

Design, Fabricate and Functional Validation of a Wetted Wall
Column for the study CO₂ Absorption Kinetics

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Abstract

To make carbon capture more economically viable, accurate CO₂ absorption kinetics estimates for new solvents are essential: slow absorption kinetics require larger, more expensive reactors to compensate. Gas absorption kinetics are the result of both mass transport and chemical reaction kinetics, so process design decisions depend on understanding what is rate-limiting: slow mass transport is best compensated by changing the reactor's fluid dynamics, whereas slow reaction kinetics are best addressed by changing the solvent chemistry. In this study, we designed a laboratory-scale wetted wall column (WWC), a reactor that provides a precise, known interfacial area to allow us to separate chemical kinetics from molecular mass transport to assist in solvent screening. We report the validation of the WWC using a standard solvent (NaOH), determining the second order rate constant from the measured CO₂ absorption flux using established reactive thin film absorption relationships and comparing our measured rate constant to kinetic data from the literature. Successful validation confirms the WWC as a reliable tool for screening new solvents, thereby accelerating the search for more cost-effective carbon capture processes.

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Introduction

The dramatic increase in atmospheric CO₂ concentrations from fossil fuel combustion has been proven to have caused ongoing global warming, leading to climate destabilization, undesirable natural calamities, melting of glaciers, and extreme weather patterns (Gao et al., 2020). In the United States, CO₂ accounts for approximately 80% of all greenhouse gas emissions in 2022, underscoring its dominant contribution to the nation's climate footprint (USEPA, 2020). The escalating concentration of CO₂ emissions necessitates the development of efficient and scalable carbon capture, utilization, and storage (CCUS) technologies. CO₂ emissions can be averted from combustion via one of three major methods: pre-combustion, post-combustion, and oxy-fuel combustion (Gao et al., 2020). Post-combustion CO₂ capture is the most widely implemented approach because it is considered the most economically viable option for existing industrial retrofits. Several technologies have been developed for post-combustion CO₂ removal, including absorption using chemical and physical solvents, cryogenic separation, and membrane separation. Among these approaches, gas absorption with chemical solvents remains the most widely used and effective method (Jamal et al., 2006).

A wetted wall column (WWC) is commonly used to study mass transfer between two fluid phases (C. Wang et al., 2017). Wetted wall columns are well-suited for this purpose due to their well-defined interfacial area, which allows for the accurate determination of mass transfer coefficients without the complexities associated with random packing geometries. In this study, we designed, fabricated and validated a wetted wall column to study gas absorption processes like CO₂ capture. To validate the column's performance for CO₂ absorption, we conducted a series of experiments measuring the CO₂ absorption rate into sodium hydroxide (NaOH) solutions. The absorption of CO₂ in NaOH solution is a well understood gas-liquid reaction with extensive literature data available (Zhu et al., 2016). Successful validation confirms the WWC as a reliable tool for screening new solvents, thereby accelerating the search for more cost-effective carbon capture processes.

Literature Review

Chemical absorption is a popular method to remove and recover CO₂ at industrial scales (Hwang et al., 2010). In this process, a gas effluent stream contacts a liquid solvent that selectively reacts with and captures the CO₂ in an absorber column. The resulting CO₂-rich solvent is then transferred to a stripper unit, where it is heated to reverse the chemical reaction, releasing a concentrated stream of CO₂ for subsequent compression and utilization or storage. The regenerated lean solvent is recirculated back to the absorber, creating a continuous loop. This process serves as benchmark against which emerging alternatives are evaluated due to its high technology readiness level, proven effectiveness, and extensive industrial history (Anderson et al., 2011). As a benchmark technology, chemical absorption provides a performance and economic baseline for comparison with newer, less mature methods like membrane gas separation, solid adsorbent-based systems, and hybrid membrane-based solvent absorption. Key metrics for benchmarking these emerging technologies include energy efficiency and cost, which must be comparable or better than chemical absorption to be industrially competitive.

CO₂ mass transfer is a basic process underlying all CO₂ absorption processes (Thee et al., 2012). To facilitate efficient mass transfer, the solvent is specifically chosen for its high affinity and capacity for CO₂, often involving not just physical dissolution but also chemical reactions that enhance capture. The goal is to create favorable thermodynamic and kinetic conditions that enable the purified gas to leave the system while the solute remains dissolved in or reacted with the solvent for subsequent recovery or disposal.

CO₂ mass transfer kinetics have been studied using wetted-wall columns (WWC) (Thee et al., 2012), stirred liquid batch reactors (Kucka et al., 2003), single sphere units and laminar jets (Jamal et al., 2006). These reactors serve as test units for studying CO₂ capture kinetics at laboratory scales prior to applying new solvents to more complex multiphase flows in more intricate large-scale equipment such as packed-bed absorbers, bubble column reactors, or spray towers. Laboratory-scale reactors can only reliably measure scalable kinetic parameters if they have a well-defined vapor-liquid interfacial area, controllable

hydrodynamics, and minimal or well-defined mass transfer resistance. Due to its simple design, the WWC is the preferred reactor over other approaches (Siy et al., 2013). For instance, stirred liquid batch reactors face difficulties in ensuring a balance between sufficiently high mixing to maintain a constant diffusive driving force and sufficiently low mixing to minimize perturbing the interface (Kucka et al., 2003). The WWC provides a thin, laminar film of liquid solvent descending under gravity along a vertical surface (Figure 1). WWC fabrication often involves precision turning or grinding of the core column, followed by polishing. The gas stream, typically a mixture of CO₂ and an inert carrier gas like N₂, can flow concurrently or counter-currently to the liquid. Counter-current flow is often preferred as it maintains a constant driving force along the column height, simplifying data analysis.

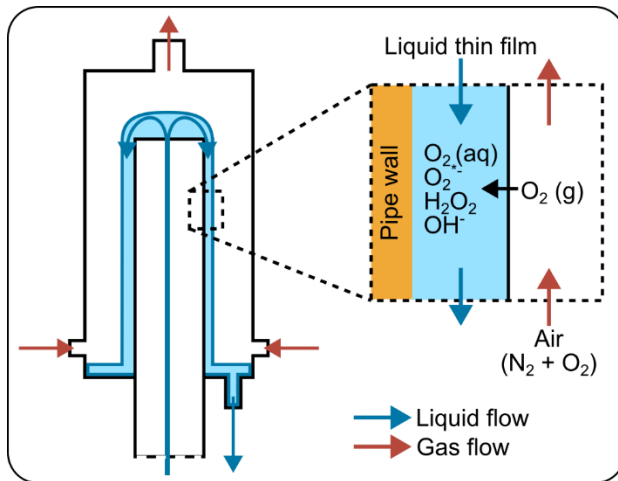


Fig 1. Simplified wetted wall column showing the thin laminar flow of liquid (Boualavong 2025)

The primary advantage of the WWC over other more popular industrial-scale contactors like packed bed columns is its precisely calculable and constant gas-liquid interface area, a critical feature not easily achieved (Grünig et al., 2012). Mass transfer within liquid film has usually been studied by absorption of slightly soluble gas such as CO₂ into water or organic solvents, and the mass transfer kinetics data are usually published in a dimensionless form as the dependence of Reynolds Number (Re_L) or Sherwood Number (Sh_L) (Haidl et al., 2016).

