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Experimental Investigation of Process Intensification in CO2 Absorption Using Monoethanolamine in a Rotating Packed Bed

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Research Article

Keywords: MEA solvent, postcombustion, CO2 capture, process Intensification, rotating packed bed

Posted Date: March 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8899362/v1

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Additional Declarations: No competing interests reported.

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Abstract

The emission of carbon dioxide (CO_2) from industrial sources, particularly power plants, remains one of the leading contributors to global climate change. While conventional post-combustion CO_2 capture technologies are effective, they are often limited by high energy consumption and large equipment size. Rotating Packed Bed (RPB) technology offers a promising solution through process intensification and improved mass transfer. This study presents an experimental investigation of a laboratory-scale RPB absorber designed for CO_2 capture using aqueous monoethanolamine (MEA) solutions. The effects of rotor speed, MEA concentration, and liquid-to-gas (L/G) ratio on CO_2 capture efficiency and the overall volumetric gas-phase mass transfer coefficient ($K_G a$) were systematically examined. The results showed that increasing rotor speed from 0 to 2400 rpm increased CO_2 capture efficiency from below 10% to over 70% due to enhanced centrifugal acceleration and improved gas–liquid contact. Higher MEA concentrations led to improved capture performance, attributed to increased reaction kinetics, while elevated L/G ratios further enhanced absorption efficiency and reduced the Height of Transfer Unit (HTU). The findings confirm the suitability of RPB technology for efficient and compact CO_2 absorption systems, with strong potential for industrial applications.

The findings provide new insights for optimizing compact CO_2 capture systems using intensified rotating packed bed technology, with the recognition that future integration with an efficient regeneration unit is essential to address the overall energy penalty of the process.

KEY WORDS: MEA solvent, postcombustion, CO_2 capture, process Intensification, rotating packed bed

1. Introduction

The global demand for energy has consistently increased in recent years, driven by population growth and rapid technological advancements [1]. Consequently, energy-related carbon dioxide (CO_2) emissions have also escalated, reaching 31.5 gigatonnes in 2021 [2, 3]. As CO_2 is the most significant anthropogenic greenhouse gas (GHG) contributing to global warming, the need for sustainable mitigation strategies is urgent. The International Energy Agency (IEA) has identified Carbon Capture, Utilization, and Storage (CCUS) as a critical technology for reducing GHG emissions and addressing climate change [4].

At the same time, global reserves of sweet natural gas are being depleted [5], leading to growing interest in developing sour gas reservoirs that often contain high CO_2 concentrations—up to 80% in some cases [6,7]. The presence of CO_2, along with hydrogen sulfide and other impurities, makes sour gas processing technically challenging. CO_2 is highly corrosive, endangering the integrity of pipelines and process equipment. Therefore, efficient and scalable CO_2 separation technologies are essential for both natural gas purification and environmental compliance.

Among the three main CO_2 capture approaches—pre-combustion, oxy-fuel combustion, and post-combustion capture (PCC)—chemical absorption-based PCC is the most mature and widely applied technology [8]. Its compatibility with existing infrastructure has enabled commercial-scale deployment, particularly for power plants and industrial facilities [9]. However, conventional PCC systems typically employ packed bed (PB) columns for CO_2 absorption and solvent regeneration. These columns are bulky, expensive, and limited by poor mass transfer rates, especially when operating with viscous, concentrated solvents such as monoethanolamine (MEA) [9,10].

To overcome these limitations, Rotating Packed Bed (RPB) technology has emerged as a promising process intensification solution. By replacing gravitational flow with centrifugal acceleration, RPBs significantly enhance gas–liquid mass transfer rates and reduce equipment size. In RPBs, the liquid is distributed at the rotor center and flows radially outward through the packing as thin films, while the gas flows countercurrently from the outer edge

toward the center [11–15]. This configuration facilitates intense phase contact, improves mixing, and enables the use of high-viscosity solvents such as concentrated MEA (>55 wt%) [16-19].

While conventional packed columns face severe operational challenges (flooding, poor wettability, excessive pressure drop) when using MEA concentrations above 30–40 wt% due to a sharp increase in solvent viscosity, Rotating Packed Bed technology fundamentally alters this limitation. The intense centrifugal force in an RPB promotes the formation of extremely thin liquid films and fine droplets, effectively mitigating the negative impact of high viscosity on fluid distribution and mass transfer. This unique capability allows for the exploration of a radically different operating regime: the use of highly concentrated MEA solutions (up to 90 wt%). The primary rationale for investigating such high concentrations is twofold: (1) Process Intensification: Higher amine concentration increases the absorption driving force and reaction kinetics per unit volume of solvent, potentially leading to a drastic reduction in required solvent circulation rate, equipment size (smaller tanks, pumps, and pipes), and associated capital costs. (2) Energy Reduction in Regeneration: A smaller mass of solvent with a higher CO_2 loading requires less sensible heat to be heated in the desorber. Although the increased viscosity and potential for corrosion are significant trade-offs, quantifying the mass transfer performance at these extremes is essential to map the true operational envelope of RPB technology and evaluate the feasibility of this intensification pathway [17, 20-21].

RPBs have been successfully applied across a range of industries, including distillation, oxidation, crystallization, polymerization, and biodiesel production [11–15]. In the context of CO_2 capture, several studies have demonstrated the potential of RPBs to improve absorption efficiency and reduce regeneration energy [22-24]. For example, Joel et al. [25] developed a rate-based RPB absorber model using MEA in Aspen Plus®, coupled with Fortran®. Their simulations showed that absorber volume could be reduced by a factor of 12 compared to conventional PB columns—highlighting the compactness and efficiency of RPBs.

Despite these advantages, process intensification in RPBs is inherently complex due to simultaneous phenomena involving mass transfer, heat transfer, and fluid dynamics [24, 26]. Accurate modeling of RPB performance remains a significant challenge, particularly at industrial scale. Many existing models rely on simplifying assumptions that, while suitable for lab-scale units, may not hold for scaled-up operations, potentially resulting in discrepancies in performance prediction [27]. Moreover, due to the complex internal flow behavior, experimental data alone is insufficient to fully understand RPB hydrodynamics. Three-dimensional computational fluid dynamics (CFD) simulations have been proposed to gain deeper insight into flow characteristics, pressure fields, and velocity distributions, though such studies remain limited [28, 29].

In light of these considerations, further research and model development are essential for optimizing RPB systems for CO_2 capture. The unique advantages of RPBs—compactness, high mass transfer efficiency, and compatibility with concentrated solvents—position this technology as a leading candidate for next-generation carbon capture systems.

Therefore, the aim of this study is to experimentally investigate the performance of a laboratory-scale RPB absorber using aqueous MEA solutions under various operating conditions, including rotor speed, MEA concentration, and liquid-to-gas (L/G) ratio. This work is novel in that it systematically examines the interaction of these parameters and evaluates their combined influence on CO_2 capture efficiency, volumetric mass transfer coefficient (KGa), and the Height of Transfer Unit (HTU). Unlike most prior experimental studies, our work explores very high MEA concentrations (up to 90 wt%) and quantifies the impact of solvent viscosity on mass transfer in RPBs. The findings provide new insights for optimizing compact and energy-efficient CO_2 capture systems using intensified rotating packed bed technology.

2. Materials and Methods

2.1. Materials

In this study, pure monoethanolamine (MEA) was used as the solvent. The MEA was sourced from the Mubarek Gas Processing Plant with a purity of >99%. A gas mixture of CO_2 and air was also used in the experiments. Aqueous MEA solutions with mass concentrations of 30%, 50%, 70%, and 90% were prepared by a gravimetric method using an analytical balance (accuracy ±0.01 g). The exact masses of MEA and deionized water were recorded for each batch to calculate the precise mass fraction. The prepared concentrations were verified by total alkalinity titration using a standard hydrochloric acid (HCl) solution (0.1 M) with methyl orange as an indicator. The measured alkalinity showed agreement with the theoretical value within a deviation of less than ±2%, confirming the accuracy of the prepared concentrations. The gas mixtures consisted of 15% CO_2 and 85% air. The chosen 15 vol% CO_2 concentration simulates flue gas compositions typical of various industrial plants. For instance, flue gases from cement kilns, steel mill boilers, and certain chemical processes often contain CO_2 in the range of 14–17 vol% [30]. This value is also commonly used as a benchmark in previous experimental studies of post-combustion CO_2 capture, enabling direct comparison and performance evaluation under realistic and representative conditions [31].

