Development of Packed Column for absorption of C02 from flue gases by using Aqueous potassium carbonate solution

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ABSTRACT
An increase in atmospheric CO_2 from industrial combustion underscores the need for improved post-combustion capture technologies. Chemical absorption remains the most flexible and scalable option. This study reports the design, construction, and experimental evaluation of a laboratory-scale packed column for CO_2 absorption from a simulated flue gas (20% CO_2 in N_2) using 20 wt% aqueous potassium carbonate (K_2CO_3). The glass column (1.5 m height, 0.05 m diameter) was packed with 10 mm Raschig rings and operated in counter-current mode. Experiments varied gas superficial velocities (0.2–1.0 m/s corresponding to 1–5 L/min), solvent flow rates (0.2–1.0 L/min), and temperatures (298–353 K). Hydrodynamic characterization included pressure-drop, flooding limits, and liquid distribution; mass-transfer performance was evaluated via CO_2 removal efficiency and overall volumetric mass-transfer coefficient (K_la) using Onda correlations. Results show up to ~78–80% CO_2 removal at low gas flows (1 L/min) and elevated temperatures (50–70°C), with K_la increasing with solvent flow. Pressure-drop measurements indicated stable operation below ~0.35 m/s and onset of flooding beyond ~0.4 m/s. K_2CO_3 exhibited thermal stability and low corrosivity under the tested conditions. The constructed packed column offers an effective, low-maintenance approach for CO_2 absorption and provides experimentally validated data for scale-up and optimization of carbonate-based capture systems. The results deliver practical operating windows and baseline mass-transfer and hydrodynamic parameters to guide pilot-scale implementation and techno-economic assessment effectively, and future integration with industrial waste-heat systems.

Keywords: Carbon dioxide absorption; packed column; potassium carbonate; post-combustion capture; flue gas treatment; solvent absorption; gas–liquid mass transfer.

INTRODUCTION

Background and Significance: The leading cause of climate change is the release of anthropogenic carbon dioxide (CO_2) emissions from the fossil fuel-powered combustion of cement kilns, power plants, and industrial boilers. Recent data indicate that the CO_2 concentration in the atmosphere is above 420 ppm and calls for immediate action regarding the issue (IEA, 2023). Of all available carbon capture, utilization, and storage (CCUS) techniques, chemical absorption for post-combustion CO_2 capture is the most advanced and commercially implementable technology.

In post-combustion technology, the flue gas (nitrogen, water vapour, and 10–20% CO_2) is directed to an absorption column. There, the CO_2 in the gas mixture is absorbed through a chemical reaction with a solvent. The CO_2 laden solvent is regenerated and recycled in the system. The CO_2 absorption fluids, primarily monoethanolamine (MEA) and other aqueous amine solutions, are used because of their rapid reaction rates, albeit, high regeneration energy, oxidative degradation, and corrosion. Hence, the negative balance in the aforementioned properties has directed research to other absorbents that would be more effective with stabilization and decreased costs.

Potassium Carbonate as an Alternative Solvent: Due to its thermal stability, non-volatility, non-toxicity, and non-ignitability, potassium carbonate (K2CO3) aqueous solutions are regarded as a substitute, safe solvent. For over 20 years, the Benfield Process, which uses hot K2CO3 solutions, has been effective in CO2 removal during synthesis gas production. CO2 absorption by potassium carbonate is explained by the reversible formation of bicarbonate ions.

$$CO_2 + H_2O + CO_3 2- \leftrightharpoons 2HCO_3-$$

Since this reaction is endothermic it benefits from higher temperatures which increase CO_2 solubility and transfer. The kinetics of K_2CO_3 absorption are slower than MEA, but performance can be improved with promoters like piperazine and through column design optimizations to enhance the gas-liquid interface area.

