

Development of a low-cost microcontroller-based carbon capture device using the Direct Air Capture (DAC) method and sodium hydroxide absorbent

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Abstract

Currently, Carbon Capture, Utilization, and Storage (CCUS) systems are emerging as a significant focus in discussions of climate change. CCUS refers to a set of technologies designed to capture Carbon Dioxide (CO₂) emissions from various sources and either utilize it for beneficial purposes or store it to prevent release into the atmosphere. CO₂, the primary gas responsible for the greenhouse effect, is generated across multiple sectors, notably in energy and transportation. In Indonesia, the energy sector is the most significant contributor to CO₂ emissions, accounting for 697.97 million tons in 2022. In this study, we have developed a cost-effective carbon capture device utilizing the Direct Air Capture (DAC) method. This device uses a microcontroller as the primary control unit, along with a compact closed chamber serving as the main reactor. Sodium hydroxide (NaOH) was utilized as the absorbent in our study. We conducted experiments on this device, keeping the NaOH concentration and reaction time fixed while varying the absorbent flow rate as the independent variable. The experiment yielded quite promising results. The absorption of CO₂ is directly related to both the flow rate of the absorbent and the reaction time. The maximum CO₂ absorption recorded is 3.960 ppm, achieved at a flow rate of 10 liters per minute with a reaction time of 5 minutes. The results have been reconfirmed by chemical titration.

Keywords:

Carbon capture, direct air capture, sodium hydroxide, microcontroller, titration method

1 Introduction

The rapid advancement of technology and the surge in global population have led to increased fossil fuel use, which has adversely affected the environment. The energy sector has emerged as the most significant contributor to carbon emissions [1], and with the rising energy demand, the associated emissions continue to grow annually [2]. The greenhouse effect refers to a phenomenon where the Earth's surface temperature rises significantly as a result of alterations in atmospheric conditions, primarily caused by the accumulation of Carbon Dioxide (CO₂) gas in the atmosphere [3]. As sunlight enters the atmosphere, it is absorbed by the Earth's surface, while a portion of this heat is reflected into space. However, the rising levels of CO₂ in the atmosphere obstruct the

heat that is reflected from the Earth's surface, leading to a rise in temperature [4].

CO₂, often referred to as carbonic acid, is a compound made up of two oxygen atoms bonded to a single carbon atom. In 2023, the concentration of this gas in the Earth's atmosphere was approximately 417 ppm [5]. The effects of rising CO₂ include climate irregularities, rising Earth surface temperatures, and elevated sea levels resulting from melting ice in the planet's polar regions.

One of the most effective strategies for lowering net carbon emissions is considered to be Carbon Capture, Utilization, and Storage (CCUS) technology [6][7][8]. This technology is designed to mitigate CO₂ levels in the atmosphere by injecting CO₂ gas into soil layers or reservoirs at depths of approximately 600 meters [9]. In the CO₂ gas injection process, several criteria must be considered, including rock type, permeability, and porosity, to ensure that CO₂ remains trapped in the rock layer for an extended period.

Among several capture technologies, absorption-based separation methods have proven especially promising for large-scale applications. A technique for extracting components from a gas mixture involves absorption of the mixture into a liquid absorbent, followed by dissolution. Diverse absorbents are accessible for CO₂ absorption, such as Sodium Hydroxide (NaOH) [10][11], Potassium Hydroxide (KOH) [12][13][14], and Potassium Carbonate (K₂CO₃) [15][16]. These alkaline solutions offer notable benefits in CCUS applications, particularly in terms of capture efficiency and process integration.

NaOH exhibits the highest absorption rates and theoretical capacity; nonetheless, it encounters issues with corrosion and elevated regeneration energy demands [10]. KOH has a superior performance profile with enhanced solubility properties compared to NaOH, albeit at a greater expense [12]. K₂CO₃, although it has slower absorption kinetics, presents a viable choice for large-scale applications owing to its diminished regeneration energy demands, lower corrosion risk, and advantageous economic characteristics [16]. The choice of a suitable absorbent significantly affects the efficiency and economic feasibility of carbon capture systems, encompassing not only absorption capacity but also operational characteristics, system stability, and life-cycle costs.

Most carbon capture technologies to date have relied on packed columns [17][18] or membrane separation [19][20], which often face limitations in mass transfer efficiency and energy demand. Previous studies have explored the use of alkaline solutions as CO₂ absorbents, yet these have been mainly applied in conventional flow systems with suboptimal gas-liquid contact. This research introduces a novel reactor design based on spray absorption, in which NaOH solution is atomized into fine droplets to maximize interfacial area with CO₂. This approach is expected to enhance reaction kinetics and absorption efficiency, while offering the potential for a more compact, energy-efficient carbon capture device compared to existing technologies.