All MEA solutions were freshly prepared for each experiment using deionized water and pure MEA, and were not preloaded with CO_2. Therefore, the lean solvent loading is assumed to be near zero, as no prior CO_2 absorption occurred.

2.2. Experimental Part

The experimental setup was assembled at the "Petroleum Chemical" laboratory of the Institute of General and Inorganic Chemistry of the Academy of Sciences of the Republic of Uzbekistan. The schematic diagram of the experimental system is shown in Figure 1. The system includes an RPB absorber, reservoirs for lean and rich MEA, a

gas cylinder filled with pure CO_2, a pump for circulating the lean MEA solution, a compressor for air injection, a GC-7860 gas chromatograph for gas analysis, and flow meter gas and liquid for measuring the flow rates of both the gas mixture and the solvent.

The system used in this study is a bench-scale RPB with dimensions optimized for intensified absorption experiments. Although compact in size (typical of lab equipment), the unit was operated at gas and liquid flow rates comparable to those found in small pilot-scale processes, in order to better simulate realistic flue gas conditions.

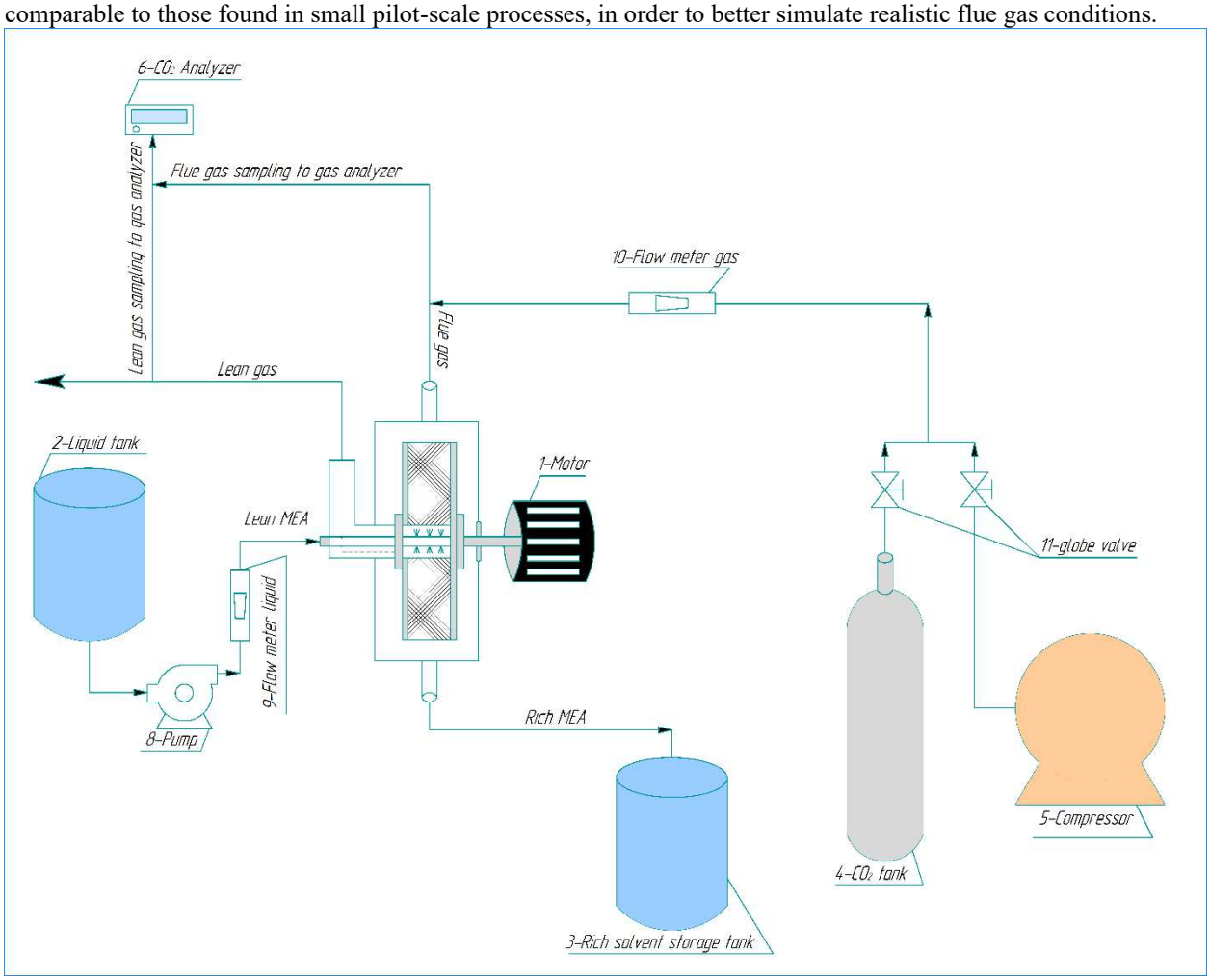


Figure1. Schematic diagram of the experimental setup for CO_2 capture using a rotating packed bed (RPB).

Figure 1. Schematic diagram of the experimental setup for CO_2 capture using a rotating packed bed (RPB). The gas mixture containing 15% CO_2 enters from the outer casing and flows radially inward through the packing. Simultaneously, the MEA solution is introduced at the center and distributed radially outward by centrifugal force through the rotating packing. This countercurrent gas–liquid flow facilitates high-intensity mass transfer. The revised figure includes arrows to indicate the flow directions of both phases. The experiment begins with the supply of a gas mixture containing 15% CO_2 and 85% air from the cylinder (4) through the compressor (5), which provides the required pressure. The gas then flows through the globe valves (11) and the gas flow meter (10) into the rotating packed bed (RPB) absorber. Simultaneously, a monoethanolamine (MEA) solution is pumped from the liquid tank (2) using a pump (8), passes through the liquid flow meter (9), and is also fed into the absorber. Inside the RPB, which is equipped with SS316 stainless steel packing, the liquid is distributed via a stationary distributor containing five sets of holes (each set has five 1 mm holes spaced 72° apart) along the inner edge of the packing. Due to centrifugal force, the liquid moves radially outward through the packing and is collected at the bottom of the stationary casing. In contrast, the gas enters from the outer stationary casing, flows inward through the packing counter-currently to the liquid flow, and exits through the central pipe of the rotor. This counter-current flow is intensified by the high rotational speed of the packing, driven by the motor (1), which enhances mass transfer efficiency. During this process, CO_2 from the gas mixture is absorbed by the MEA solution. The CO_2-depleted gas (lean gas) exits through the rotor's central pipe and is directed to the CO_2 analyzer (6) to monitor residual CO_2 concentration. The CO_2-rich MEA (rich MEA) is collected at the bottom in the storage tank (3) for further regeneration. This setup simulates an industrial CO_2 capture process using an advanced rotating packed bed technology. The inlet and outlet CO_2 concentrations were measured using a GC-7860 gas chromatograph.

The rotor speed was varied from 0 to 2400 rpm. The centrifugal field in the RPB enables the formation of thinner liquid films and smaller droplets. This system is capable of operating at higher gas–liquid flow ratios due to its reduced tendency for flooding. One of the most critical advantages of this configuration is its ability to significantly

enhance mass transfer coefficients—by an order of magnitude—thereby reducing equipment size compared to conventional packed bed columns.

The packing used in the RPB was expanded stainless steel mesh (expamet). It was shaped into cylindrical layers and fixed inside the rotating basket. This structured packing offers a high surface area (1200 m^2/m^3) and high void fraction (0.92), which facilitates effective gas–liquid contact. The inner and outer diameters of the packing were 5 cm and 14 cm, respectively, and the axial height was 3 cm. These parameters are summarized in Table 1. The MEA solution was pumped into the rotating packed bed with a flow rate ranging from 0.161 to 0.567 L/min.