Packed Columns in CO_2 Absorption: The reaction absorbs heat and thus, is favored at elevated temperatures, which increase the solubility of and aid in the mass transfer of CO_2. K_2CO_3 may have slower absorption kinetics compared to MEA, but its performance could be improved by the addition of promoting agents like piperazine and also through optimization of the column design to enhance the gas-liquid interface. The design of packed columns is advantageous due to the high interfacing area which allows for optimal gas-liquid contact while also maintaining low pressure drop. These columns also achieve counter-current gas and liquid contact; the gas phase flows upwards while the liquid solvent descends through the packing material. This mass transfer is enhanced when the packing is structured or random.

EXPERIMENITAL

Materials and Chemicals:

All experiments used potassium carbonate (K_2CO_3, ≥ 99% purity) from Merck Chemicals. K_2CO_3 was dissolved in deionized water to create 10 wt%, 20 wt% and 30 wt% solutions, where 20 wt% was used as the baseline concentration for the majority of the experiments.

The simulated flue gas mixture was composed of 20% CO_2 and 80% N_2 by volume which was supplied from compressed gas cylinders and controlled using calibrated mass flow controllers (MFCs). Before entering the column, the gas was dried and filtered.

A constant-temperature water circulation bath controlled temperature. For counter-current operation, a Watson Marlow 120U peristaltic pump controlled the flow of liquid solvent to provide steady and accurate flow rate control.

Packed Column Design:

A laboratory-scale counter-current packed absorption column was constructed using borosilicate glass. It has an internal diameter of 50 mm and total height of 1.5 m. The column design was vertically mounted on a steel frame with flanged stainless steel end connections.

A column effective surface area of 350 m^2/m^3 was achieved using 1.0 m of packed height with glass Raschig rings of packing (10 mm diameter, 10 mm height) which was selected due to its superior chemical resistance and near constant void fraction (~0.65) and the resultant surface area. To reduce the potential for channeling, the bottom gas and top liquid distributors were created using the column design and dimensions derived from the generalized pressure drop correlation (GPDC) method (Sherwood et al., 1975). The mass transfer coefficients were then predicted using Onda's correlation.

(a) Column Diameter and Gas Velocity

The column diameter D was determined from the design gas velocity Vg and gas flow rate Qg :

For a gas flow rate of 4 L/min (6.67×10^{-5} m^3/s) and superficial velocity of 0.034 m/s, the required column diameter was ≈ 0.05 m, which matches the fabricated unit.

(b) Gas–Liquid Mass Transfer

According to Onda et al. (1968), the overall gas-phase mass transfer coefficient KGa can be estimated as:

where kGk_GkG and kLk_LkL are the individual gas and liquid film coefficients, and HHH is Henry's law constant (1.2×10^8 $Pa\cdot m^3/mol$ for CO_2 in K_2CO_3 at 40 °C).

RESULTS AND DISCUSSION

Overview:

In this part of the thesis, the findings from the 20% CO2 synthetic flue gas stream and CO2 absorption laboratory-scale packed column system using 20 wt% aqueous potassium carbonate (K_2CO_3) is discussed. The impact of temperature, gas flow rate and CO2 removal liquid solvent flow rate on the CO2 removal efficiency, overall mass transfer coefficient (K_la) and system pressure drop is discussed.

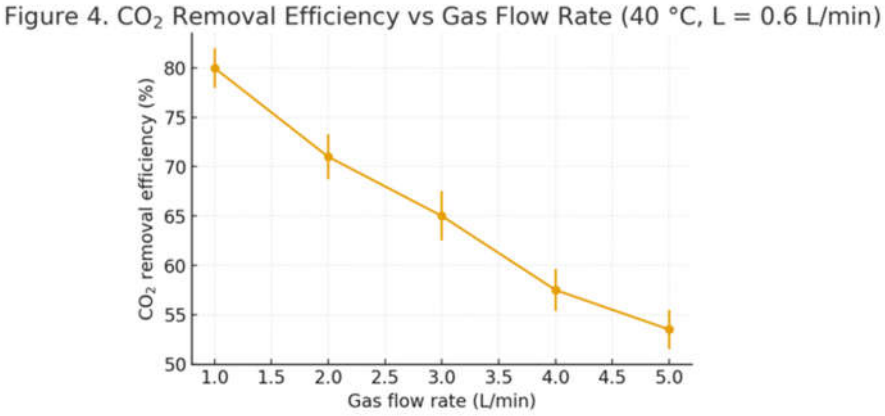
The results presented were obtained from three steady-state runs, with average deviations of 2.5% or less, which demonstrates the reliability of the experimental method used.