In various studies, numerous efforts have been made to reduce carbon levels using the Chemical Absorption method. However, the system implemented in the Absorption Reactor remains manual. This study presents the design of a prototype carbon capture system that uses a microcontroller for automatic and batch control. The system is intended to monitor several process parameters, including CO₂ content and solution flow rate, which serve as the electrical energy source to meet the operational requirements of the Absorption Reactor.

2 Method

The prototype design created in this study is illustrated in Fig. 1. This prototype comprises several key components that work together to facilitate the intended process. The initial component consists of a collection of tanks and reactors that serve as both containers and reaction sites, specifically T-1001, T-1002, T-1003,

and V-1004. Every tank serves a distinct purpose in this prototype. The subsequent components include various instrumentation

devices, pumps, sensors, and control valves. The components facilitate the process's functioning in this prototype.

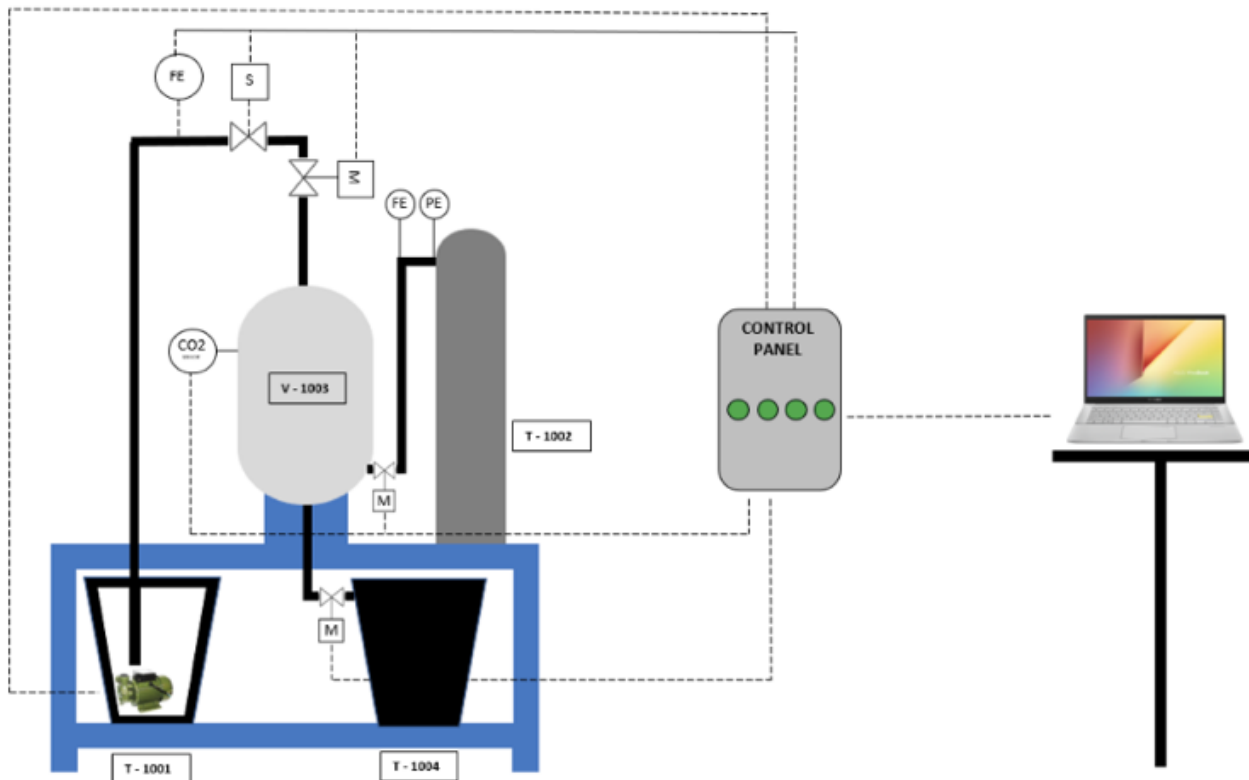


Fig. 1. Prototype design

As shown in Fig. 1. The first tank, T-1001, stores NaOH solution that will be further processed in the system. This tank is designed to hold a solution at a specific concentration, which is then transferred to other processing units. For the piping, 0.5-inch PVC pipes are used to convey the solution from tank T-1001 to the process vessel, and 0.375-inch carbon-steel pipes for discharge or inter-component connections. These pipes were chosen based on the material's resistance to the corrosive NaOH solution and the need to flow a sufficiently large volume of solution at stable pressure.