The lean MEA used in each experiment was newly prepared and not recirculated, ensuring a consistent and low initial CO_2 loading for all experimental conditions. The initial CO_2 loading was essentially 0 mol CO_2/mol MEA.

The CO_2–air gas mixture entered from the stationary casing and flowed radially inward through the packing. The CO_2 concentration in the inlet gas was maintained at 15% of the total mixture volume. The gas flow rate was 13.4 L/min, and the liquid flow rate ranged from 0.161 to 0.567 L/min. A steady state (dynamic equilibrium) in the absorber was considered reached when the outlet CO_2 concentration stabilized, typically within 7–12 minutes of operation. This steady state reflects a balance between the rate of CO_2 supply from the gas phase and its rate of chemical absorption into the liquid phase under the given flow conditions. It is important to note that in this study, each experiment was conducted in a single-pass mode: the fresh (lean) MEA solution flowed through the absorber only once and was then collected as rich solvent. This approach was chosen to precisely control and know the initial solvent condition (zero CO_2 loading) for every data point, eliminating the cumulative effects of solvent degradation, heat buildup, and fluctuating lean loading that occur in closed-loop recirculation systems. While recirculation is representative of industrial operation, the single-pass method allows for a more fundamental and unambiguous investigation of the intrinsic absorption performance of the RPB under defined, reproducible solvent conditions. All experiments were conducted at an ambient temperature of approximately 25°C and under atmospheric pressure.

Table 1. Rotating packed bed specification.

Item	Value
Inner diameter of the packing, cm	5
Outer diameter of the packing, cm	14
Axial height of the packing, cm	3
Specific surface area of the packing, m^2/m^3	1200
Voidage	0.92

Uncertainty Analysis: All experiments were conducted under steady-state conditions, confirmed by a stable outlet CO_2 concentration (variation within ±0.5 vol%). Each operating point was repeated three times, and the average values are reported. The standard deviation for the calculated CO_2 capture efficiency (η) and the overall mass transfer coefficient (KGa) was generally within ±1.5–2.5%, indicating good reproducibility. The combined experimental uncertainty for these key parameters, estimated through error propagation, did not exceed ±3%.

2.3. Chemical Reactions between CO_2, Water, and MEA

The primary mechanisms of the reaction between carbon dioxide (CO_2) and monoethanolamine (MEA) have been investigated using two distinct approaches: the zwitterion mechanism and the termolecular mechanism.

According to studies by Aboudheir et al. [32], a series of chemical reactions describing the interaction of CO_2 with aqueous MEA solutions have been proposed. These reactions cover the key stages of the absorption process, including the formation of intermediate compounds and equilibrium transformations.

Water ionization:

$$2H_2O \leftrightarrow OH^- + H_3O^+ \quad (1)$$

Water undergoes spontaneous dissociation, producing hydroxide ions (OH^-) and hydronium ions (H_3O^+). This reaction plays an important role in the acid–base processes occurring in the solution.

Dissociation of dissolved CO_2 in water:

$$CO_2 + H_2O \leftrightarrow HCO_3^- + H_3O^+ \quad (2)$$

When carbon dioxide (CO_2) dissolves in water, it reacts with water molecules to form carbonic acid (H_2CO_3), which rapidly dissociates into bicarbonate ions (HCO_3^-) and hydronium ions (H_3O^+).

The dissociation of bicarbonate proceeds as follows:

$$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+ \quad (3)$$

Bicarbonate (HCO_3^-) can further dissociate to form carbonate ions (CO_3^{2-}) and hydronium ions (H_3O^+), which contributes to a decrease in the solution's pH.

Zwitterion formation reaction during the interaction of MEA with CO_2:

$$CO_2 + RNH_2 \leftrightarrow RNH_2^+COO^- \quad (4)$$

The amino group of monoethanolamine (RNH_2) reacts with CO_2 to form a zwitterion ($RNH_2^+COO^-$), where the carboxylate group carries a negative charge and the amine group becomes protonated.

Deprotonation of the zwitterion and formation of the carbamate:

$$RNH_2^+COO^- + RNH_2 \leftrightarrow RNH_3^+ + RNHCOO^- \quad (5)$$

The zwitterion reacts with an additional MEA molecule, resulting in the formation of a protonated MEA (RNH_3^+) and a carbamate ion ($RNHCOO^-$).

Hydrolysis of carbamate and its reverse conversion to bicarbonate:

$$RNH_2^+COO^- + H_2O \leftrightarrow H_3O^+ + RNHCOO^- \quad (6)$$

Carbamate may undergo hydrolysis, resulting in the release of a hydronium ion (H_3O^+) and partial regeneration of the carbamate structure.

Dissociation of protonated MEA:

$$RNH_3^+ + H_2O \leftrightarrow RNH_2 + H_3O^+ \quad (7)$$

The protonated form of monoethanolamine (RNH_3^+) can donate a proton to water, returning to its neutral amine form (RNH_2), thereby influencing the pH of the solution.

Formation of bicarbonate:

$$CO_2 + OH^- \leftrightarrow HCO_3^- \quad (8)$$

CO_2 can also react with hydroxide ions (OH^-), to form bicarbonate (HCO_3^-), which is a significant reaction in alkaline environments.

Yu et al. [33] identified three key processes that govern CO_2 absorption using MEA within a pseudo-first-order reaction framework: molecular diffusion, physical dissolution, and chemical interaction. As noted by Arunvilas et al. [34], the chemical reaction between CO_2 and MEA occurs almost instantaneously. After CO_2 enters the liquid phase via physical absorption, it rapidly transforms into various chemical species. The greatest resistance to mass transfer is associated with the step involving the movement of CO_2 from the bulk gas phase to the gas–liquid interface.

2.4. Theoretical Analysis Method

2.4.1. Evaluation of Mass Transfer Efficiency in RPB

The mass transfer performance in a rotating packed bed (RPB) is determined by a combination of parameters, among which the overall volumetric gas-phase mass transfer coefficient ($K_G a$). plays a central role. This coefficient provides a quantitative measure of the intensity of mass transfer between the gas and liquid phases, which is essential for the design and optimization of RPB systems.

In general, the coefficient ($K_G a$) can be determined using the following expression [35,36]:

$$K_G a = \frac{G_1}{\pi PZ(r_{out}^2 - r_{in}^2)} \int \frac{1}{(y_{CO_2} - y_{CO_2}^*)} d\left(\frac{y_{CO_2}}{1 - y_{CO_2}}\right) \quad (9)$$

where **P** — the total pressure, **Z** — the axial height of the packing in the RPB, r_{in} and r_{out} represent the inner and outer radii of the packing, respectively. G_1 denotes the inert gas flow rate. y_{CO_2} and $y_{CO_2}^*$ refer to the mole fraction of CO_2 in the gas phase and the equilibrium mole fraction of CO_2, respectively.

Since the interaction between CO_2 and the aqueous solution of monoethanolamine (MEA) is characterized by a very fast chemical reaction, it is reasonable to assume that $y_{CO_2}^* = 0$. This assumption simplifies the integration of the mass transfer equation, leading to the following expression (Equation 10):

$$K_G a = \frac{G_1}{\pi PZ(r_{out}^2 - r_{in}^2)} \times \left[ln \frac{y_{in}(1 - y_{out})}{y_{out}(1 - y_{in})} + \left(\frac{1}{1 - y_{in}} + \frac{1}{1 - y_{out}}\right)\right] \quad (10)$$

where y_{in} and y_{out} are the mole fractions of CO_2 in the gas phase at the inlet and outlet, respectively. Additionally, the CO_2 capture efficiency (η) defined as the ratio of the amount of CO_2 removed to its initial amount in the gas stream, is calculated using the following equation (Equation 11):

$$\eta = \left(1 - \frac{y_{out}}{y_{in}}\right) \times 100\% \quad (11)$$

This definition of CO_2 capture efficiency is consistent with commonly accepted formulations reported in the literature [37, 38]. This expression provides a quantitative assessment of CO_2 absorption efficiency in the RPB, which is essential for further analysis and scaling of gas purification processes. These parameters form the basis for optimizing the design characteristics of the unit and selecting appropriate operating conditions for the process.