$$Re_L = \frac{4\Gamma}{u_L}$$

Reynolds number cited from (Haidl et al., 2016)

Eqn. 1

Re_L is the critical Reynolds number of the liquid phase, which characterizes the flow regime of the liquid film along the wetted wall of the column. Γ is the liquid mass flow rate per wetted perimeter, describing the amount of liquid distributed along the column wall per unit length of the wetted surface. This parameter is commonly used in wetted wall column analyses because the liquid forms a thin film rather than occupying the entire cross-sectional area of the column. u_L is the liquid film velocity according to the Nusselt's theory for laminar falling films.

$$Sh_L = \frac{k_L}{D_{co2l}} \sqrt{\frac{u^2}{p_L^2 g}}$$

Sherwood number cited from (Haidl et al., 2016)

Eqn. 2

Sh_L is the liquid phase Sherwood number, a dimensionless parameter that characterizes the ratio of convective mass transfer to diffusive mass transport within the liquid phase. It quantifies the effectiveness of solute transport from the gas-liquid interface into the bulk liquid. The liquid phase mass-transfer coefficient is denoted by k_L , which describes the rate at which a solute, such as carbon dioxide, is transferred from the gas phase across the liquid film. D_{co2} is the molecular diffusivity of the solute in the liquid which governs the rate of molecular diffusion through the liquid film. u is the dynamic viscosity of the liquid and p is the pressure which can influence gas solubility. g is the gravity acceleration, a fundamental physical constant that drives the downward flow of the liquid film in a wetted wall column. The characteristic dimensions used in Sh_L and Re_L in their standard form are the film thickness, δ , and the mean film velocity u_L . However, when used in problems involving flowing films, substitution for these are not easily measurable quantities. They are usually performed on the basis of the Nusselt's theory (Haidl et al., 2016). The theory models laminar film condensation on a vertical surface, assuming heat transfer occurs through pure conduction across a smooth, stagnant liquid film.

(Bishnoi & Rochelle, 2000) presented a pseudo-first-order expression for mass-transfer flux based on surface renewal theory, which is widely applied in the analysis of experimental data obtained from chemical absorption studies using a wetted wall column (WWC).

$$N_{CO_2} = k_L^0 \sqrt{1 + \frac{k_1 D_{CO_2}}{k_L^{0^2}} \frac{P_{CO_2}^I - P_{CO_2}^*}{H_{CO_2}}}$$

Pseudo-first-order expression for flux

Eqn. 3

N_{CO_2} represents the molar flux of carbon dioxide, which is the rate of transfer of CO_2 across the gas-liquid interface. The term k_L^0 is the liquid-phase physical mass transfer coefficient in the absence of any chemical reaction. The rate constant for a pseudo-first-order reaction involving CO_2 in the liquid phase is denoted by k_1 ($= k_2[sorbent]$), while D_{CO_2} is the diffusion coefficient of CO_2 within the liquid. The driving force for mass transfer is represented by the difference between the partial pressure of CO_2 at the gas-liquid interface, $P_{CO_2}^I$, and its hypothetical equilibrium partial pressure, $P_{CO_2}^*$, which would be in equilibrium with the bulk liquid concentration. H_{CO_2} is Henry's law constant, which relates the interfacial partial pressure to the corresponding liquid-phase concentration. Based on these equations, by precisely controlling variables in the WWC such as liquid flow rate, gas composition, and temperature, researchers can isolate the chemical reaction kinetics from the confounding effects of mass transport.

WWCs have been used to deconvolute the individual contributions of blended amines like PZ/MEA and AMP/MDEA, informing synergies (N. Wang et al., 2022). In such blends, the overall CO_2 absorption rate is not a simple sum of the individual components' rates; instead, the amines interact through intricate reactions in the liquid phase. By providing precise, intrinsic kinetic data under controlled conditions the column is typically housed in a thermostatic environment, e.g., a water bath as shown in figure 2, to maintain isothermal conditions because kinetic parameters can be highly temperature sensitive and the CO_2 absorption reaction is exothermic. The key measured variable is the CO_2 absorption flux, from which the CO_2 absorption rate constant can be determined and the WWC provides conditions under which the CO_2 flux can be measured using blended amines. This approach enables the quantification of the individual and synergistic contributions of each amine, distinguishing, for example, the fast-carbonating role of a primary amine like MEA from the rapid buffering capacity of a cyclic diamine like PZ, all while considering the high equilibrium

capacity of a tertiary amine like MDEA. The resulting data inform a deeper understanding of reaction pathways and diffusion processes within the blend.

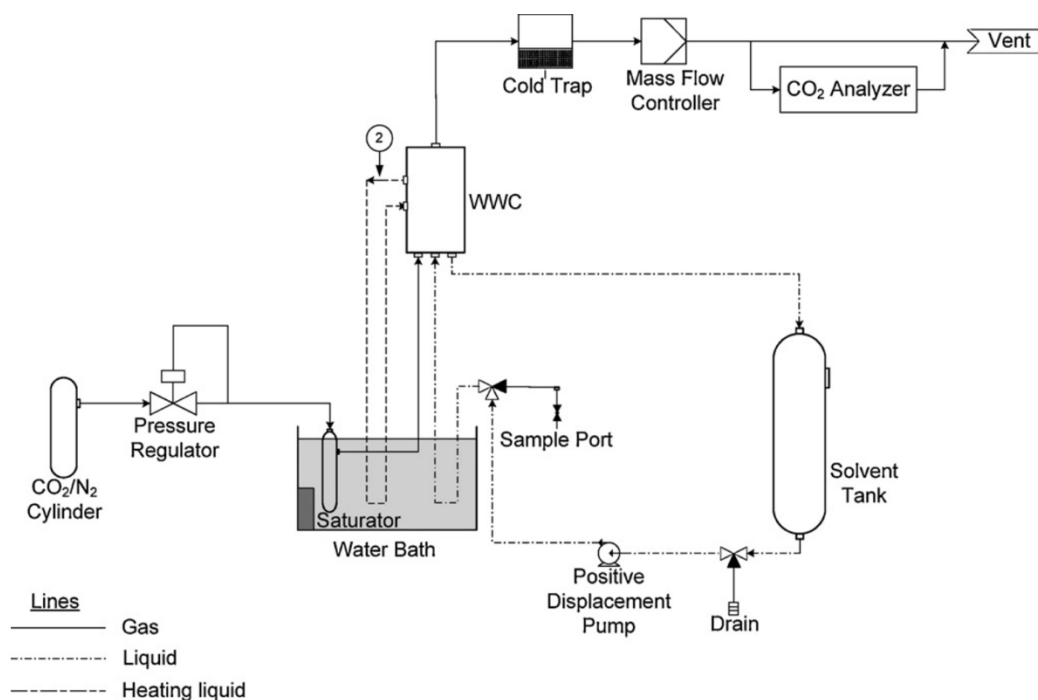


Fig 2. Process flow diagram of the wetted-wall column cited from (Thee et al., 2012)

To determine its functionality, the wetted wall column (WWC), must be validated with previously reported experimental data (C. Wang et al., 2017). This project aims to validate a custom-built wetted wall column (WWC) designed as a cost-effective experimental apparatus. The WWC is intended to function as a reliable screening device that enables systematic testing of different absorbent solutions in order to identify those with the most effective CO₂ capture characteristics. The development of this system includes the conceptual design, fabrication, calibration, and experimental validation of the WWC to ensure that it produces reliable and reproducible results comparable to established methods reported in the literature. The complete methodology, from the initial design phase through construction, experimental setup, and validation procedures, is described in detail in the subsequent chapters of this report.