The flow of the solution from tank T-1001 to the process vessel is regulated by an AC pump that delivers it in a controlled manner. This AC pump is designed to provide consistent pressure and flow, enabling effective spraying. To ensure a precise, controlled flow of solution, a solenoid valve (S-02) is installed after the pump, enabling automatic flow control. This solenoid valve opens or closes the flow path according to the system's needs, which can be programmed or controlled by an automatic control system.

Additionally, to monitor and measure solution flow in real time, a rotameter flow sensor (FE-02) is installed after the solenoid valve. This rotameter sensor measures the solution flow rate in specific units (e.g., liters per minute), providing the data needed to ensure it meets the process specifications. Data from this rotameter can also be used by the control system to automatically adjust the flow when operational conditions or process requirements change.

The second tank, T-1002, stores CO₂ gas to simulate the carbon capture process. CO₂ can be stored in either liquid or gaseous form, depending on the system's and the experiment's pressure and temperature conditions. CO₂ is carefully directed from T-1002 to V-1003 through a 0.375-inch carbon-steel pipe. The choice of carbon steel pipe is based on its corrosion resistance and ability to handle the high pressures that may occur during CO₂ transfer.

A pressure gauge (PE-01) has been installed on the pipeline exiting T-1002 to monitor the condition of the flowing CO₂ gas. This pressure gauge is designed to measure the pressure of CO₂ gas leaving the tank, ensuring it remains within safe limits and meets the required parameters for the carbon capture process. This

pressure reading is essential to prevent excessive pressure that may harm equipment or impact process efficiency.

A rotameter flow sensor (FE-02) has been installed to accurately measure the flow rate of CO₂ gas directed towards the process vessel V-1003. This rotameter provides precise gas flow measurements in designated units, such as liters per minute, enabling operators to monitor flow in real time and verify that CO₂ is supplied in the appropriate quantity per process specifications. The sensor is integrated with a control system that adjusts the gas flow as needed, ensuring process stability.

A solenoid valve (S-02) is positioned after the rotameter to regulate CO₂ flow, automatically opening or closing the flow path in response to signals from the control system. This solenoid valve enables more accurate regulation of CO₂ gas flow, which is essential for carbon capture simulation experiments that require precise gas flow control.

The V-1003 vessel process features a capsule shape to enhance carbon capture efficiency. This vessel features CO₂ sensors installed to monitor CO₂ levels within the vessel, both before and after the carbon capture process. The carbon capture process in this vessel uses a NaOH solution, which reacts with CO₂ to form carbonate compounds, effectively capturing CO₂ and lowering its concentration in the gas stream. This process plays a vital role in simulations focused on carbon capture, intending to mitigate greenhouse gas emissions in the atmosphere.

A motorized valve is installed at the bottom of vessel V-1003, functioning as a drainage outlet to facilitate the removal of reactant liquids and by-products from the carbon capture reaction, including the generated carbonate compounds. The motorized valve enables automatic regulation of liquid flow from the vessel, enhancing system functionality and ensuring that the disposal process is executed efficiently and safely. This valve plays a crucial role in preventing the buildup of reactant residues in the vessel, which could interfere with the efficiency of subsequent processes.

On the opposite side of the CO₂ sensor, an inlet for CO₂ gas entering the vessel is present. This inlet features a motorized valve that regulates the flow of CO₂ entering the ship, ensuring the gas supplied to the boat aligns with the process requirements. Accurate

regulation of CO₂ gas flow is essential, given the carbon capture chemical reaction's sensitivity to variations in the gas flow rate.

Flow and pressure indicators have been installed on the CO₂ inlet line to monitor the conditions of the CO₂ gas entering the vessel. The instruments measure CO₂ flow rate and inlet gas pressure, enabling the operator to maintain CO₂ flow and pressure within the optimal range for effective carbon capture. Precise pressure measurement is essential to avoid excessive pressure that may harm equipment or disrupt process efficiency. In contrast, flow measurement ensures CO₂ is supplied in the appropriate quantity for the chemical reaction.

The CO₂ sensor used in this vessel is an infrared CO₂ sensor that operates according to the non-dispersive infrared (NDIR) principle. This sensor can precisely measure CO₂ concentration within the range of 400–5000 ppm, meeting the measurement criteria for the carbon capture process. This sensor operates at 5 V and features a Pulse Width Modulation (PWM) output, enabling the transmission of measurement data to the control system for ongoing monitoring and adjustments. This principle allows the sensor to accurately detect CO₂ with high sensitivity, unaffected by other gas components in the flow, thereby enhancing its effectiveness in applications such as carbon capture simulation.

To measure CO₂ gas flow, a Hall-effect flow sensor is used, selected for its ability to measure flow rates of 1–25 L/min. This flow sensor operates over a 5–15 V voltage range and delivers precise flow data, which is crucial for maintaining the efficiency of the carbon capture process. This sensor uses Hall-effect technology for non-contact flow measurement, improving durability in challenging operational environments and ensuring consistent, precise measurements.