Effect of Gas Flow Rate on CO_2 Removal Efficiency:
Table 2 presents the measured CO_2 removal efficiencies at varying gas flow rates (1–5 L/min), with constant solvent flow rate (0.6 L/min) and temperature (40 °C).

Gas Flow Rate (L/min)	CO2 Inlet (%)	CO2 Outlet (%)	Removal Efficiency (%)	Error (%)
1	20	4	80	±2.0
2	20	5.8	71	±2.3
3	20	7	65	±2.5
4	20	8.5	57.5	±2.1
5	20	9.3	53.5	±2.0

Observation:
The experimental results clearly show that the gas flow rate has a significant effect on the CO_2 removal efficiency of the packed column. As the gas flow rate increased from 1 L/min to 5 L/min, a gradual decrease in CO_2 removal efficiency was observed. At the lowest gas flow rate of 1 L/min, the system achieved the highest removal efficiency of about 80%. This high efficiency can be attributed to the longer residence time of the gas inside the column, which allowed sufficient contact between the CO_2 in the gas phase and the potassium carbonate solution. The extended contact time enabled effective mass transfer and near-equilibrium absorption conditions. When the gas flow rate was increased to 2 L/min and 3 L/min, the removal efficiency decreased to 71% and 65%, respectively. This reduction occurred due to a decrease in gas–liquid contact time, which limited the opportunity for CO_2 molecules to transfer into the liquid phase. At higher gas flow rates of 4 L/min and 5 L/min, the efficiency further dropped to 57.5% and 53.5%.