Materials and Methods

Wetted Wall Column Design & Experimental Setup

The wetted wall column designed in this project is a benchtop apparatus that provides stable, well-characterized, and precisely controlled gas-liquid contact conditions essential for reliable kinetic measurements. The central component of the experimental setup is a vertical absorption column made of stainless steel, chosen for its excellent resistance to corrosion when exposed to aggressive chemicals such as NaOH. A metal was chosen over a ceramic or polymeric material because future studies are interested in the effect of surface electrification. Its smooth surface finish further facilitates the formation of a stable, uniform laminar liquid film, which is essential for reliable mass transfer performance. The column specifications include an inner tube with an outer diameter of 1-inches and a length of 11.5 cm (Figure 3).

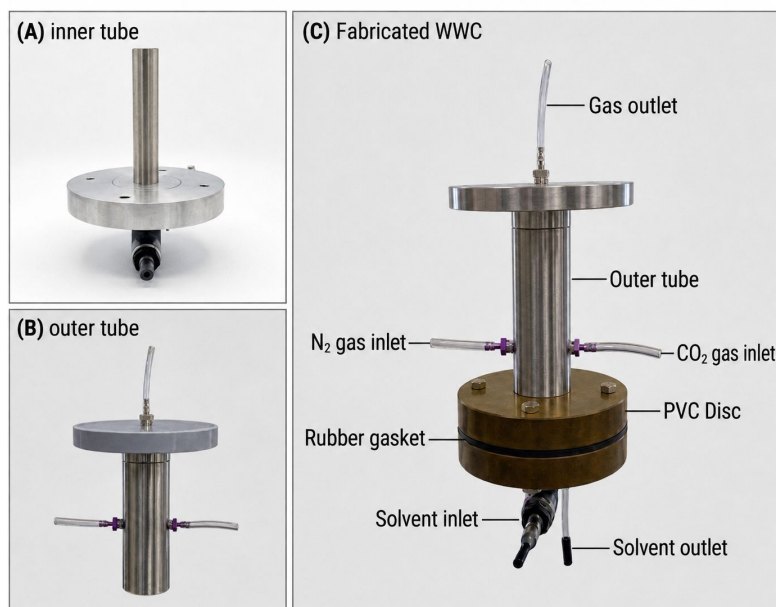


Fig. 3 Fabricated WWC showing outer and inner tube.

The outer stainless tube, featuring an outer diameter of 2-inches length of 18 cm, concentrically surrounds the inner tube (Figure 2.1). The 1-inch radial clearance between the inner and outer tubes provides space for both the liquid film and for gas flow. Both the lower

and upper ends of the column are capped with polyvinyl chloride (PVC) discs, each measuring 6-inches in diameter and 1 inch in thickness. These PVC discs act as lightweight, corrosion-resistant headers that enclose the reactor and center the inner tube within the outer column tube. The two PVC pieces at the bottom end are sealed with a water and steam resistant gasket to prevent leakage, creating a fully closed system where the working fluid is separated from the ambient air. Gas enters the column at the bottom of the outer stainless-steel tube, flowing antiparallel to the liquid film to maximize the driving force for absorption while maintaining stable hydrodynamic conditions. Prior to entering the column (Figure 2.4), the gas stream passes through a humidification system (pure water) that saturates it with water vapor to prevent evaporation that would complicate data interpretation. Any unabsorbed gas exits the column via the overhead gas outlet and is passed to an in-line gas sensor, from which CO_2 concentrations. CO_2 absorption flux can be calculated by completing the mass balance given known gas inlet and outlet concentrations. The aqueous solutions employed in this experiment were (a) 1 M sodium hydroxide (NaOH) and (b) sulfuric acid (H_2SO_4), diluted to a pH of 4.3. This pH value was selected to avoid aqueous phase absorption reactions with hydroxide, leaving only physical absorption and CO_2 hydration (assuming $k_1 = 0$ in Eq. 3).

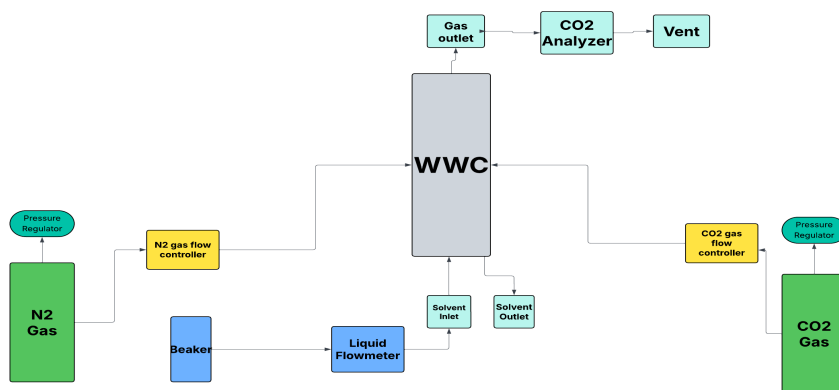


Fig. 4 Experimental Setup Flowsheet

Sensor Calibration

Two in-line IR sensors for carbon dioxide (Dynament) were employed to monitor gas-phase CO₂ concentrations coming out of the reactor throughout the experiment. Dynament's IR configurator software was employed for the absorbance measurement, and the process is described in the figure below.