3. Results and discussions

3.1. Effect of rotational speed on CO_2 capture efficiency

The energy requirements of a Rotating Packed Bed (RPB) are closely linked to the rotor speed, which also plays a crucial role in determining the capture efficiency. To achieve an optimal balance between energy consumption and capture performance, it is important to investigate the relationship between rotor speed and separation efficiency. In this work, the rotor speed was varied in the range of 0 rmp to 2400 rpm. This range was selected based on the maximum operational frequency of the motor (3000 rmp), while 0 rmp was included as a reference point to evaluate the influence of rotation in comparison to a stationary packed bed.

A 30% MEA (monoethanolamine) aqueous solution and a synthetic flue gas containing 15% CO_2 were used in this study. Figure 3 illustrates the effect of rotation speed on CO_2 capture efficiency under the following operating conditions: 30% MEA concentration, temperature of 25 °C, and pressure of 101,325 N/m².

The results indicate a positive correlation between rotor speed and CO_2 capture efficiency. This trend is consistent with findings reported by Burns et al. [39,40], which suggest that the rotation of the absorber enhances mass transfer due to the combined action of droplet and film flows.

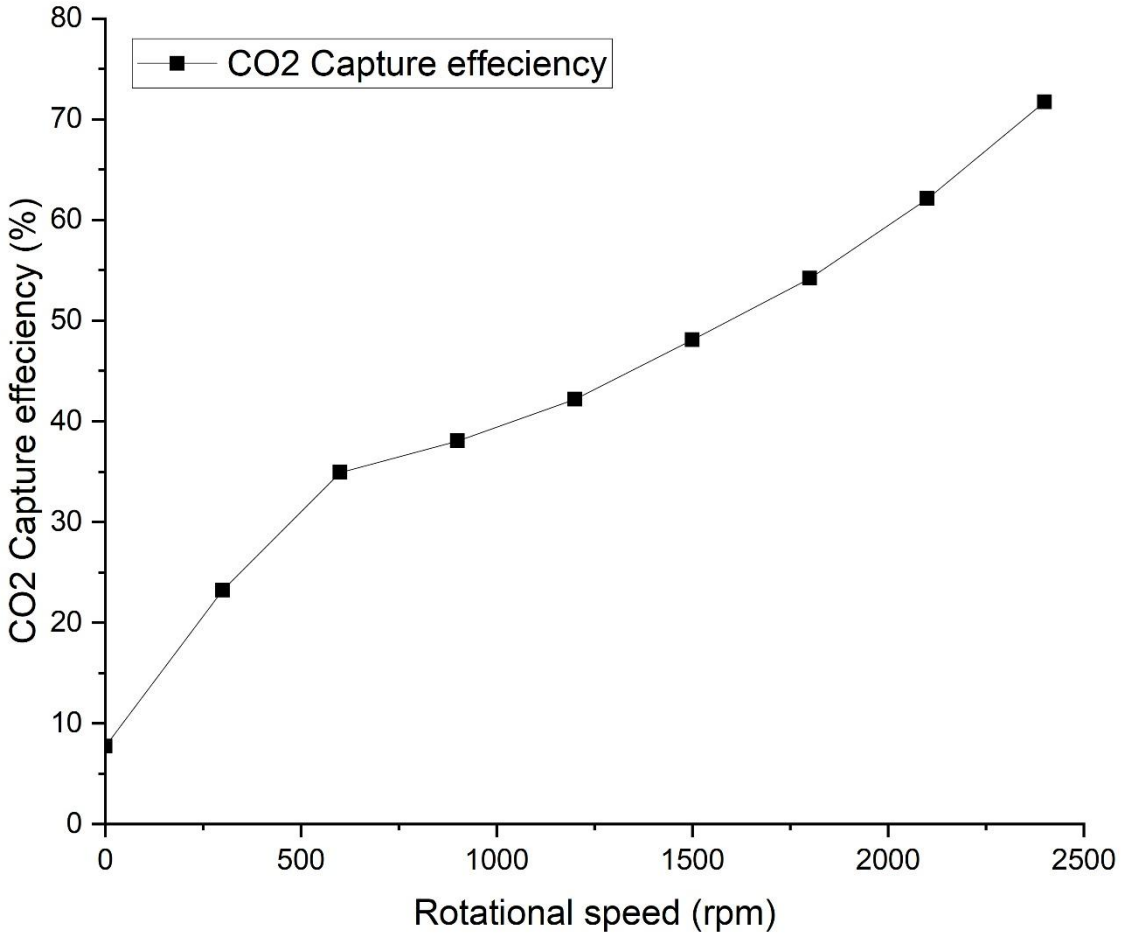


Figure 3. *Effect of rotational speed on CO_2 capture efficiency using 30% MEA solution at 25 °C and atmospheric pressure (101,325 N/m²).*

Figure 3 shows the effect of rotational speed on CO_2 capture efficiency in the rotating packed bed (RPB) absorber. The rotational speed was varied from 0 to 2400 rpm in order to compare the performance of the rotating system with that of a stationary packed bed.

At 0 rpm, the CO_2 capture efficiency is only 7.7%, indicating very limited gas–liquid mass transfer under gravity-driven conditions. When the rotor speed is increased to 300 rpm, the capture efficiency rises sharply to 23.2%, demonstrating the immediate impact of centrifugal force on liquid dispersion and interfacial area.

Further increases in rotational speed lead to a continuous and monotonic enhancement in capture efficiency. The efficiency increases from 34.9% at 600 rpm to 42.2% at 1200 rpm, followed by a more pronounced rise from 48.1% at 1500 rpm to 71.7% at 2400 rpm. This trend reflects the transition from an initial centrifugal regime to a fully intensified mass-transfer regime, where thin liquid films and fine droplets dominate the flow inside the packing.

The sharp improvement observed between 0 and 600 rpm is attributed to the suppression of rivulet flow and the onset of effective liquid spreading across the packing surface. At higher rotational speeds (>1500 rpm), centrifugal acceleration significantly enhances surface renewal and gas–liquid contact, resulting in substantially higher CO_2 absorption efficiency. However, the incremental gain in efficiency gradually decreases at the highest speeds, suggesting diminishing returns due to hydrodynamic and residence-time limitations. The results confirm that rotational speed is a critical operating parameter in RPB absorbers and plays a dominant role in intensifying CO_2 absorption compared to conventional stationary packed beds.