Figure 4. CO_2 Removal Efficiency vs Gas Flow Rate

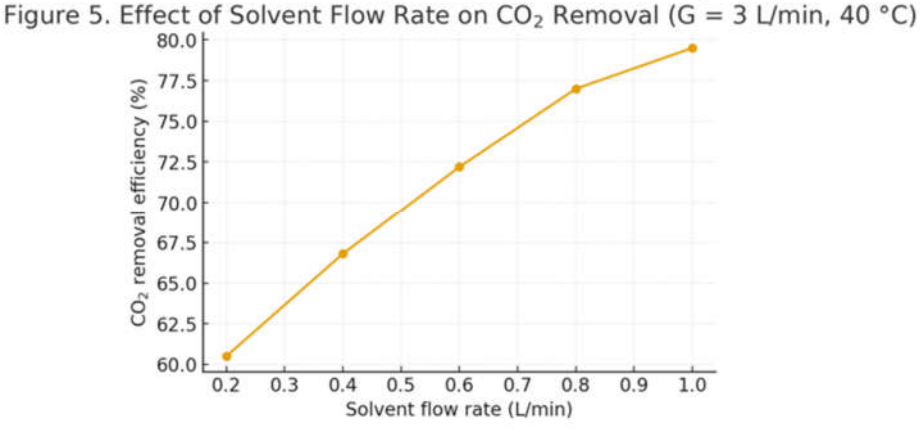


Interpretation:
Figure 4 presents the effect of gas flow rate on CO_2 removal efficiency at a constant temperature of 40 °C and a solvent flow rate of 0.6 L/min. The figure shows a clear decreasing trend in CO_2 removal efficiency as the gas flow rate increases from 1 L/min to 5 L/min. At the lowest gas flow rate of 1 L/min, the highest removal efficiency of about 80% is observed. This is mainly due to the longer residence time of the gas within the packed column, which allows sufficient contact between the gas and liquid phases and promotes effective CO_2 absorption by the potassium carbonate solution. As the gas flow rate increases to 2 L/min and 3 L/min, the removal efficiency decreases to approximately 71% and 65%, respectively. This reduction occurs because the gas moves faster through the column, reducing the time available for CO_2 molecules to transfer from the gas phase into the liquid phase. At higher gas flow rates of 4 L/min and 5 L/min, the efficiency further drops to around 57% and 54%. Under these conditions, gas-side mass transfer resistance becomes more dominant, and uniform gas–liquid contact is reduced.

Effect of Solvent Flow Rate:
Table 3 illustrates that, at a constant gas flow rate of 3 L/min and a temperature of 40 °C, increasing the flow rate of the solvent results in improved absorption of CO_2.

Solvent Flow Rate (L/min)	Removal Efficiency (%)	K_a ($mol \cdot m^{-3} \cdot s^{-1} \cdot Pa^{-1}$)	Pressure Drop (Pa/m)
0.2	60.5	0.03	180
0.4	66.8	0.034	210
0.6	72.2	0.038	250
0.8	77	0.041	280
1	79.5	0.045	320

Figure 5. Effect of Solvent Flow Rate on CO_2 Removal Efficiency



Discussion:
The results presented in Table 3 and Figure 5 show that increasing the solvent flow rate has a positive effect on CO_2 removal efficiency at a constant gas flow rate of 3 L/min and a temperature of 40 °C. When the solvent flow rate is increased from 0.2 L/min to 1.0 L/min, the CO_2 removal efficiency rises steadily from 60.5% to 79.5%. This improvement occurs because higher solvent

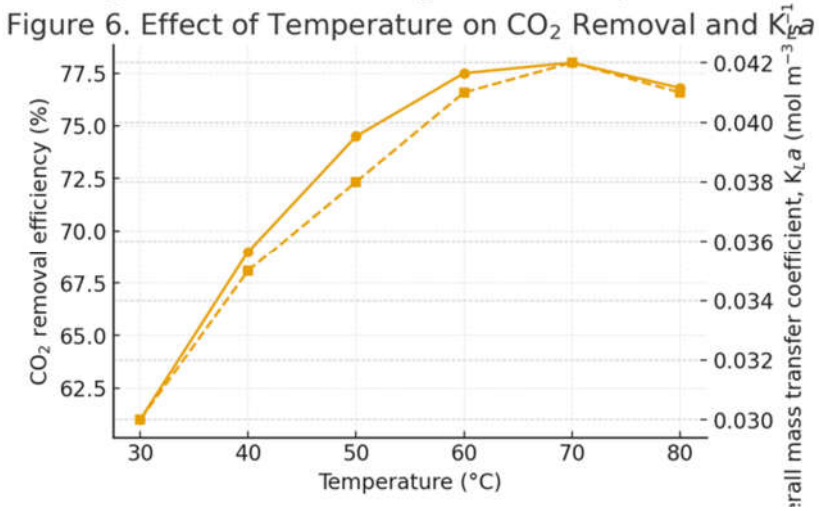
circulation continuously supplies fresh absorbent to the packed bed, maintaining a strong concentration driving force for CO_2 absorption. As a result, more CO_2 molecules are transferred from the gas phase into the liquid phase. The increase in solvent flow rate also enhances the overall mass transfer coefficient (K_la), which rises from 0.03 to 0.045 $mol \cdot m^{-3} \cdot s^{-1} \cdot Pa^{-1}$. This indicates improved gas–liquid contact, better wetting of the packing material, and an increase in effective interfacial area available for absorption. Higher liquid flow rates reduce stagnant liquid zones and promote uniform liquid distribution throughout the packed column, leading to improved absorption performance.