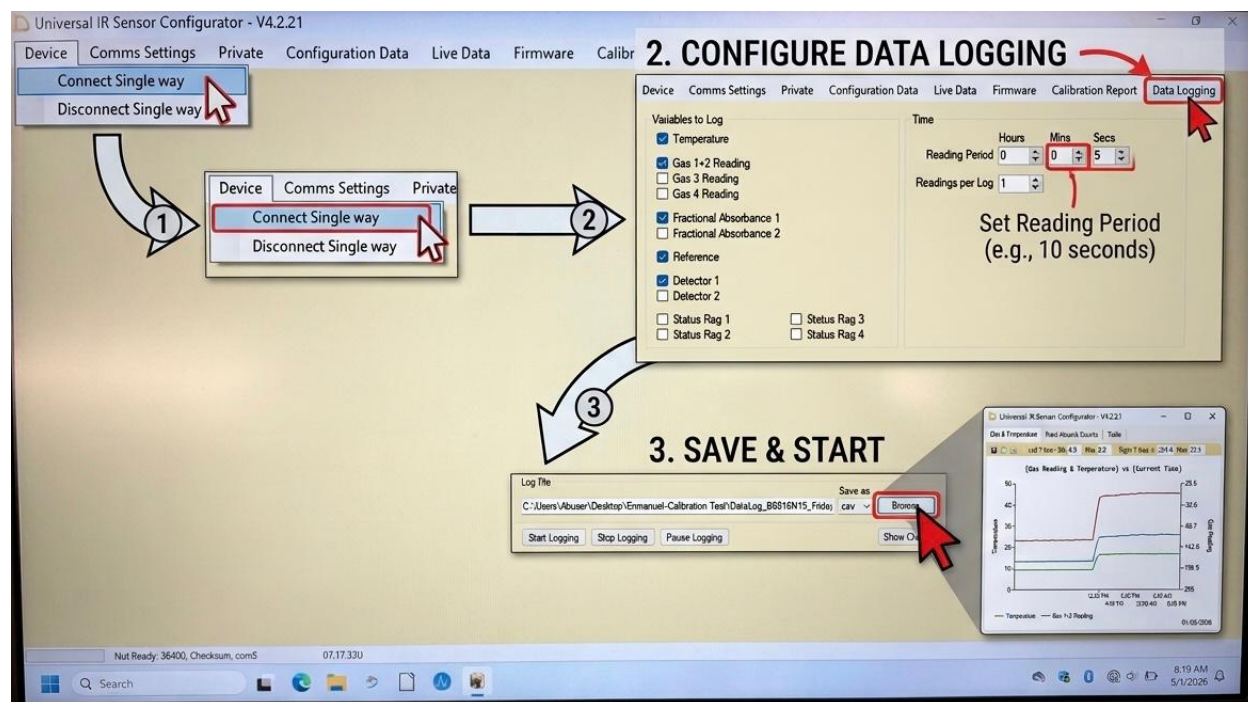


Fig 5. IR Configurator software process

A sensor with a measurement range of 0–100% CO₂ (“high-range sensor”) and a second sensor with a range of 0–10% CO₂ (“low-range sensor”) but with greater resolution in this range. The sensor was enclosed within a fitted cap to ensure proper positioning and to prevent leakage (Figure 6). An elastic band was used to secure the cap firmly to the sensor, further minimizing the risk of leakage. Preliminary studies without the elastic band showed poor sensor responses to CO₂ concentration changes.

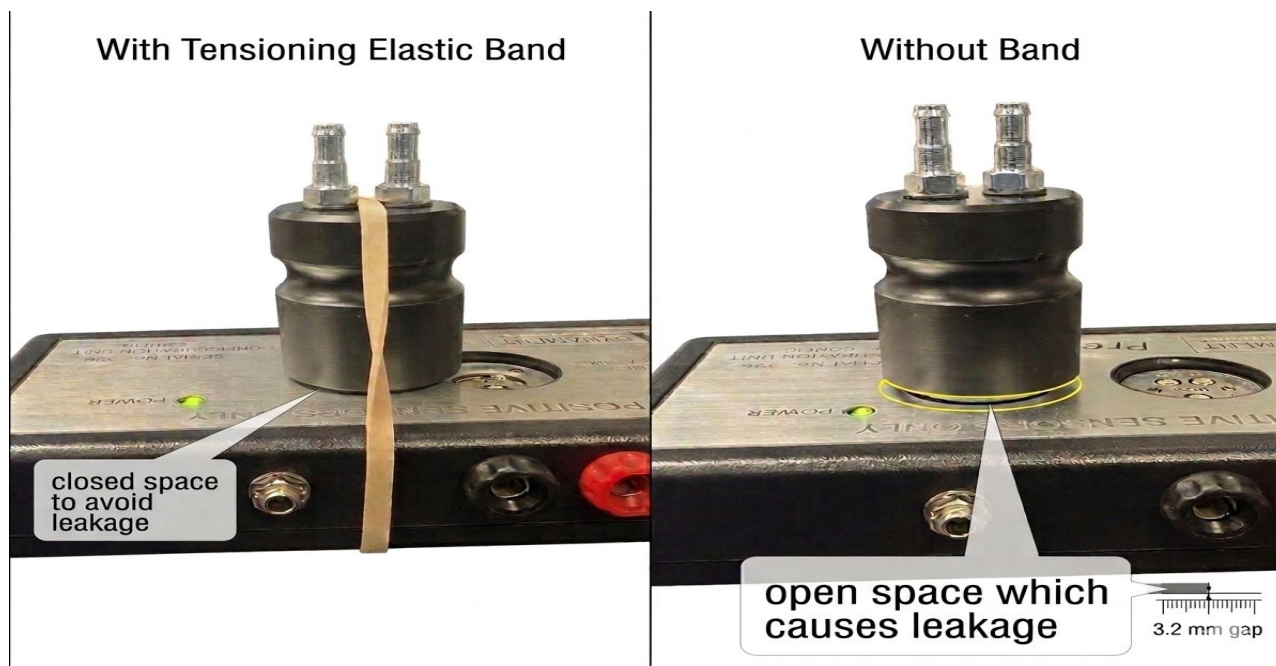


Fig. 6 Sensor cap with and without elastic band

Sensor absorbance measurements were calibrated by mixing known concentrations of CO_2 over the sensor. Sensor absorbance measurements were calibrated by flowing CO_2/N_2 mixtures of known concentrations into the sensor housing. The CO_2 mixtures were first hydrated to be consistent with typical reactor operation. Calibrations were performed at a total gas flow rate of 100 mL/min using mass flow controllers (Aalborg). Sensor absorbance measurements showed moderate agreement with expectations from Beer-Lambert Law (Figures 2.4-2.5), though calibration data were consistent across multiple measurements ($n=3$).

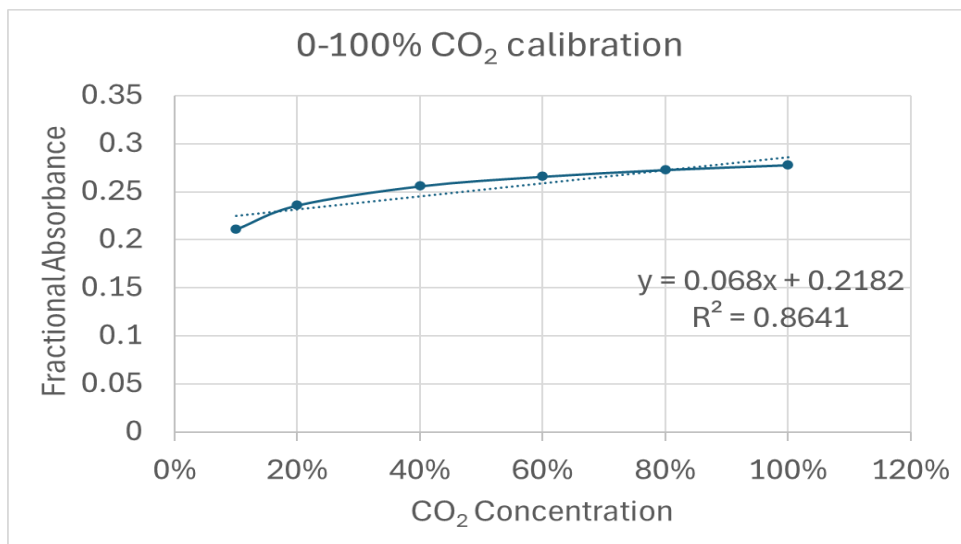


Fig. 7 High Concentration CO₂ Sensor Calibration Results. Error bars are 1 standard deviation (n = 3),