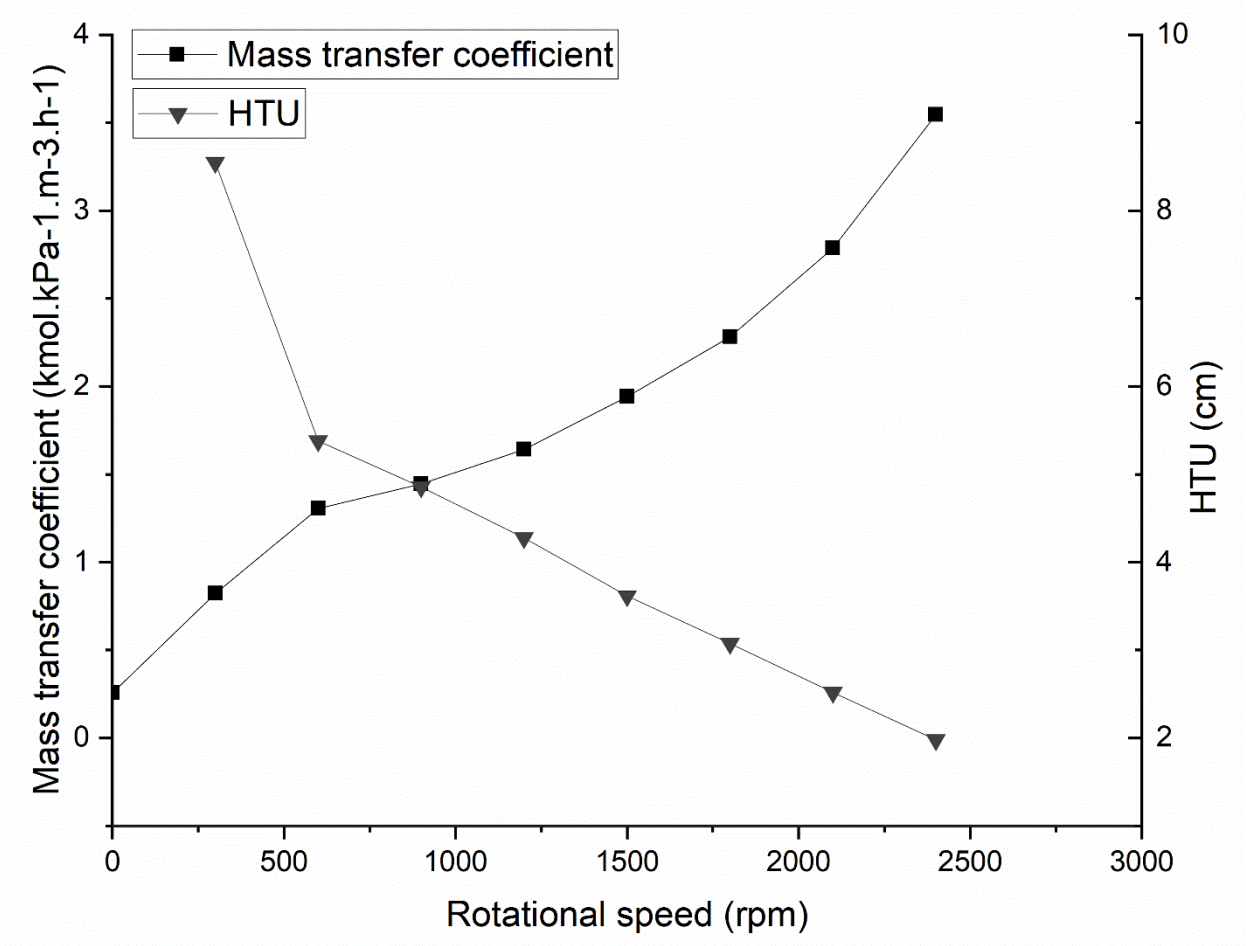


Figure 4.*Effect of rotational speed on the overall gas-phase mass transfer coefficient* $(K_G a)$ *and height of transfer unit using 30% MEA solution at 25 °C and atmospheric pressure (101,325 N/m²)*

Figure 4 shows the variation of the overall gas-phase overall mass transfer coefficient $(K_G a)$ as a function of rotor speed in a Rotating Packed Bed (RPB) system. The experiments were conducted using a 30% MEA solution under standard conditions.

The results reveal a clear upward trend: as the rotor speed increases from 0 to approximately 2500 rpm, the value of $(K_G a)$ significantly rises—from about 0.2 to over 3.5 kmol·kPa^{-1}·m^{-3}·h^{-1}. This substantial enhancement can be attributed to the intensified centrifugal forces and improved gas-liquid contact at higher rotational speeds, which promote the thinning of the liquid film, the dispersion of droplets, and an increase in interfacial area for mass transfer.

At lower speeds (0–750 rpm), the increase in $(K_G a)$ is relatively moderate, indicating the initial contribution of mechanical rotation to overcoming natural convection limitations. Beyond 1000 rpm, the growth becomes more pronounced, with the steepest rise observed between 2000 and 2500 rpm, suggesting a nonlinear relationship likely influenced by turbulence and droplet entrainment.

In addition to the increase in the mass transfer coefficient, a significant reduction in HTU (Height of Transfer Unit) was observed as the rotor speed increased. The HTU decreased from approximately X cm at 0 rpm to Y cm at 2400 rpm, indicating that the absorption process becomes more compact and efficient at higher rotational speeds. This is attributed to the enhanced gas–liquid contact area and reduced resistance to mass transfer, which results from the thinning of the liquid film and improved phase mixing. These findings further support the process intensification benefits of RPBs and align with previously reported results in the literature [25; 35].

These findings are consistent with the theory that RPB systems provide intensified mass transfer by reducing diffusion resistance and enhancing the surface renewal rate. Thus, optimizing rotor speed is a key parameter in designing energy-efficient CO_2 absorption systems with high mass transfer performance.

3.2. Effect of MEA concentration on CO_2 capture efficiency, Mass transfer coefficient $(K_G a)$ and Height of Transfer Unit (HTU).

In this study, the impact of varying monoethanolamine (MEA) concentrations on CO_2 capture efficiency and the overall volumetric mass transfer coefficient was thoroughly examined under controlled conditions. The experimental data obtained from different concentrations of MEA (30%, 50%, 70%, and 90% by weight) are analyzed, and their implications for CO_2 absorption efficiency and mass transfer are discussed below.

Figure 5 shows the effect of monoethanolamine (MEA) concentration on CO_2 capture efficiency in the rotating packed bed (RPB) absorber. The MEA concentration was varied from 30 to 90 wt% under otherwise identical operating conditions.

At the lowest MEA concentration of 30 wt%, the CO_2 capture efficiency is 36.2%. Increasing the MEA concentration to 50 wt% results in a substantial improvement, with the capture efficiency rising to 54.7%. A further increase to 70 wt% MEA enhances the capture efficiency to 65.6%, while the highest concentration investigated, 90 wt% MEA, yields the maximum efficiency of 78.2%.

The monotonic increase in CO_2 capture efficiency with MEA concentration is primarily attributed to the higher availability of reactive amine groups and hydroxide ions, which enhance the chemical reaction rate between CO_2 and MEA. Higher MEA concentrations increase the absorption driving force and reduce CO_2 breakthrough, leading to improved overall capture performance.

Despite the known increase in solvent viscosity at elevated MEA concentrations, the RPB maintains high absorption efficiency even at 70–90 wt% MEA. This behavior highlights the advantage of centrifugal acceleration in promoting thin liquid films and effective liquid distribution, thereby mitigating the adverse impact of high viscosity on mass transfer. These results demonstrate that RPB technology enables stable and efficient operation in concentration regimes that are typically impractical for conventional packed columns.

These findings are consistent with previous studies by Freguia and Rochelle [41], who observed that the reaction rate of a pseudo-first-order reaction depends directly on the concentration of MEA. As MEA concentration rises, the reaction rate increases, leading to higher CO_2 absorption. This phenomenon explains why higher MEA concentrations are more effective in capturing CO_2. Furthermore, these results align with reports by Jassim et al. [17], which found that higher concentrations of MEA result in lower CO_2 penetration due to improved absorption kinetics.

The second aspect of the study focused on the effect of MEA concentration on the overall volumetric mass transfer coefficient. As illustrated in Figure 6, the increase in MEA concentration is correlated with a rise in the mass transfer coefficient. This indicates that the efficiency of mass transfer improves as MEA concentration increases. This result can be explained by the enhanced CO_2 absorption rate, which is a direct consequence of higher MEA concentration. With more hydroxide ions available to react with CO_2, the rate of mass transfer increases, improving the overall performance of the CO_2 capture process.

However, while higher MEA concentrations improve both CO_2 capture efficiency and mass transfer, there are practical considerations to address. As the MEA concentration increases, so does the solvent viscosity, which leads to thicker liquid films and a reduction in the driving force for mass transfer. This trade-off between increased capture efficiency and reduced mass transfer efficiency at higher MEA concentrations must be considered when optimizing the process for industrial applications.

The experimental data also reveal the relationship between MEA concentration and the Height of Transfer Unit (HTU), as shown in Figure 6. HTU values were found to increase with decreasing MEA concentration. This result suggests that a higher concentration of MEA leads to a lower HTU, indicative of improved mass transfer efficiency at higher concentrations. The decrease in HTU can be attributed to the enhanced absorption kinetics at higher MEA concentrations, which leads to a more efficient overall mass transfer process.