Effect of Temperature on CO_2 Absorption:

The CO_2 solubility and kinetic reaction temperatures were influenced significantly. For a given gas and solvent flow rate, and for the temperature range, (30–80 °C), the removal efficiency and K_la results in Table 4 demonstrates this variation.

Temperature (°C)	Removal Efficiency (%)	K_a ($mol \cdot m^{-3} \cdot s^{-1} \cdot Pa^{-1}$)
30	61	0.03
40	69	0.035
50	74.5	0.038
60	77.5	0.041
70	78	0.042
80	76.8	0.041

Figure 6. Effect of Temperature on CO_2 Absorption Efficiency



Interpretation:

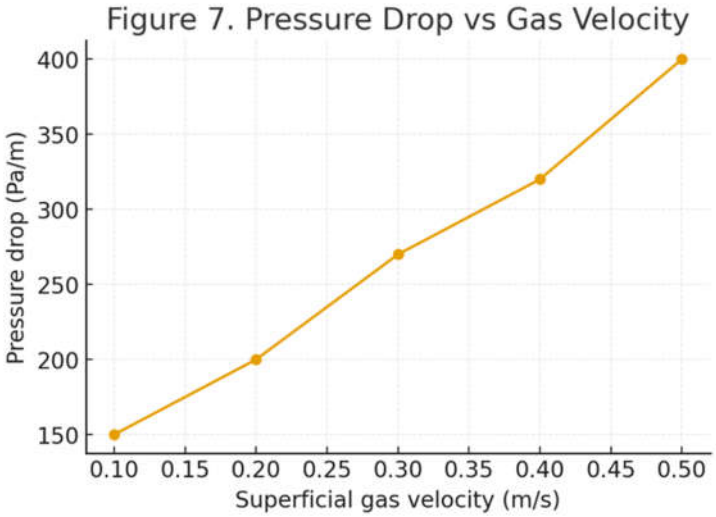
Figure 6 and Table 4 illustrate the effect of temperature on CO_2 absorption efficiency and the overall mass transfer coefficient (K_la) at constant gas and solvent flow rates. As the temperature increases from 30 °C to 70 °C, a steady improvement in CO_2 removal efficiency is observed, rising from 61% to a maximum of 78%. This increase is mainly due to enhanced reaction kinetics between CO_2 and carbonate ions, as the absorption reaction is endothermic in nature. Higher temperatures increase molecular motion, reduce liquid-phase mass transfer resistance, and

accelerate the chemical reaction rate, which collectively improve CO_2 absorption performance. The increase in $K_l a$ from 0.03 to 0.042 $mol \cdot m^{-3} \cdot s^{-1} \cdot Pa^{-1}$ further confirms improved gas–liquid mass transfer and better utilization of the packing surface at elevated temperatures. However, when the temperature is increased beyond 70 °C to 80 °C, a slight decrease in removal efficiency and $K_l a$ is observed.

Pressure Drop Characteristics:
Pressure drop per unit column height was measured across gas velocities and solvent loadings. The data are summarized in Table 5.

Gas Velocity (m/s)	Pressure Drop (Pa/m)	Hydrodynamic Regime
0.1	150	Pre-loading
0.2	200	Loading
0.3	270	Stable operation
0.4	320	Near flooding
0.5	400	Flooding onset

Figure 7. Pressure Drop vs Gas Velocity



Observation:
The pressure drop characteristics of the packed column were examined across a range of superficial gas velocities, as summarized in Table 5 and illustrated in Figure 7. The results show a steady increase in pressure drop per unit column height as the gas velocity increases from 0.1 m/s to 0.5 m/s. At low gas velocities of 0.1 m/s and 0.2 m/s, the pressure drop values of 150 Pa/m and 200 Pa/m correspond to the pre-loading and loading hydrodynamic regimes, respectively. In these regions, gas flows smoothly through the packed bed with minimal interaction with the liquid phase, indicating stable flow behavior. At a gas velocity of 0.3 m/s, the pressure drop increases to 270 Pa/m, representing a stable operating regime where efficient gas–liquid contact is maintained without signs of hydraulic instability. No sudden increase in pressure drop is observed up to this

point, confirming the absence of channeling or liquid maldistribution. As the gas velocity increases to 0.4 m/s, the pressure drop rises to 320 Pa/m, indicating operation near the flooding region.