The third tank, T-1004, stores a Sodium Carbonate (Na₂CO₃) solution produced by the carbon capture process in vessel V-1003. Upon completion of the carbon capture process, a Na₂CO₃ solution is generated as a byproduct resulting from the reaction between NaOH and the absorbed CO₂ gas. The solution is subsequently moved to tank T-1004 for temporary storage. The transfer of Na₂CO₃ solution from vessel V-1003 to tank T-1004 is regulated by a solenoid valve (S-03) positioned along the pipeline. This solenoid valve facilitates automatic regulation of solution flow by adjusting the flow path, opening or closing in response to commands from the control system.

The system's electrical components are consolidated in a central control panel, serving as the core for overseeing and managing the entire carbon capture process. This control panel contains essential electrical components, including a controller, relays, terminal blocks, Miniature Circuit Breakers (MCBs), and power supplies. The Arduino Uno has been chosen as the central controller, offering a flexible and economical solution for managing system inputs and outputs. The Arduino Uno serves as the central processing unit, managing signals from various sensors and executing commands to control the system's actuators, including solenoid and motorized valves.

Pilot lamps are installed in front of the panel to provide real-time visual feedback on the process status. The lights indicate different system states, including power-on, fault conditions, and process status, enabling operators to swiftly evaluate the system's operational condition without delving into detailed data. Implementing pilot lamps ensures operators receive prompt notifications of any significant alterations or issues in the process.

A Human-Machine Interface (HMI) has been developed alongside the pilot lamps to provide a more comprehensive, interactive control interface. The HMI uses the Virtual Instrumentation System Architecture (VISA), enabling a versatile, robust user interface design via the LabVIEW software platform.

Table 1. This Table provides a detailed overview of the pin assignments and wiring configuration, ensuring the system is configured correctly for peak performance. The wiring configuration is meticulously crafted to ensure all components are

This interface is set up on a personal computer, allowing users to oversee and manage the system either remotely or on-site. The HMI provides a visual representation of essential parameters, such as flow rates, pressures, and CO₂ concentrations, enabling operators to adjust set points or take corrective action when necessary.

The HMI system utilizes a serial communication interface to interact with the Arduino Uno, facilitating efficient data transfer between the controller and the visualization software. The communication protocol enables real-time data exchange, allowing operators to monitor the system's performance and make dynamic adjustments to settings. The integration of the Arduino with the HMI ensures that hardware and software components work in harmony, creating a dependable and intuitive platform for managing processes. A schematic diagram has been developed to illustrate the electrical structure of the carbon capture device prototype, as shown in Fig. 2. This diagram presents a comprehensive layout of the electrical and control systems, elucidating the interactions among each component within the broader system. This document acts as an essential guide for addressing issues, performing maintenance, and planning for future system enhancements.

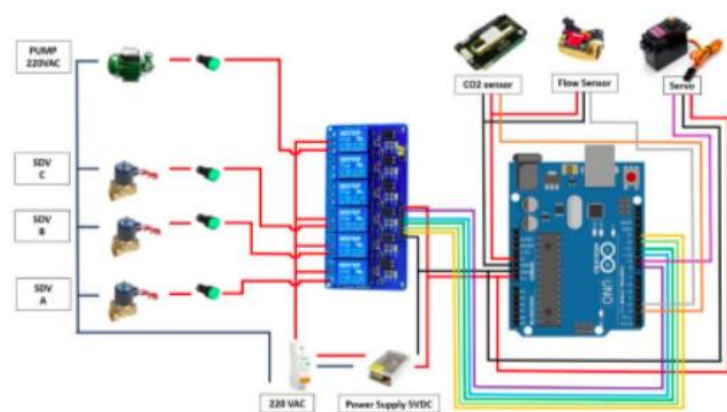


Fig. 2. Schematic diagram of microcontroller and electrical/instrumentation components

The system employs two distinct power supplies to power its electrical components: a 220 VAC supply and a 5 V DC supply. The 220 VAC power supply is specifically designed to energize the solenoid valves and pump, which require a higher voltage for optimal functionality. The regulation of the NaOH solution and CO₂ gas flow in the process hinges on these components. The 220 VAC power is converted to an appropriate operating voltage by the power supply, ensuring consistent operation of the solenoid valves and pump during the carbon capture process.

A 5 VDC power supply powers the microcontroller, relays, and servo valve, all of which operate at reduced voltages. The 5 V supply is crucial for ensuring that low-power components, including the microcontroller and relays, receive the appropriate voltage for their processing and control functions. The microcontroller, typically an Arduino Uno, serves as the core of the system, acting as the central control unit that interprets sensor inputs and transmits output commands to operate solenoid valves, servo valves, and other actuators. Furthermore, the CO₂ and flow sensors are directly connected to the microcontroller's 5 V and GND pins. The sensors deliver immediate data on CO₂ concentration and gas or liquid flow rate within the system, which is essential for effectively monitoring and controlling the carbon capture process.