While the results demonstrate the benefits of higher MEA concentrations for CO_2 capture, several practical challenges must be considered. Higher MEA concentrations not only improve CO_2 capture but also increase the risk of equipment corrosion, which is a significant concern in industrial applications. Additionally, the increase in solvent viscosity at higher MEA concentrations can lead to operational challenges related to fluid dynamics and mass transfer resistance.

Therefore, it is essential to identify the optimal MEA concentration that maximizes CO_2 capture while minimizing the adverse effects of increased viscosity and potential corrosion. Further studies are needed to evaluate the trade-offs between these factors and to explore the impact of other process variables, such as temperature, pressure, and flow rates, on the overall efficiency of the CO_2 capture process.

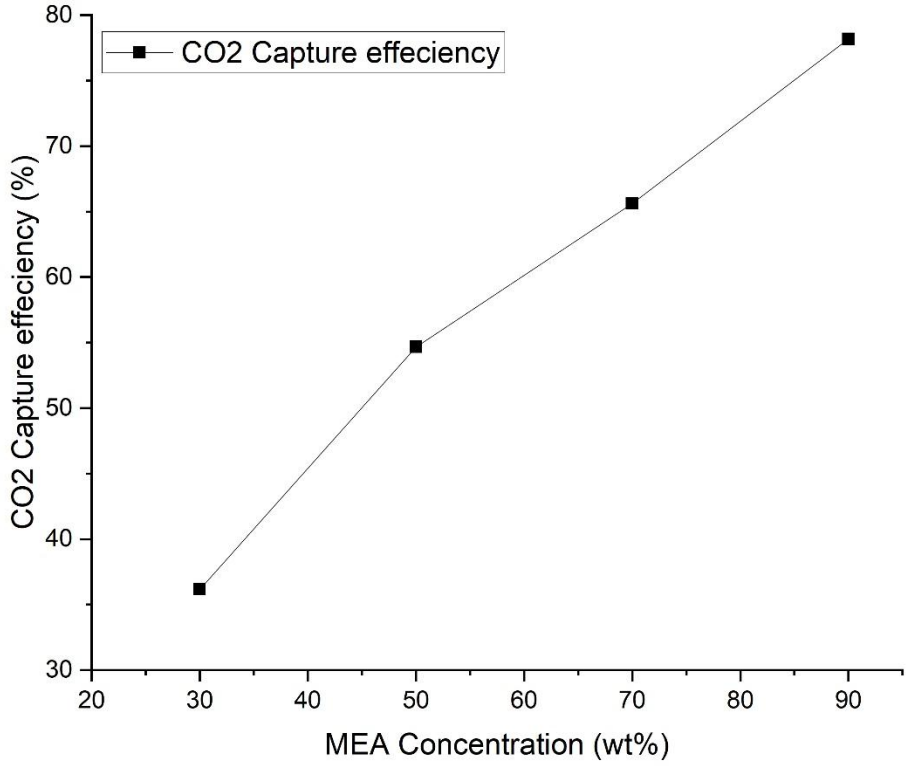


Figure 5. The effect of monoethanolamine concentration on CO_2 capture efficiency. Experimental conditions: Liquid flow rate = 0.23 l/min; Gas flow rate = 13.4 l/min; Inlet CO_2 concentration = 15%; Pressure = 101.325 N/m²; Temperature = 25°C; Rotational speed = 1500 rpm

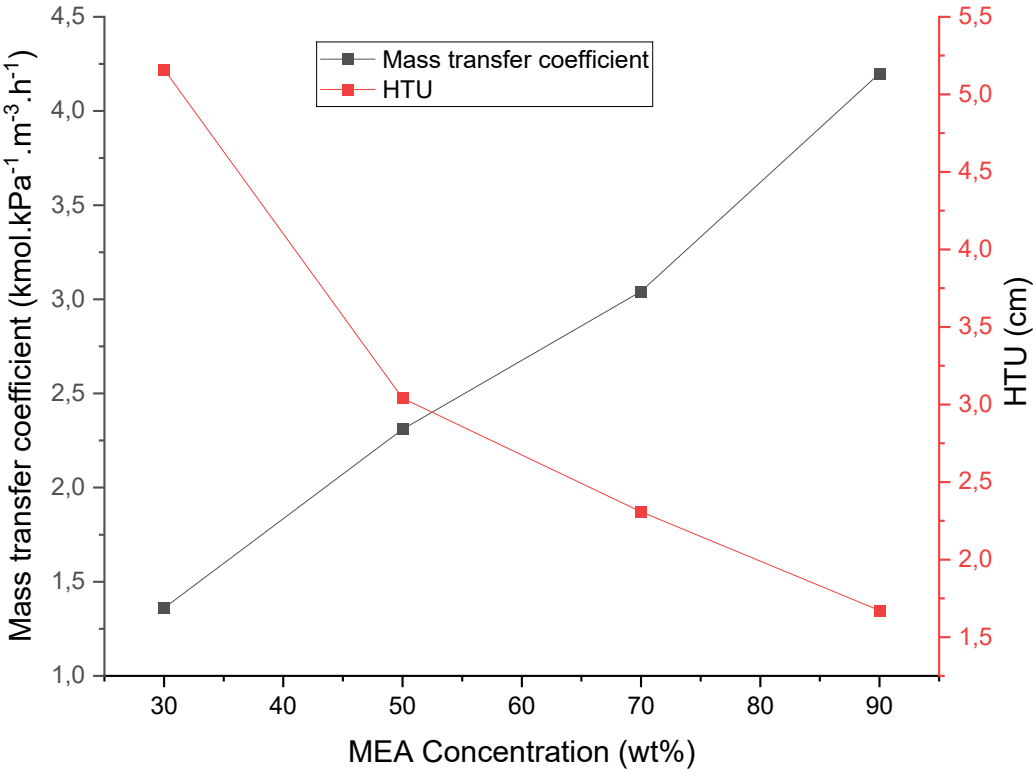


Figure 6. The effect of monoethanolamine concentration on volumetric mass transfer coefficient and height of transfer unit. Experimental conditions: Liquid flow rate = 0.23 l/min; Gas flow rate = 13.4 l/min; Inlet CO_2 concentration = 15%; Pressure = 101.325 N/m²; Temperature = 25°C; Rotational speed = 1500 rpm

3.3. Effect of liquid to gas ratio on CO_2 capture efficiency, volumetric mass transfer coefficient ($K_G a$) and Height of Transfer Unit (HTU)

Figure 7 presents the influence of the liquid-to-gas ratio (L/G) on CO_2 capture efficiency in the rotating packed bed (RPB) absorber. The L/G ratio was varied from 0.012 to 0.042, while all other operating conditions were kept constant.

At the lowest L/G ratio of 0.012, the CO_2 capture efficiency is 49.4%, indicating insufficient solvent availability relative to the gas flow rate. Increasing the L/G ratio to 0.017 leads to a noticeable improvement, with capture efficiency rising to 54.3%. A further increase to 0.021 results in a more pronounced enhancement, reaching 68.0%, which reflects a transition toward improved gas–liquid contact and solvent utilization.

At higher L/G ratios, the CO_2 capture efficiency increases sharply. When the L/G ratio is raised to 0.028, the efficiency reaches 77.4%, and further increases to 0.033 and 0.042 yield capture efficiencies of 86.4% and 89.1%, respectively. This trend demonstrates that higher solvent flow rates significantly enhance CO_2 absorption by increasing the available reactive liquid volume and prolonging effective gas–liquid contact within the RPB.

The observed behavior confirms that the L/G ratio is a dominant operating parameter governing absorption performance. At low L/G ratios, the process is limited by solvent availability, whereas at higher ratios, the absorption becomes increasingly controlled by mass transfer kinetics rather than solvent supply. The gradual reduction in the incremental efficiency gain at the highest L/G values suggests the approach of a practical upper limit, beyond which further increases in solvent flow would yield diminishing returns while increasing pumping energy requirements.