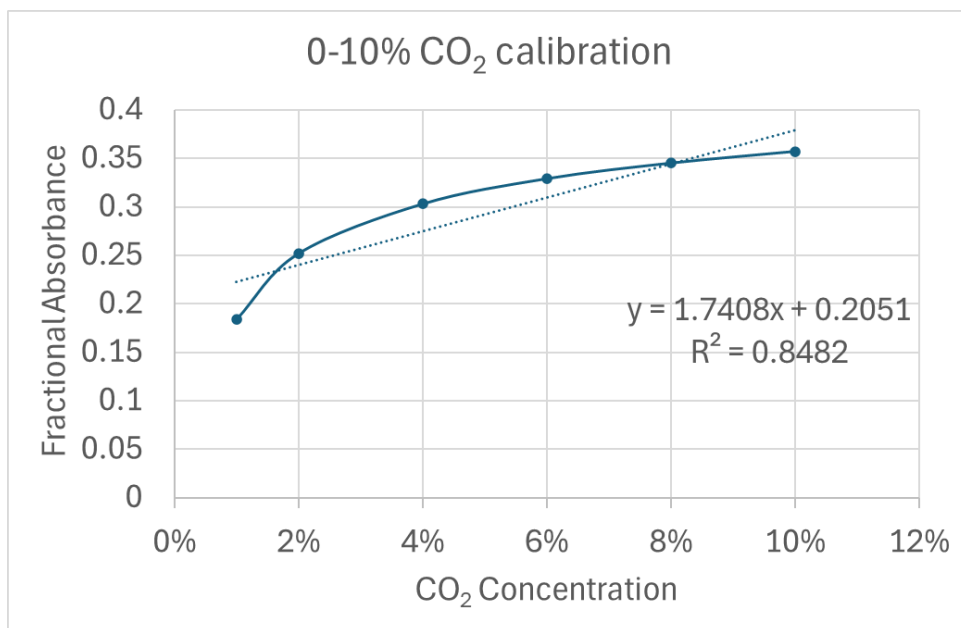


Fig. 8 Low Concentration CO₂ Sensor Calibration Results. Error bars are 1 standard deviation (n = 3).

WWC Reactor Operation

Hydrated CO₂-containing gas (100%, 80%, 60%, 40%, 20%, and 10% CO₂ for the high-range sensor and 10%, 8%, 6%, 4%, and 2% CO₂ for the low-range sensor; concentrations are before hydration) was flowed into the reactor at a total flow rate of 100 mL/min in the absence of liquid flow until the sensor gave a stable measurement (approximately 10-15 minutes) for 4-5 data points. The time intervals between the datapoints are 5 seconds. Both CO₂ and N₂ gas were supplied at a pressure of 15 psi gauge going into the mass flow controller. During this initialization stage, the liquid inlet and outlet ports of the WWC column were attached to the liquid absorbent solution to prevent gas leaks, but the peristaltic pump was not turned on, meaning the gas was not in contact with the liquid absorbent. After initialization to a stable reading, the liquid absorbent (H₂SO₄ or NaOH) was recirculated in the WWC at the maximum flow rate of 132 mL/min. Flow rates above this threshold cause splashing, which disrupts the laminar flow regime and results in undesirable gas-liquid interactions. The minimum liquid flowrate at which a film is formed is 127 mL/min. Below this flow rate, the pressure is insufficient to pump the solution through the inner tube, preventing the formation of a stable liquid film along the outer tube surface. Recirculation and measurement continued until a new stable outlet CO₂ measurement was achieved. Tests were conducted in series with the same liquid absorbent solution, periodically purging any absorbed CO₂ by sparging the solution with pure N₂ for a minimum of 30 min.

The accuracy of the WWC was validated by estimating the liquid-side mass transport coefficient (k_L) and the pseudo-first order rate constant (k_1) for NaOH by fitting experimental data to Eq. 3 and comparing these results to literature values. While our value of k_L is not expected to be identical to literature values because it varies with reactor geometry and fluid dynamics conditions, literature values of similar reactors (Table 2.1) provide a reference point that can identify potential experimental or data analysis errors.

Data Processing

The best fit calibration was applied to convert sensor measurements into the continuous %CO₂ measured at the outlet. All processed data were analyzed using Microsoft Excel. The difference between the known inlet CO₂ concentration and the measured outlet steady-state concentration (as illustrated in Fig. 9) was then computed to determine the total CO₂ absorbed. This absorbed concentration, combined with the known gas molar flow rate and the determined wetted interfacial area, enabled the calculation of the CO₂ absorption flux.

Results and Discussions

Absorption into H_2SO_4

H_2SO_4 is a strong acid that dissociates completely in aqueous solution to yield H^+ and SO_4^{2-} ions. Critically, this solution lacks a significant concentration of free hydroxide ions (OH^-) capable of forming a stable chemical bond with dissolved CO_2 . Consequently, the pseudo-first-order reaction rate constant in the flux equation becomes effectively zero. Under this condition, no chemical enhancement of mass transfer occurs, and the absorption process is governed solely by physical diffusion of CO_2 across the gas-liquid interface and into the liquid bulk.

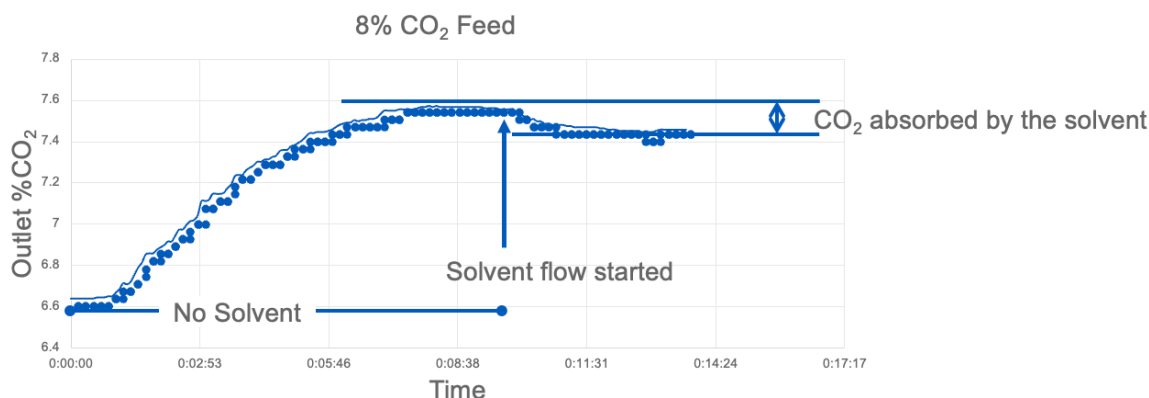


Fig 9. Graphical representation of 8% CO₂ feed

The absorption of carbon dioxide in dilute sulfuric acid (H_2SO_4) was investigated as a function of inlet CO_2 concentration, employing two calibrated sensors with measurement ranges of 0–10% and 0–100% CO_2 , respectively. When utilizing the 0–100% CO_2 sensor, no detectable CO_2 flux was observed for a feed gas containing 100% CO_2 . This absence of measurable absorption suggests that the driving force for mass transfer under pure CO_2 conditions may be offset by limited chemical interaction between CO_2 and the dilute acidic medium, or by instrumental sensitivity constraints at the upper bound of the sensor's calibration range. In contrast, a substantial increase in CO_2 flux was recorded when the inlet CO_2 concentration was reduced to 60%. The maximum flux at 60% CO_2 likely reflects an optimal balance between the gas-phase concentration gradient and potential solution-mediated effects, such as pH buffering or limited CO_2 hydration kinetics in dilute H_2SO_4 .