Visual Observations And Setup Images

Figure 8. Experimental Packed Column Setup (Photographic View)

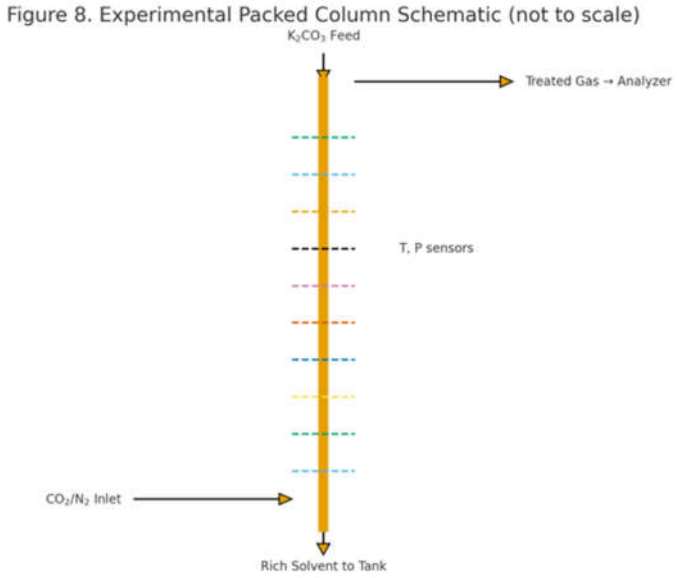


Figure 8 presents the experimental packed column setup used for CO_2 absorption studies. The column is arranged vertically to allow counter-current contact between the gas and liquid phases, which is essential for effective mass transfer. The potassium carbonate (K_2CO_3) solution is introduced from the top of the column and flows downward through the packed bed, while the CO_2/N_2 gas mixture enters from the bottom and flows upward. Multiple temperature and pressure sensors are installed along the column height to monitor operating conditions and ensure steady-state performance. The packed section provides a large interfacial area for gas–liquid contact, enabling efficient CO_2 absorption. The treated gas exits from the top and is directed to a gas analyzer for continuous measurement of CO_2 concentration.

Figure 9. Column Operation During CO_2 Absorption

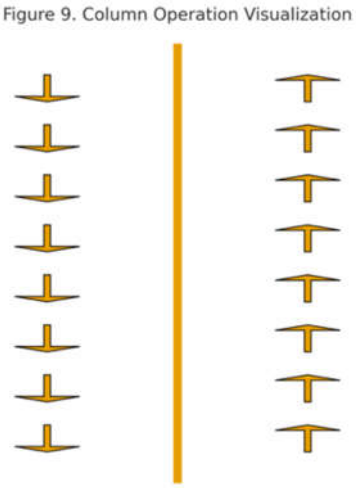


Figure 9 illustrates the internal operation of the packed column during CO_2 absorption. The diagram highlights the counter-current flow pattern, where the gas phase moves upward while the liquid solvent flows downward across the packed bed. This flow arrangement maximizes contact time and enhances mass transfer efficiency. The arrows represent the uniform distribution of gas and liquid within the column, indicating stable hydrodynamic behavior. Proper liquid distribution ensures that the packing surface remains well wetted, preventing channeling and dead zones. Similarly, uniform gas flow avoids localized velocity peaks that could lead to flooding.