The wiring specifics of the microcontroller, encompassing the connections to the sensors, relays, and servo valve, are detailed in

securely and effectively interconnected, maintaining appropriate voltage levels and grounding to prevent electrical interference or damage to delicate components. Using suitable power supplies for the system's various segments, combined with meticulous wiring,

ensures the system functions reliably and efficiently, with each

Table 1. Microcontroller wiring list

No.	Devices	Microcontroller pins	Description
1	CO ₂ sensor		Connect the CO ₂ sensor pins to the corresponding microcontroller pins
	- IN	D2	
	- VSS	5V	
	- GND	GND	
2	Flow sensor		Connect the flow sensor pins to the corresponding microcontroller pins
	- IN	D2	
	- VSS	5V	
	- GND	GND	
3	Relay		Connect the four relay pins to the corresponding microcontroller pins and power supply pins
	- IN	D9, D10, D11, D12	
	- VSS	5V (power supply)	
	- GND	GND (power supply)	
4	Servo valve		Connect the servo valve pins to the corresponding microcontroller pins
	- IN	D8	
	- VSS	5V	
	- GND	GN	

The HMI for the system features a user-friendly layout that offers operators a clear and intuitive perspective on the key parameters and control functions related to the carbon capture process, as shown in Fig. 3. A bar chart and a line chart are used to illustrate CO₂ concentration, effectively showing levels in parts per million (ppm). The graphical representations enable operators to monitor CO₂ levels in real time, facilitating the detection of fluctuations or deviations from desired concentrations. Using both bar and line charts provides a comprehensive view of the data, with the bar chart delivering an immediate overview of current CO₂ levels and the line chart facilitating trend analysis over time. A gauge-style indicator is used to monitor the flow of Na₂CO₃. This display is well-suited for illustrating real-time flow rates, offering a clear, analog-style depiction of the Na₂CO₃ solution's flow. The gauge helps operators maintain ideal flow conditions throughout the carbon capture process, ensuring the chemical reaction occurs at the appropriate rate and efficiency.



Fig. 3. HMI design

element receiving the appropriate voltage for its operation.

To ensure transparent status feedback on essential components like the pump and solenoid valves, lamp indicators are incorporated into the HMI. The lamps use a color-coded system (e.g., green indicating operational status, red indicating a fault) to provide instant visual feedback on the condition of the pump and solenoid valves. This enables operators to swiftly evaluate the functionality of these components and identify any issues that may require addressing.

Alongside the monitoring features, the HMI design includes options to select a Communication port (COM port) and enable data logging. The COM port selection feature allows users to configure and select the appropriate communication port for connecting the system to the personal computer, ensuring effective communication between the HMI, microcontroller, and other devices. This feature offers adaptability, enabling the system to interface with various computers or devices as required

3 Results and discussion

We have successfully developed a CO₂ capture device prototype based on the design outlined in the previous chapter (Fig. 4). The prototype, which can be seen in Fig. 1. Incorporates the key components and configurations required to simulate the carbon capture process. For the piping system, PVC pipes were selected for all fluid streams due to their durability, ease of installation, and corrosion resistance, which are crucial for handling the NaOH solution and CO₂ gas. The pipes were carefully installed to ensure proper alignment and secure connections, minimizing the risk of leaks during operation. The reactor vessel, which plays a critical role in the carbon capture process, is made of steel, chosen for its strength and ability to withstand the pressures and chemical reactions involved in capturing CO₂.



Fig. 4. Carbon capture device prototype

A CO₂ capture device prototype was successfully developed and implemented based on the theoretical framework presented in the preceding chapter. The prototype apparatus, illustrated in Fig. 1 it incorporates essential components and configurations designed to facilitate the simulation of the carbon capture process under controlled conditions.

The fluid transport system utilizes Polyvinyl Chloride (PVC) conduits for all fluid streams, selected for their optimal mechanical properties, ease of installation, and superior resistance to chemical degradation, essential characteristics for the safe transport of NaOH solution and CO₂ gas. The installation protocol emphasized precise alignment and connection integrity to minimize potential fluid escape during operational cycles. The primary reaction vessel, constructed from high-grade steel, was selected for its mechanical strength and chemical stability under the pressure differentials and chemical conditions inherent to CO₂ sequestration processes.