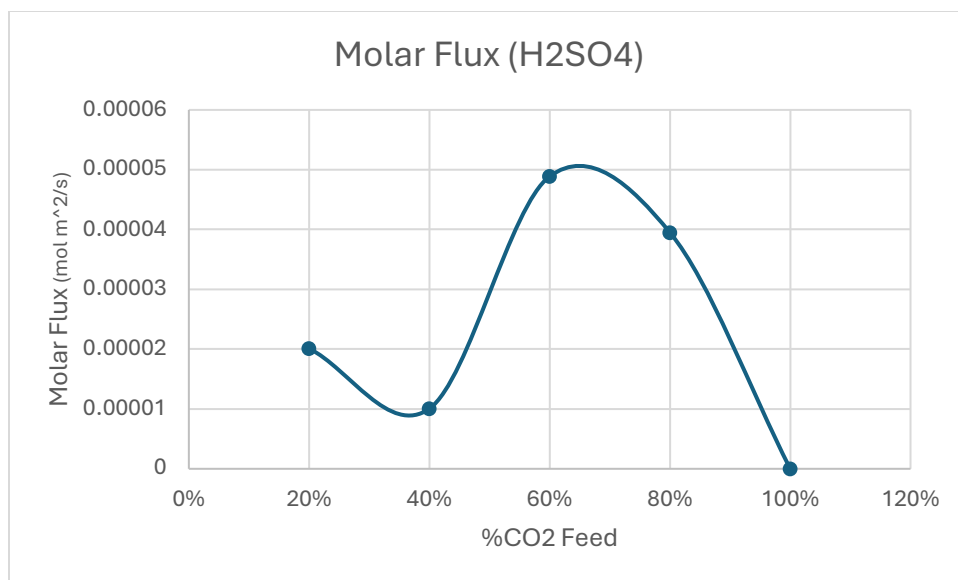


Fig. 10. Flux for H₂SO₄ using 0-100% CO₂ sensor

For measurements conducted using the calibrated 0–10% CO₂ sensor, the absorption behavior of CO₂ in dilute H₂SO₄ exhibited a distinct dependence on inlet concentration within the low-concentration range. When the feed gas contained 10% CO₂, the observed CO₂ flux was near zero. This value lies within the typical noise threshold or detection limit of the sensor and therefore is interpreted as effectively no net measurable absorption. The slightly negative reading may arise from baseline drift, minor calibration offset, or low-level desorption of residual dissolved gases, but it is not considered physically significant. In contrast, reducing the inlet CO₂ concentration to 8% yielded the highest CO₂ flux observed with this sensor, approximately 0.0007 mol·m⁻²·s⁻¹. The observation that a 10% CO₂ feed produces negligible absorption while an 8% feed yields a positive, non-zero flux may be due to optimal pH effect.

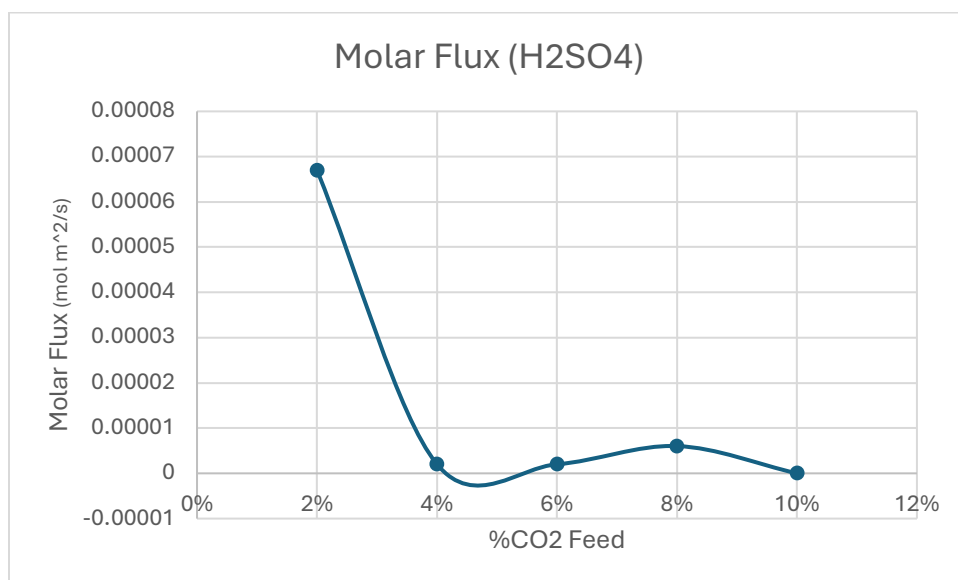


Fig 11. Flux results for H₂SO₄ using 0-10% CO₂ Sensor

The liquid-side mass transfer coefficient (k_L) for a CO₂ feed concentration of 20% was determined using the experimental setup and the simplified mass transfer model (Equation 3), given the negligible chemical reaction effects ($k_1 = 0$). The calculated value of K_L was found to be 2.011×10^{-5} (in consistent units, e.g., m/s). This value represents the overall physical mass transfer resistance in the liquid phase under the given hydrodynamic and operating conditions.

Comparison between the benchmark data reported in the literature and the experimental results reveals a notable difference. Specifically, Zhu et al. reported a K_L value of approximately 2×10^{-6} , while Darde et al. found a similar value of 1.99×10^{-6} under comparable conditions. The value obtained in this study (2.011×10^{-5}) is approximately one order of magnitude higher than these literature benchmarks. Several factors may contribute to this deviation. The differences in the reactor geometry could significantly enhance or reduce the liquid-side mass transfer coefficient.

Absorption into NaOH

When using sodium hydroxide (NaOH), a marked reduction in carbon dioxide (CO₂) concentration was observed immediately following the introduction of the NaOH solution into the system. This initial decrease is consistent with the expected chemical absorption mechanism, wherein CO₂ reacts with NaOH to form sodium carbonate (Na₂CO₃) and/or sodium bicarbonate (NaHCO₃), thereby removing CO₂ from the gas stream.

However, an unusual trend was noted after the absorption column, contrary to the anticipated continued low concentration, the CO₂ concentration exhibited a secondary increase during the post-absorption phase (Figure 11). Specifically, after reaching a minimum concentration downstream of the column, the CO₂ level gradually rose again, suggesting possible desorption processes or back-mixing phenomena within the system. Such a rebound effect is not typically observed in ideal chemical absorption systems and may indicate either saturation of the absorbent near the column outlet or the presence of unaccounted physical and chemical equilibrium shifts.