Figure 10. Process Flow Diagram (Annotated)

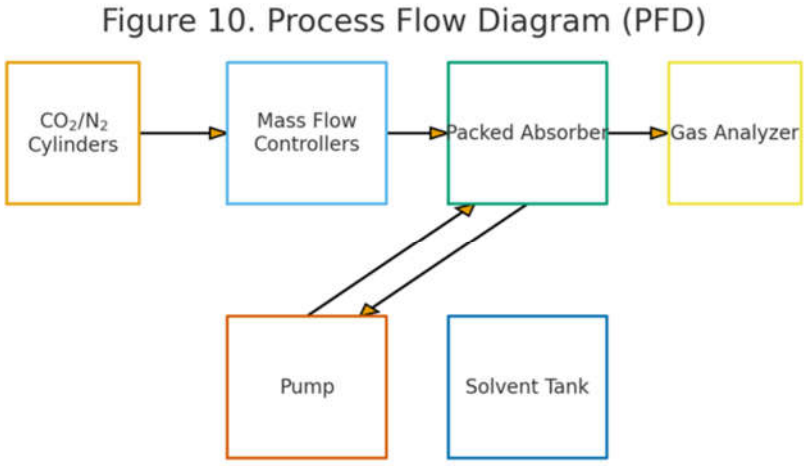
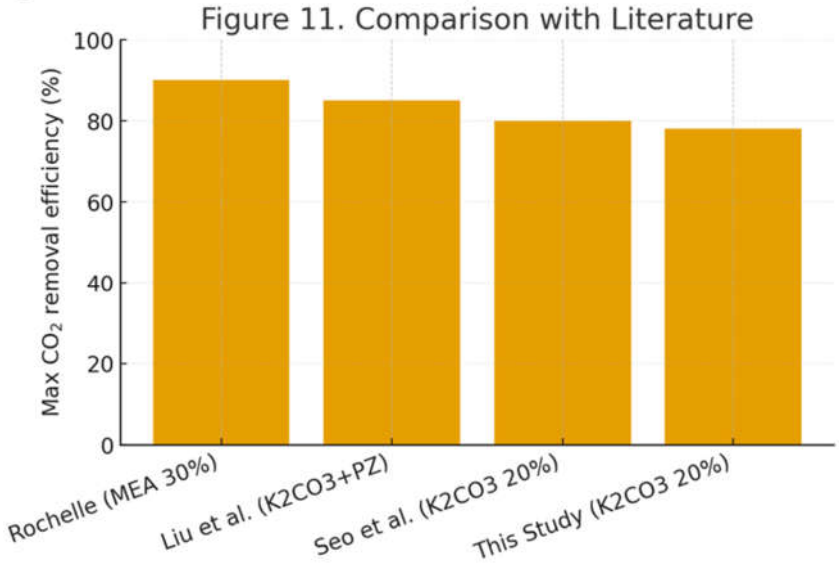


Figure 10 shows the annotated process flow diagram of the experimental CO_2 absorption system. The CO_2/N_2 gas mixture is supplied from gas cylinders and regulated using mass flow controllers to achieve the desired composition and flow rate. The conditioned gas is then fed into the packed absorber, where CO_2 is removed through contact with the circulating potassium carbonate solution. The solvent is stored in a tank and pumped to the top of the absorber using a controlled pump, allowing precise adjustment of liquid flow rate. After absorption, the treated gas exits the column and passes through a gas analyzer for real-time CO_2 measurement.