Figure 8 shows the relationship between the liquid to gas ratio (L/G) and both the overall mass transfer coefficient ($K_G a$) and Height of Transfer Unit (HTU). As the L/G ratio increases, the mass transfer coefficient also increases, reaching its highest value at an L/G ratio of 0.04 L/G. This is consistent with the observed increase in CO_2 capture efficiency, as higher mass transfer rates correspond to better absorption of CO_2. At higher liquid flow rates, there is more solvent available to absorb CO_2, which leads to faster absorption and, therefore, a higher mass transfer coefficient. This is indicative of more efficient mass transfer between the gas and liquid phases. Conversely, the HTU decreases as the L/G ratio increases. At lower L/G ratios, HTU is higher, indicating that more space is required to achieve the same level of CO_2 absorption. As the L/G ratio increases, the absorption efficiency improves, and the required HTU decreases. The decrease in HTU with increasing L/G ratio suggests that the process of CO_2 absorption becomes more efficient as the liquid flow rate increases. With more solvent available, the mass transfer efficiency improves, reducing the required height of the absorption column.

At high MEA concentrations, conventional packed columns often suffer from decreased mass transfer due to increased solvent viscosity and reduced wettability of the packing. However, in RPBs, the strong centrifugal acceleration enhances liquid distribution and promotes film thinning, which helps mitigate viscosity-related limitations. This advantage allows RPBs to maintain high absorption performance even when using viscous solvents such as concentrated MEA. The current study confirms that KGa and CO_2 capture efficiency remain high at 70–90 wt% MEA, supporting previous reports on the robustness of RPBs under such conditions [42, 43].

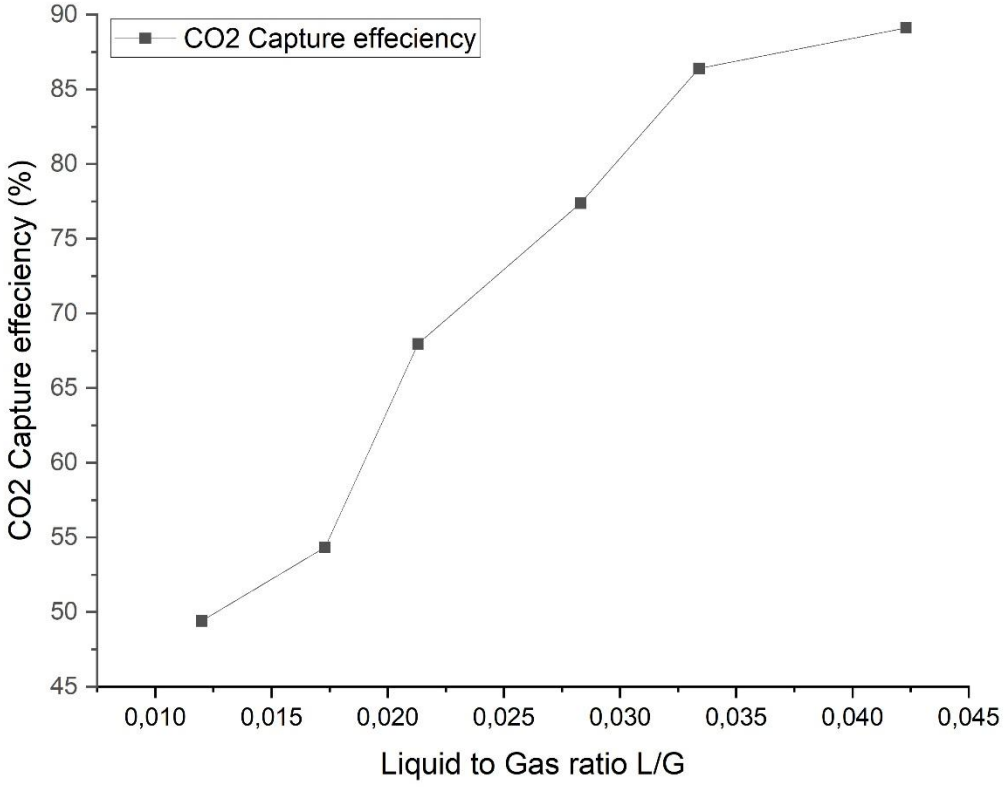


Figure 7. The effect of liquid to gas ratio on CO_2 capture efficiency. Experimental conditions: Liquid flow rate = 0.161-0.567 l/min; Gas flow rate = 13.4 l/min; Inlet CO_2 concentration = 15%; Pressure = 101.325 N/m²; Temperature = 25°C; Rotational speed = 1500 rpm; MEA concentration = 30 wt%.

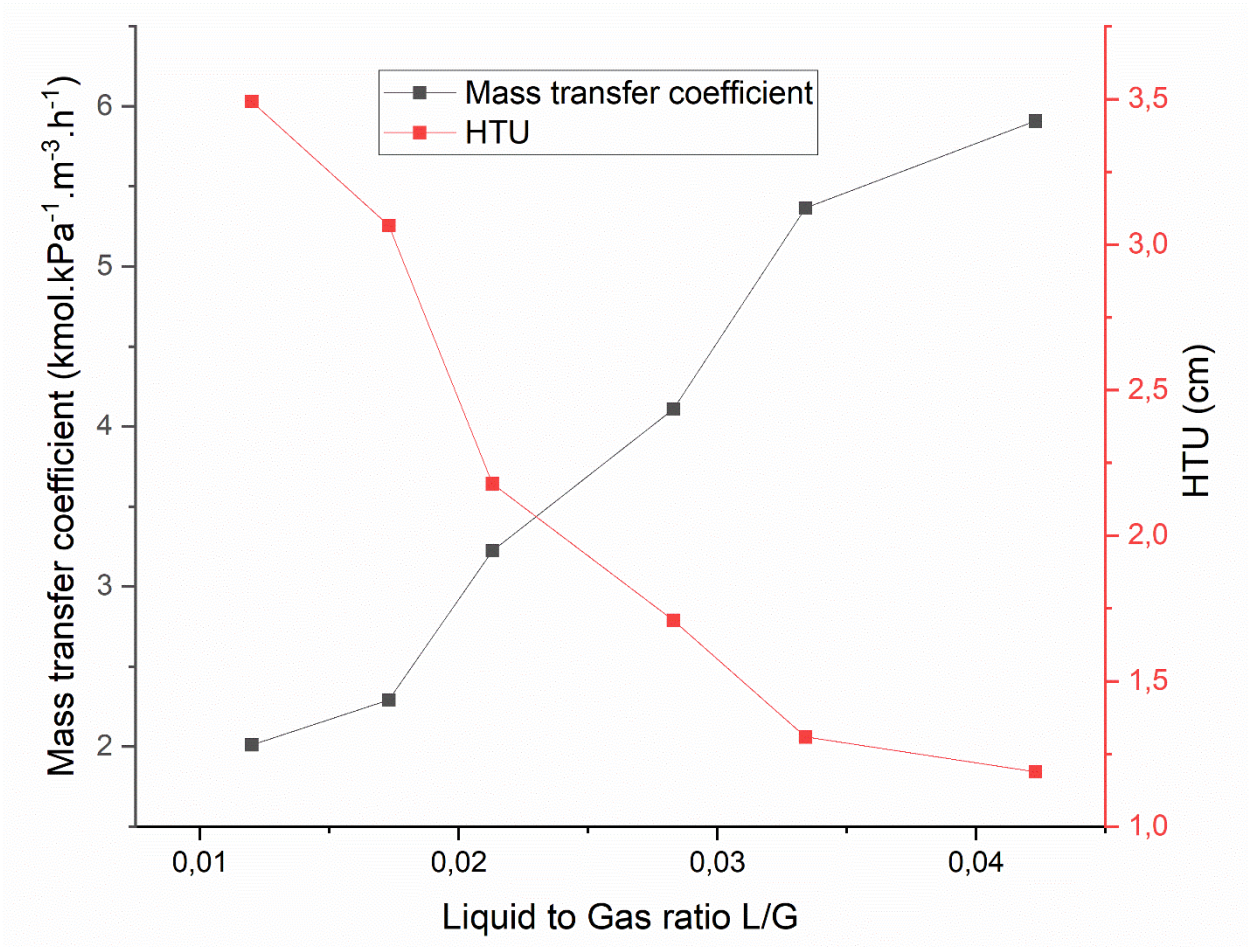


Figure 8. The effect of liquid to gas ratio on overall mass transfer coefficient ($K_G a$) and Height of Transfer Unit (HTU). Experimental conditions: Liquid flow rate = 0.161-0.567 l/min; Gas flow rate = 13.4 l/min; Inlet CO_2 concentration = 15%; Pressure = 101.325 N/m²; Temperature = 25°C; Rotational speed = 1500 rpm; MEA concentration = 30 wt%.