The experimental validation phase included rigorous integrity testing of the fluid transport system for both CO₂ and NaOH streams. Leak detection protocols were implemented under simulated operational conditions, with a comprehensive evaluation

of all connection points, valve assemblies, and sealing mechanisms to verify system integrity and operational safety parameters. This validation phase was crucial for ensuring containment of both gaseous and liquid phases.

The CO₂ delivery system was configured to simulate industrial emission conditions, facilitating controlled introduction of CO₂ for the capture process. System functionality was verified through empirical observation of the CO₂-NaOH reaction kinetics under operational conditions. This experimental setup enabled quantitative validation of CO₂ sequestration efficiency and system performance relative to design parameters.

Continuous monitoring protocols were implemented throughout the testing phase to evaluate the performance of all system components, including fluid transport mechanisms, electromagnetic valve assemblies, and monitoring instrumentation. The successful

development and validation of this prototype represent a significant advancement in CO₂ capture technology. The empirical data obtained from this prototype implementation will provide critical insights for future system optimizations and scaling considerations. The initial experimental trial of the carbon capture prototype was conducted using 1 M NaOH solution with a total volume of 20 liters. The absorbent solution was prepared by dissolving 800 grams of NaOH powder in 20 liters of deionized water, followed by thorough homogenization. This NaOH solution served as the primary absorbent medium in the carbon capture prototype system.

The experimental protocol involved systematic variation of the absorbent solution flow rate to 6.8 L/min, 10.2 L/min, 12.75 L/min, and 15.3 L/min, with a fixed reaction time of 5 minutes per trial. The experimental results are presented in Fig. 5, demonstrating the CO₂ absorption dynamics under varying flow conditions.

