109/eicccc.2006.277211.
- [22] A. Aroonwilas and A. Veawab, "Characterization and Comparison of the CO<sub>2</sub> Absorption Performance into Single and Blended Alkanolamines in a Packed Column," *Industrial & Engineering Chemistry Research*, vol. 43, no. 9, pp. 2228–2237, Apr. 2004, doi: 10.1021/ie0306067. Available: <https://pubs.acs.org/doi/10.1021/ie0306067>