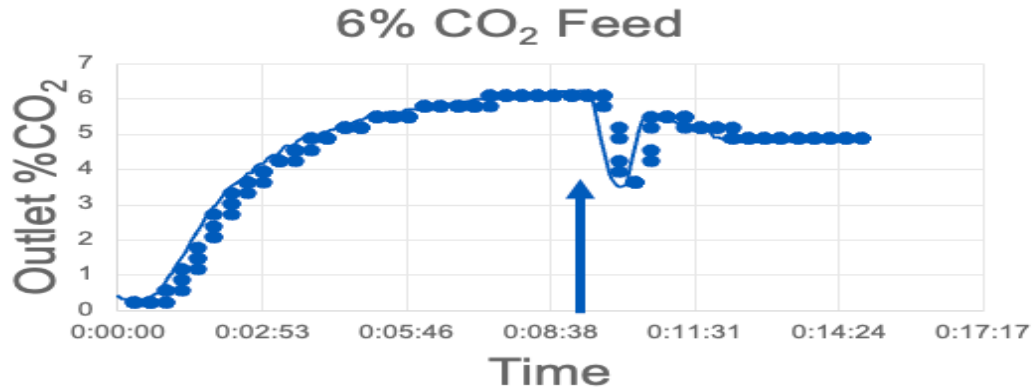


Fig 12. Graphical representation of the outlet CO₂ concentration for the 6% CO₂ feed and NaOH absorbent condition. Arrow represents the start time of NaOH recirculation.

When using the high-range sensor, significant CO₂ Flux was observed for feed concentrations of 60%, 40%, and 20% CO₂ (Figure 13). Among these, the 20% CO₂ feed exhibited the highest level of CO flux. In contrast, feed concentrations of 100% and 80% CO₂ resulted in no measurable absorption, suggesting a possible saturation or kinetic limitation under these conditions.

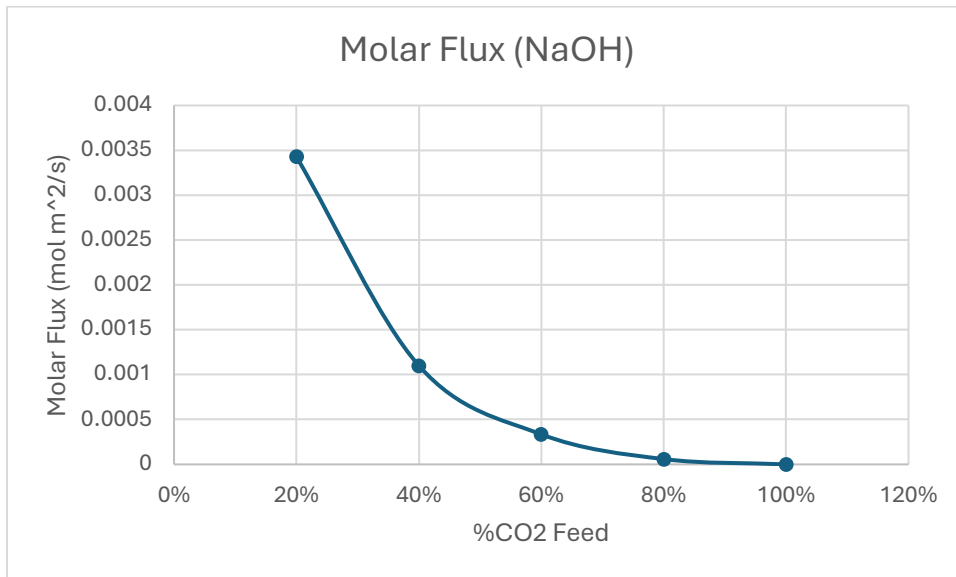


Fig 13. Absorption results for 0-100%CO₂ Sensor into NaOH

The absorption of carbon dioxide into a sodium hydroxide (NaOH) solution was investigated using the calibrated low-range (0–10%) CO₂ sensor. Measurements of CO₂ flux were recorded for feed gas concentrations of 10%, 8%, 6%, and 4% CO₂, as presented in Figure 14. Among the tested inlet concentrations, the 6% CO₂ feed demonstrated the highest absorption efficiency, yielding the greatest positive CO₂ flux. This result indicates that for the

NaOH scrubbing solution used in this study, an intermediate CO₂ partial pressure (6%) promotes more effective mass transfer than either higher or lower feed concentrations within the 0–10% range. At the upper end of the tested range (10% CO₂), the observed flux was measurably lower than that at 6%, suggesting that increasing the CO₂ loading does not proportionally enhance absorption into NaOH under these conditions, possibly due to limitations in liquid-side mass transfer. The 8% and 4% CO₂ feeds produced positive but progressively lower flux values relative to the peak at 6%.

In contrast, the 2% CO₂ feed resulted in a near-zero flux. The result implies the existence of a practical concentration threshold near or below 2% CO₂, where the driving force for gas–liquid mass transfer becomes insufficient to produce a measurable absorption flux under the tested operating conditions

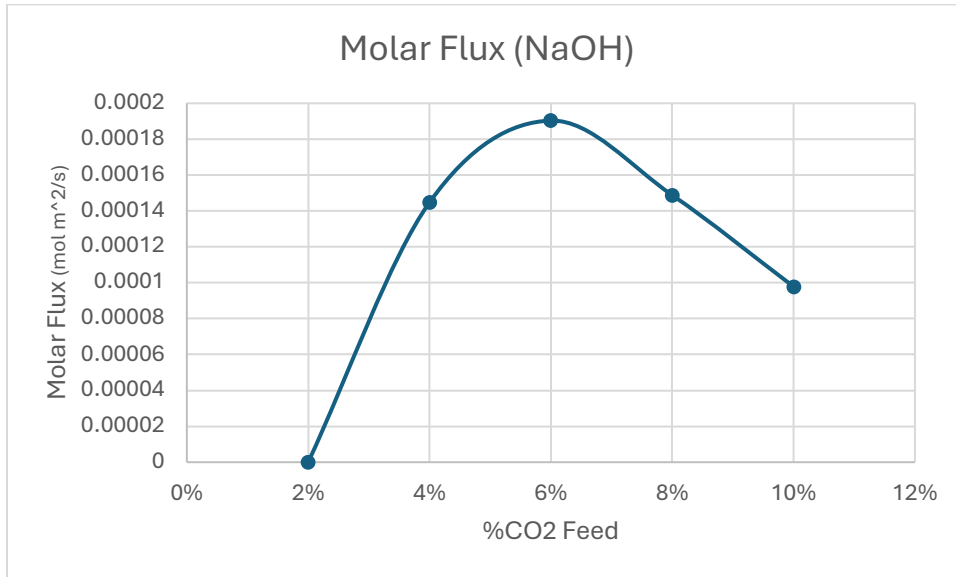


Fig 14. Absorption results for 0-10%CO₂ Sensor into NaOH

The pseudo-first-order reaction rate constant (k_1) for the absorption of CO₂ from a 20% feed gas was determined from the experimental flux data and the enhancement factor model. The calculated value was $k_1 = 1.54 \times 10^{22} \text{ s}^{-1}$. This value is exceptionally high compared to typical kinetic regimes in gas–liquid absorption processes. Physically, such a large rate constant indicates that the chemical reaction between CO₂ and the absorbing liquid is extremely fast, occurring nearly instantaneously relative to the characteristic time scale of physical mass transfer across the liquid film.

To contextualize this result, benchmark kinetic data reported by Wilcox (2012) provide a range of k_1 values for CO₂ absorption systems between $6.7 \times 10^{-4} \text{ mol} \cdot \text{m}^2 / \text{s}^{-1}$ and $1.2 \times 10^8 \text{ mol} \cdot \text{m}^2 / \text{s}^{-1}$. The value obtained in this study ($1.54 \times 10^{22} \text{ mol} \cdot \text{m}^2 / \text{s}^{-1}$) exceeds the

upper end of this literature range by approximately 14 orders of magnitude. This result may indicate that the assumed reaction mechanism is not the rate-limiting step under the present experimental conditions.