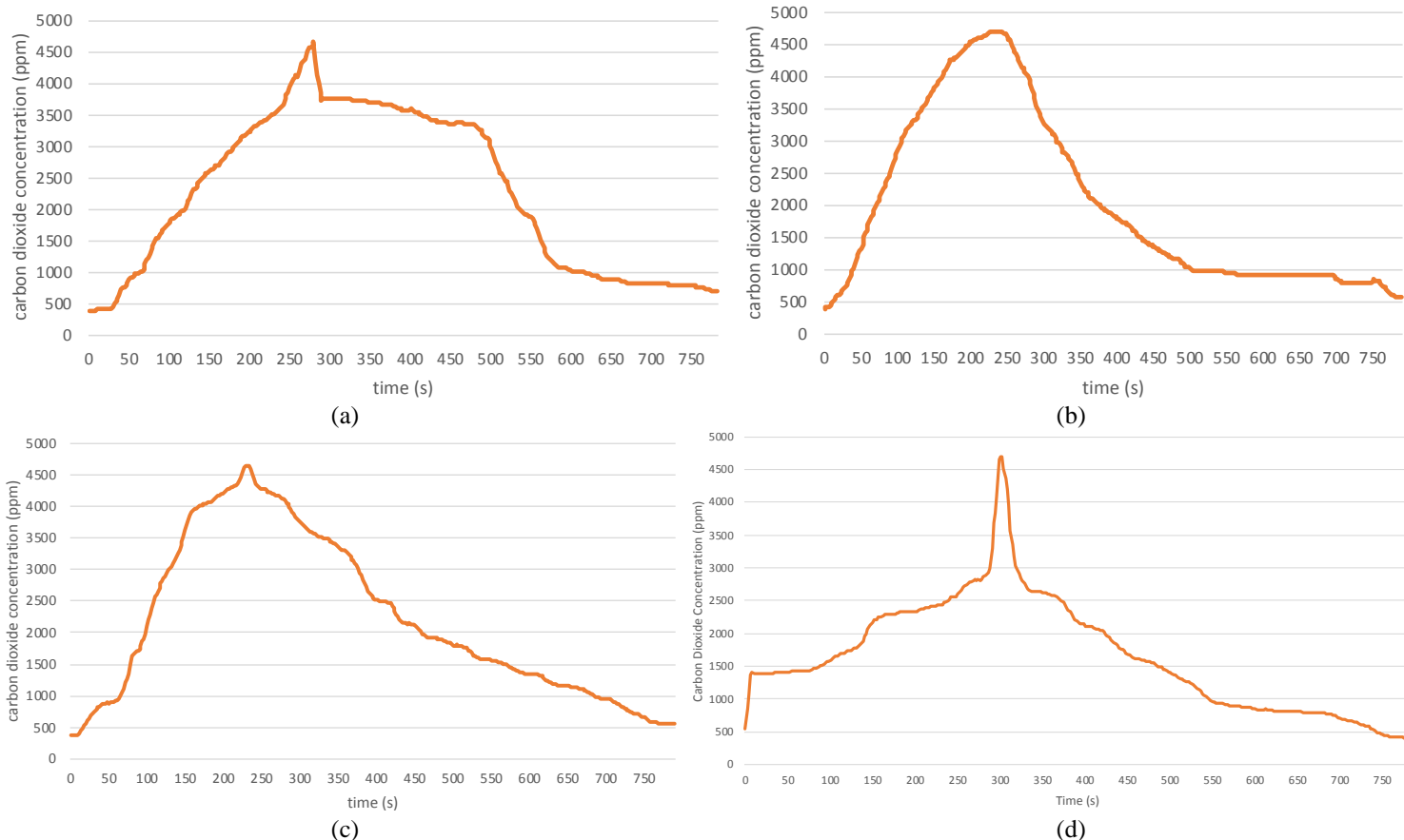


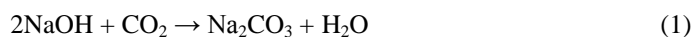
Fig. 5. Experimental results: (a) 6,8 liters/minute, (b) 10,2 liters/minute, (c) 12,75 liters/minute, and (d) 15 liters/minute of absorbent flow rate

Fig. 5(a) illustrates the CO₂ capture experiment using an absorbent flow rate of 6.8 L/min. During the initial 300 seconds of CO₂ injection into the reactor, the concentration increased from 398.97 ppm to 4690.97 ppm, as indicated by the sensor readings. Subsequently, the absorbent solution was sprayed into the reactor at a flow rate of 6.8 L/min for 500 seconds. During this period, CO₂ reacted with the absorbent, resulting in a continuous decline in concentration, reaching 704.00 ppm at 800 seconds.

Similar experiments were performed with absorbent flow rates of 10.2 L/min, 12.75 L/min, and 15 L/min, as shown in Fig. 5(b), Fig. 5(c), and Fig. 5(d), respectively. In these cases, the CO₂ concentration during the injection phase increased from 402.35 ppm to 4697 ppm, from 400.00 ppm to 4699 ppm, and from 407.97 ppm to 4695 ppm, respectively. At 800 seconds, the CO₂ concentrations measured were 583.63 ppm, 550.00 ppm, and 403.35 ppm, respectively.

Analysis of the experimental data reveals successful CO₂ capture by the NaOH solution pumped into the reactor vessel, as evidenced by the progressive decrease in CO₂ concentration (ppm) from the initial CO₂ injection to the reaction completion. These findings validate the theoretical framework regarding NaOH's CO₂ absorption capability, which is attributed to its basic properties. The

hydroxide ions in NaOH readily react with CO₂ to produce carbonate (CO₃²⁻) and bicarbonate (HCO₃⁻) ions according to the reactions $\text{CO}_2 + \text{OH}^- \rightarrow \text{HCO}_3^-$ and $\text{HCO}_3^- + \text{OH}^- \rightarrow \text{CO}_3^{2-} + \text{H}_2\text{O}$. These reaction pathways further substantiate the effectiveness of NaOH as a strong chemical absorbent for DAC of CO₂. The mechanism involves hydroxide ions (OH⁻) from the NaOH solution accepting protons (H⁺) from the acidic CO₂ gas, forming carbonate ions and water. This overall process can be represented by Reaction (1).



Furthermore, the experimental results demonstrate a positive correlation between the flow rate of the NaOH solution and the CO₂ absorption efficiency. Higher flow rates consistently led to greater CO₂ capture, as evidenced by lower CO₂ concentrations. The relationship between solution flow rate and CO₂ concentration is quantitatively illustrated in Fig. 6, providing crucial insights into the system's performance characteristics.

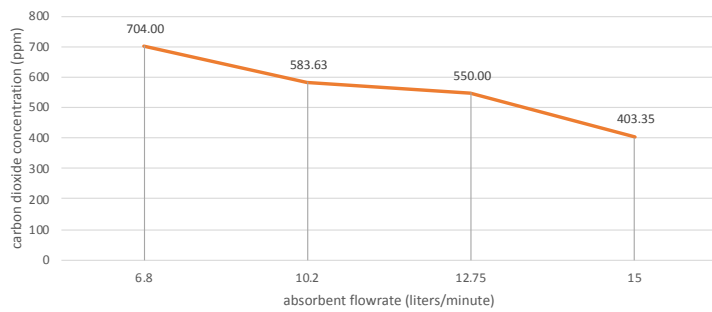
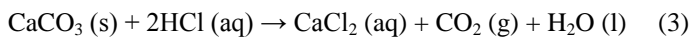


Fig. 6. Absorbent flowrate & CO₂ concentration relationship

To validate the carbon-capture efficiency of the prototype system, quantitative analysis was performed on the Na₂CO₃ solution produced during the capture process. Theoretically, the resultant Na₂CO₃ solution contains chemically bound CO₂ with NaOH. The verification process employed titrimetric analysis methodology. This analytical procedure utilized Calcium Chloride (CaCl₂) as a supplementary reagent to generate calcium ions in the solution, facilitating the substitution of sodium ions in the sodium bicarbonate salt formed during the CO₂ absorption process. The reaction proceeds as described in Reaction (2).