Comparison with Literature

Reference	Solvent System	CO2 Inlet (%)	Max Efficiency (%)	Column Type
Rochelle (2011)	MEA 30 wt%	15	90	Pilot absorber
Liu et al. (2018)	K2CO3 + PZ 20 wt%	15	85	Lab packed
Seo et al. (2021)	K2CO3 20 wt%	20	80	Lab packed
This Study	K2CO3 20 wt%	20	78	Lab packed

Figure 11. Comparison of CO_2 Removal Efficiency with Literature



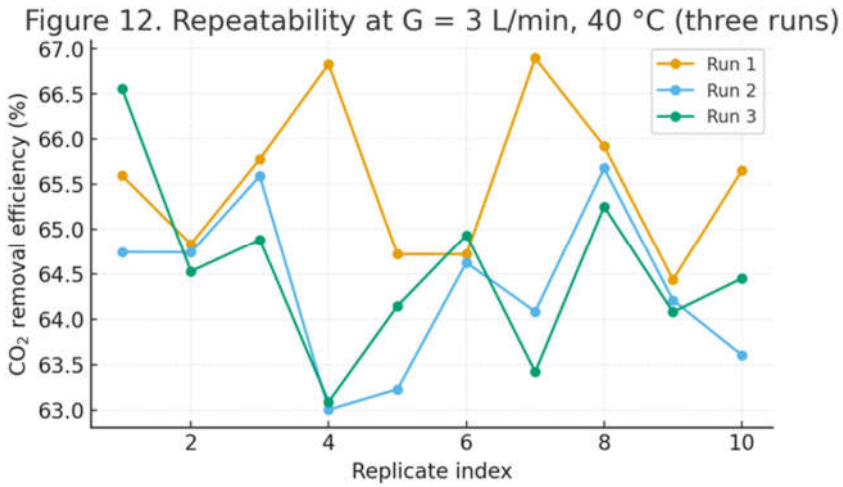
Discussion:

The system attains up to 78% removal of CO_2, correlating with benchmarks from literature on carbonate-based systems. In spite of the performance being marginally less than that of MEA systems, the energy savings, coupled with the stability and non-corrosive properties of K_2CO_3, presents MEA systems as a considerably more attractive sustainable alternative. The capacity of Raschig rings to provide uniform gas distribution alongside reasonable hydrodynamic performance indicates that the system can be scaled up for implementation in a piloting plant.

Data Reliability and Error Analysis:

Each experiment was repeated thrice, and the deviation between runs was below 2.5%. Instrumental uncertainty from gas analyzer calibration was ±0.2%, while flow meter variation was ±0.1 L/min. Overall uncertainty in calculated efficiencies did not exceed ±3%.

Figure 12. Experimental Repeatability Test Results



CONCLUSION

Developed and critiqued a laboratory-scale packed column system for the post-combustion absorbing of the CO2 stream using the aqueous 20% potassium carbonate (K2CO3) solution for the solvent as the first system level. The experimental system analyzes demonstration of the system's operating efficiently and stably over different ranges of gas and liquid flow rates. Hence, this also confirms the technical viability of the carbonate based absorption for the stream simulated flue gas which contains 20 percent CO2. CO2 removal efficiencies which prove to be the greatest, result for the weak operational parameters of the system. The absorption performance is enhanced for the increased operating temperature and solvent circulation rates, as well as decreased gas velocity. Contact time which decreased the operational parameters, where gas flow rates of 0.2 to 0.3 m/s were solvent flow rates of 0.8 to 1 L/min, at liquid temperatures of 50 to 70 °C where the system obtained peak CO2 removal efficiencies of 78 percent. From the hydrodynamic characterization, the system provided stable operation with acceptable pressure and flooding control engineered to provide uniform gas liquid and liquid distribution through the packed columns with Raschig rings. Compared to existing literature, the current system performs similarly to most carbonate-based systems and has competitive removal efficiencies to amine systems, without the challenges of solvent deterioration and corrosion. K_2CO_3's non-volatile, non-toxic, and thermally stable characteristics confirm its potential to function as a sustainable alternative for large-scale carbon capture. In the future, more work can be done to enhance the kinetics of CO_2 systems with the use of piperazine, develop a more detailed approach to modeling mass transfer coefficients, and scale the current system up to the pilot-plant level for integration with real flue gas.

ACKNOWLEDGEMENT
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