From the two figures (figure 7-8), it is evident that there is an inverse relationship between the mass transfer coefficient and HTU. As the mass transfer coefficient increases, the HTU decreases, and vice versa. This inverse relationship is typical in absorption processes, where improved mass transfer leads to more efficient CO_2 absorption and, as a result, reduces the amount of space (HTU) needed for the same level of CO_2 capture. The results highlight the importance of optimizing the liquid to gas ratio to achieve maximum CO_2 capture efficiency. Increasing the liquid flow rate improves both the mass transfer coefficient and CO_2 capture efficiency, while simultaneously reducing HTU. However, it is important to consider the operational costs associated with higher liquid flow rates, such as increased energy consumption for pumping and potential equipment wear. Moreover, the optimal liquid to gas ratio should balance the trade-off between increasing CO_2 capture efficiency and minimizing energy and operational costs. Further experiments are needed to explore the effect of varying other parameters, such as gas flow rate, pressure, and temperature, to achieve a comprehensive understanding of the factors influencing the CO_2 absorption process.

While the RPB system in this study demonstrated significantly enhanced mass transfer performance compared to conventional absorbers, the maximum CO_2 capture efficiency reached ~70% under optimal conditions. Achieving >90% removal, as typically required for industrial post-combustion capture, remains challenging in a single-stage, compact RPB due to short gas residence time (0.3–0.5 s), increased viscosity at high MEA concentrations, and distribution limitations. Multi-stage configurations or scale-up strategies may be necessary to reach capture rates ≥95%.

Compared to conventional packed column absorbers, the RPB system used in this study demonstrates enhanced volumetric mass transfer coefficients (KGa) and significantly reduced Height of Transfer Unit (HTU), indicating more efficient gas–liquid contact. Literature data [42, 43] show that RPBs can achieve 2–5 times higher mass transfer rates at similar operating conditions due to the high centrifugal acceleration and thin liquid films. Additionally, the compact size of RPBs offers advantages in terms of equipment footprint and potentially lower capital costs. Although direct comparison experiments were not conducted in this study, the presented results are in line with prior RPB vs. column studies and support the feasibility of intensified CO_2 capture using RPB technology.

The present investigation provides detailed insights into the absorption performance of an RPB using MEA. However, it should be noted that the overall energy efficiency of a carbon capture plant is dominated by the regeneration step. The observed improvements in absorption efficiency and mass transfer coefficients at high MEA

concentrations and rotor speeds may lead to higher rich solvent loadings, which subsequently affect the heat duty of the desorber. A comprehensive techno-economic assessment would require an integrated study of the complete absorption-stripping cycle, which is proposed as a critical direction for future work.

4. Conclusions

This study experimentally investigated the performance of a Rotating Packed Bed (RPB) absorber for CO_2 capture using aqueous monoethanolamine (MEA) solutions under various operating conditions. The influence of rotor speed, MEA concentration, and liquid-to-gas (L/G) ratio on CO_2 capture efficiency, overall mass transfer coefficient ($K_G a$), and Height of Transfer Unit (HTU) was systematically analyzed.

The results demonstrated a clear positive correlation between rotor speed and CO_2 capture efficiency, with an observed from less than 10% under stationary conditions to over 70% at high rotational speeds (2400 rpm). This increase was accompanied by a significant rise in the overall mass transfer coefficient, highlighting the role of centrifugal acceleration in intensifying gas–liquid interactions.

Increasing MEA concentration from 30% to 90% wt significantly improved CO_2 capture efficiency and mass transfer performance due to enhanced reaction kinetics. However, the associated increase in solvent viscosity presents practical trade-offs that must be considered during process design. A similar trend was observed in HTU reduction, confirming more efficient mass transfer at higher MEA concentrations.

Furthermore, the study revealed that higher liquid-to-gas ratios substantially enhance CO_2 absorption efficiency and ($K_G a$) while reducing HTU, demonstrating the importance of solvent availability and interfacial area in optimizing absorber performance. Nonetheless, the energy and operational costs associated with increased solvent flow must be carefully balanced.

While this study demonstrates the significant potential of rotating packed bed technology for intensifying the CO_2 absorption stage, it is crucial to acknowledge that the energy penalty associated with solvent regeneration remains the primary economic and operational challenge in amine-based carbon capture processes. The absorption parameters optimized in this work — such as high MEA concentration, elevated rotor speed, and favorable L/G ratio — directly influence the rich solvent loading and physicochemical properties, which in turn determine the thermal duty and size of the downstream regenerator. Therefore, the overall process viability and energy efficiency can only be fully assessed through an integrated analysis of the absorption-regeneration loop. Future research should focus on coupling the RPB absorber with an intensified stripper (e.g., another RPB or a compact column) to evaluate the combined effects of operating conditions on the total specific regeneration energy, which is essential for the scale-up and commercialization of RPB-based carbon capture systems.

Furthermore, while this study focused on establishing baseline performance with a single, benchmark amine (MEA), future work should prioritize the evaluation of advanced amine blends within the RPB. Solvents such as AMP–PZ (2-amino-2-methyl-1-propanol – piperazine) or MEA–PZ blends are renowned for their higher absorption capacity, faster kinetics, and lower regeneration energy compared to MEA. Investigating these blends in an RPB is a logical and critical next step to combine the benefits of advanced solvent chemistry with the process intensification offered by rotating packed beds. Such studies could identify synergistic combinations that maximize overall capture efficiency while minimizing both capital footprint (via intensification) and operating costs (via reduced energy penalty).

Overall, the findings confirm that RPB technology is a highly effective process intensification approach for post-combustion CO_2 capture. The insights gained from this study provide valuable data for designing, scaling up, and optimizing industrial CO_2 absorption systems using RPBs.

Despite the promising results, several operational challenges were noted during the use of RPBs. Mechanical vibrations at high rotor speeds (>2400 rpm) required careful balancing, and motor wear became more noticeable over extended runs. Ensuring uniform liquid distribution was also critical, as improper inlet design can lead to maldistribution or foaming. These factors highlight the need for robust mechanical design and precise flow control in future scale-up efforts. Furthermore, scaling RPBs from laboratory to industrial scale poses structural and hydrodynamic challenges that must be addressed before full commercial deployment.

Acknowledgments

This work was carried out as part of basic research conducted at the Laboratory of Petroleum Chemistry, Institute of General and Inorganic Chemistry of the Academy of Sciences of the Republic of Uzbekistan.

The authors gratefully acknowledge the financial support provided by the Government of the Republic of Uzbekistan within the framework of the applied research project entitled “Development of a technology for cleaning flue gases from harmful components using an efficient absorber device”.

The project was supported under the Applied Research Program, scientific field Engineering Sciences, Competition Type 113, Project No. AL-11325078246.

Author Contributions:

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review and editing. Bekzod Rakhimov: Experimental investigation, operation of the rotating packed bed system, data acquisition, validation. Sayyora Ganiyeva: Data analysis, visualization, uncertainty analysis, writing – review and editing. Kuatbergen Kosnazarov: Chemical analysis, solvent preparation and characterization, validation of experimental data. Mukhammad Tajetdinov: Theoretical analysis, mass transfer modeling, interpretation of kinetic and hydrodynamic results. Dilshod Radjibaev: Experimental setup design, instrumentation, maintenance of laboratory equipment. Abdurasul Qayumov: Data interpretation, critical revision of the manuscript, writing – review and editing. Alisher Azimov: Resources, technical support, supervision of experimental work. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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