In this reaction mechanism, carbonate ions from Na₂CO₃ react with calcium ions from CaCl₂, precipitating Calcium Carbonate (CaCO₃) and forming a Sodium Chloride (NaCl) solution. This represents a neutralization reaction between basic Na₂CO₃ and neutral NaCl salt. The resultant precipitate was dried, after which the dried CaCO₃ was reacted with Hydrochloric Acid (HCl) solution, yielding CaCl₂ and releasing CO₂ gas, as illustrated in Reaction (3).



Following CO₂ liberation, the remaining CaCl₂ solution underwent titration with NaOH to determine the quantity of CO₂ initially dissolved in Na₂CO₃. The titration volume of NaOH was subsequently utilized to calculate the detected CO₂ concentration using Eq. (4).

Table 2. This analysis reveals the correlation between theoretical calculations and experimental measurements, validating both the carbon capture efficiency and the measurement methodology. Based on a comparative study of sensor-based measurements and titrimetric determinations, the captured CO₂ concentrations showed strong concordance between the two analytical approaches. The mean absolute deviation between the

Table 2. CO₂ capturing results in a 500-second reaction comparison

No.	Flowrate (liters/minute)	CO ₂ capturing based on LabVIEW (ppm)	CO ₂ capturing based on the titration method (ppm)	Deviation (%)
1	6.8	3588	3520	1.93
2	10.2	3711.02	3740	0.77
3	12.75	3749	3828	0.02
4	15	3883.68	3960	0.01

4 Conclusion

This study successfully developed and validated a low-cost prototype of a carbon capture system using DAC technology. The results demonstrated a clear linear relationship between absorbent flow rate and CO₂ capture efficiency, with the best performance observed at a NaOH flow rate of 15 L/min, reducing CO₂ by 3960 ppm. Validation by titrating the Na₂CO₃ output showed high accuracy, with an average variance of only 0.68%, confirming the reliability of the reactor design and capture mechanism. These findings highlight the potential of DAC systems with NaOH absorbents for effective CO₂ removal and advance carbon capture research. Future work should focus on improving energy efficiency, scalability, long-term stability, and cost-effectiveness for potential industrial applications, including NaOH regeneration as part of a

$$\text{CO}_2 \text{ Concentration} = (y/1000 \text{ L} \times A \text{ mol/L})/(0.01 \text{ L}) \quad (4)$$

Y represents the NaOH titration volume expressed in milliliters, while A denotes the molarity of the NaOH solution used during the titration. The constant 0.01 L corresponds to the standard sample volume used in the analysis and serves as the reference volume for calculating the concentration of CO₂ absorbed in the solution.

The molar concentration values obtained from the titrimetric analysis were converted to mass concentration units through Eq. (5). C [g/L] represents the mass concentration expressed in grams per liter. At the same time, C[mol/L] denotes the molar concentration obtained from the titrimetric analysis. The term M[CO₂] refers to the molar mass of CO₂ (44 g/mol), which is used as a conversion factor to convert molar concentration to mass concentration, thereby allowing the quantitative determination of the amount of CO₂ absorbed in the solution.

$$C[\text{g/L}] = C[\text{mol/L}] \times M[\text{CO}_2] \quad (5)$$

To enable direct comparison with the digital CO₂ sensor readings, the mass concentration values were further converted to volumetric parts per million (ppm) using Eq. (6). C[ppm] represents the concentration expressed in parts per million. The term R is the ideal gas constant (0.08206 L·atm/mol·K), T is the ambient temperature in Kelvin, and P denotes the atmospheric pressure in atmospheres. These parameters are derived from the ideal gas law, which relates a gas's molar volume to its temperature and pressure. The factor 10⁶ is included as a conversion constant to express the molar ratio of CO₂ to air in ppm. Units, thereby enabling quantitative evaluation of CO₂ concentration in the system.

$$C[\text{ppm}] = (C[\text{g/L}] \times RT)/(P \times M[\text{CO}_2]) \times 10^6 \quad (6)$$

The comparative data between the calculated CO₂ concentrations from the titration method and the sensor measurements are presented in

two measurement methodologies was 365.65 ppm, indicating reasonable agreement within the acceptable experimental uncertainty. The slight variations observed between calculated and measured values can be attributed to several factors: environmental conditions affecting sensor readings, minor losses during titrimetric analysis, systematic uncertainties in the measurement instruments, and potential dissolved CO₂ retention in the solution.

complete life cycle approach and the selection of corrosion-resistant materials for reactors and piping.

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