Conclusion

This study successfully designed, fabricated, and validated a laboratory-scale wetted wall column (WWC) as a cost-effective platform for measuring CO₂ absorption kinetics. The complete experimental setup was constructed at an approximate cost of \$500, representing a substantial reduction compared to commercially available laboratory-scale WWC systems, which typically exceed \$13,000. Validation experiments using sodium hydroxide (NaOH) as a reference solvent demonstrated that the custom-built WWC might need more extensive validation process to prove that it can reliably measure CO₂ absorption flux over a range of inlet concentrations. The observed decrease in CO₂ concentration upon exposure to NaOH confirmed the expected chemical absorption behavior, while flux measurements across varying feed concentrations (4–60% CO₂) provided a basis for estimating kinetic parameters. Although some anomalies were observed, including a secondary rise in CO₂ concentration following the absorption phase and near-zero flux at very high (100%, 80%) and very low (2%) CO₂ feed concentrations, the overall system performance indicates that the apparatus can effectively distinguish between physical absorption and chemically enhanced absorption. This was further supported by comparative tests using H₂SO₄ and NaOH.

Recommendations

To ensure that the wetted wall column is robustly validated and confirmed as fit for routine laboratory use in solvent screening applications, future work should prioritize the collection of additional experimental data using the WWC across a broader range of operating conditions. Specifically, more extensive replicate measurements should be performed at each inlet CO₂ concentration to improve statistical power and enable rigorous quantification of measurement uncertainty. Furthermore, a systematic validation should be conducted by comparing WWC-derived rate constants against literature values obtained from established reactor configurations. This comparative validation is essential to confirm that the cost-reduced design does not introduce uncharacterized mass transfer resistances. Attention should be directed toward resolving the anomalous desorption-like behavior observed during NaOH experiments and the inconsistent flux-concentration relationships noted in both absorbent systems, as these phenomena may indicate incomplete gas-liquid equilibration, potential bypassing, or sensor response artifacts at concentration extremes. Once these validation targets are met, the WWC can be confidently deployed for its intended purpose: screening novel solvent formulations to identify cost-effective candidates for post-combustion CO₂ capture processes.

REFERENCES

- Anderson, C., Scholes, C., Lee, A., Smith, K., Kentish, S., Stevens, G., Webley, P. A., Qader, A., & Hooper, B. (2011). Novel pre-combustion capture technologies in action—Results of the CO2CRC/HRL Mulgrave capture project. *Energy Procedia*, 4, 1192–1198. <https://doi.org/10.1016/j.egypro.2011.01.173>
- Bishnoi, S., & Rochelle, G. T. (2000). Absorption of carbon dioxide into aqueous piperazine: Reaction kinetics, mass transfer and solubility. *Chemical Engineering Science*, 55(22), 5531–5543. [https://doi.org/10.1016/S0009-2509\(00\)00182-2](https://doi.org/10.1016/S0009-2509(00)00182-2)
- Gao, W., Liang, S., Wang, R., Jiang, Q., Zhang, Y., Zheng, Q., Xie, B., Toe, C. Y., Zhu, X., Wang, J., Huang, L., Gao, Y., Wang, Z., Jo, C., Wang, Q., Wang, L., Liu, Y., Louis, B., Scott, J., ... Park, S.-E. (2020). Industrial carbon dioxide capture and utilization: State of the art and future challenges. *Chemical Society Reviews*, 49(23), 8584–8686. <https://doi.org/10.1039/D0CS00025F>
- Grünig, J., Lyagin, E., Horn, S., Skale, T., & Kraume, M. (2012). Mass transfer characteristics of liquid films flowing down a vertical wire in a counter current gas flow. *Chemical Engineering Science*, 69(1), 329–339. <https://doi.org/10.1016/j.ces.2011.10.049>
- Haidl, J., Rejl, F. J., Valenz, L., Kordač, M., Moucha, T., Labík, L., & Schultes, M. (2016). Absorption in wetted-wall column with phase properties close to distillation conditions. *Chemical Engineering Science*, 144, 126–134. <https://doi.org/10.1016/j.ces.2015.12.027>

- Hwang, K.-S., Park, D.-W., Oh, K.-J., Kim, S.-S., & Park, S.-W. (2010). Chemical Absorption of Carbon Dioxide into Aqueous Solution of Potassium Threonate. *Separation Science and Technology*, 45(4), 497–507. <https://doi.org/10.1080/01496390903529919>
- Jamal, A., Meisen, A., & Jim Lim, C. (2006). Kinetics of carbon dioxide absorption and desorption in aqueous alkanolamine solutions using a novel hemispherical contactor—I. Experimental apparatus and mathematical modeling. *Chemical Engineering Science*, 61(19), 6571–6589. <https://doi.org/10.1016/j.ces.2006.04.046>
- Kucka, L., Müller, I., Kenig, E. Y., & Górak, A. (2003). On the modelling and simulation of sour gas absorption by aqueous amine solutions. *Chemical Engineering Science*, 58(16), 3571–3578. [https://doi.org/10.1016/S0009-2509\(03\)00255-0](https://doi.org/10.1016/S0009-2509(03)00255-0)
- Siy, S. J. P., Villanueva, J. C. S., Roces, S. A., & Dugos, N. P. (2013). *DESIGN, FABRICATION AND TESTING OF WETTED WALL COLUMN FOR CARBON CAPTURE USING AQUEOUS AMMONIA*.
- Thee, H., Smith, K. H., Da Silva, G., Kentish, S. E., & Stevens, G. W. (2012). Carbon dioxide absorption into unpromoted and borate-catalyzed potassium carbonate solutions. *Chemical Engineering Journal*, 181–182, 694–701. <https://doi.org/10.1016/j.cej.2011.12.059>
- U.S. Environmental Protection Agency. Carbon Dioxide Emissions 2022. <https://www.epa.gov/ghgemissions/carbon-dioxide-emissions> (accessed March 02, 2026).

- Wang, C., Xu, Z., Lai, C., Whyatt, G., Marcy, P., & Sun, X. (2017). Hierarchical calibration and validation for modeling bench-scale solvent-based carbon capture. Part 1: Non-reactive physical mass transfer across the wetted wall column. *Greenhouse Gases: Science and Technology*, 7(4), 706–720. <https://doi.org/10.1002/ghg.1682>
- Wang, N., Peng, Z., Gao, H., Sema, T., Shi, J., & Liang, Z. (2022). New insight and evaluation of secondary Amine/N-butanol biphasic solutions for CO₂ Capture: Equilibrium Solubility, phase separation Behavior, absorption Rate, desorption Rate, energy consumption and ion species. *Chemical Engineering Journal*, 431, 133912. <https://doi.org/10.1016/j.cej.2021.133912>
- Zhu, C., Yao, X., Zhao, L., & Teng, H. H. (2016). A composite reactor with wetted-wall column for mineral carbonation study in three-phase systems. *Review of Scientific Instruments*, 87(11), 115115. <https://doi.org/10.1063/1.4967715>