Modular Air Capture System Incorporating Process Intensification Techniques and Energetically Efficient Electronics for Monitoring and Control

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Abstract. Reducing CO_2 emissions alone is no longer sufficient to mitigate climate change. Achieving net-negative emissions through carbon removal is essential to reverse the damage caused by fossil fuel combustion and deforestation. Direct Air Capture (DAC) has gained attention for its flexible deployment, but its viability is often constrained by sorbent performance and costs. This study presents an innovative and multidisciplinary approach to DAC technology development by enhancing CO_2 removal efficiency through process intensification. Specifically, custom-designed, 3D-printed static mixers were integrated into the system to improve the performance of physical solid adsorbents. While static mixers have been used to improve mass transfer applications, their effect has not yet been studied for adsorption with solid adsorbent systems for CO_2 capture. Additionally, the proposed modular DAC unit incorporates IoT technologies, utilizing microcontrollers and sensors for real-time monitoring and control. Experimental results demonstrate that static mixers increase CO_2 removal efficiency by 32.1% and extend the adsorbent's breakthrough time by 24 minutes, while IoT integration reduces power consumption by 32.7%. A cost analysis confirms that the unit's low manufacturing cost (180 USD) supports the widespread adoption of energy-efficient, cost-effective DAC technology.

1 Introduction

Climate change, driven by the excessive accumulation of greenhouse gases such as carbon dioxide (CO_2) in the atmosphere, presents a significant threat to the planet [1]. This accumulation is a result of human activities such as fossil fuel consumption and deforestation. CO_2 is particularly dangerous due to its long atmospheric lifespan, which allows it to trap heat for centuries, amplifying global warming and delaying climate system recovery even after emissions are reduced [1]. Direct Air Capture (DAC) technology provides a favourable solution to this problem by removing and storing CO_2 from the air which can later be used in industrial applications [2]. Thus, DAC is an important factor to reduce climate change and reach net-zero carbon emissions [3].

DAC technologies offer certain advantages, including flexible deployment which enables it to reduce emissions that are difficult to eliminate, such as those produced by transportation, the steel and cement industries, and wildfires from anywhere [4].

Among DAC approaches, liquid-based CO_2 methods require very high temperatures, ranging from 300 to 900 °C, typically supplied by natural gas combustion. In contrast, solid sorbents require less temperatures that can be provided by energy from renewable sources [5]. Moreover, adsorption with solid adsorbents is favoured for its simplicity and lack of liquid waste [6].

Nevertheless, adsorption has its limitations, such as the saturation of the adsorbent material, after which it ceases to capture CO_2. Although extending the time of maximum removal of the adsorbate (breakthrough time) can be achieved by modifying operating conditions, this typically leads to higher operational costs. Another potential approach to increase breakthrough time is the use of 3D-printed static mixers, which can enhance the performance and efficiency of the adsorbent.

To the best of our knowledge, static mixers have not yet been tested in adsorption with solid adsorbent systems for CO_2 capture, making this approach an unexplored and innovative area of study. However static mixers have been used to intensify processes in several studies. Yu et al. previously utilized static mixers to enhance CO_2 absorption, as these mixing elements promote turbulent flow, improving phase interaction and mass transfer within the pipeline [7]. Ugwu and Ogbonna proved that static mixers can increase the volumetric oxygen transfer coefficient ($k_{L\alpha}$) by 140% and enhance biomass productivity by 70% in tubular photo-bioreactors [8]. Altabash and Al-Hindi used static mixers to improve CO_2 absorption by achieving high $k_{L\alpha}$ values (up to 0.899 s^{-1}) [9].

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This study presents a modular carbon capture device prototype that employs solid adsorbents and IoT technologies to remove CO_2 from the air. The chosen adsorbent is zeolite 13X, a molecular sieve that demonstrates high working capacity for CO_2 and requires minimal purging [10].

The device incorporates custom-designed static mixers to intensify CO_2 adsorption and IoT systems to enable real-time monitoring and optimization of operating conditions. These features ensure low energy consumption, cost-effectiveness, and intelligent operation, making carbon capture technology more accessible and viable for widespread use, fostering its adoption in diverse settings.

2 Direct air capture unit design and manufacturing

The designed modular air capture unit is a compact 0.98×1×0.98 feet cube shaped by fixed aluminium slot 3030 profiles arranged at 90°. The electrical components are placed at the rear, within a medium-density fibreboard (MDF). The electronics are connected via a printed circuit board (PCB) which is covered by a layer of dielectric coating to ensure no direct or indirect contact with outer components of the cube.

The front of the drawer hosts an MDF platform with 3D printed resin fixed column holders designed to support three 1 ¼" acrylic tubes that make up the external structure of the adsorbent columns. Positioned at the rear, a Jadeshay 12V air pump achieves a flow rate that ranges from 1.5 L/min to 3.4 L/min. In operation, ambient air is drawn through a 1/8" inner diameter PVC tube and channelled through the air pump.

The air then proceeds through a packed bed containing blue silica beads (2-4 mm particle diameter). Silica gel is one of the most widely used solid desiccants in the industry due to its numerous drying properties, low cost, and availability [11].

Subsequently, the airflow encounters two packed beds in series, with zeolite 13X beads (3-5 mm particle diameter) enabling the selective and safe adsorption of CO_2 from the ambient air. A silica packed bed was placed before because CO_2 and moisture were competitive when absorbed by zeolite 13X according to experiments [6].

The device features two micro-controllers: Teensy 4.1 and ESP32. Teensy 4.1 controls CO_2, humidity and temperature sensors, it also delivers a customizable power source to an air pump using its Pulse Width Modulator (PWM) and a TIP120 transistor to achieve a flow rate of 1.5 L/min. The ESP32 receives the data recollected by the Teensy 4.1 and transmits it via Bluetooth Serial Communication to portable devices. This ensures that the user has access to real-time cube performance data. The circuity connects to a 12V power supply which then is stepped down by three L7805 five-volt regulators that deliver the correct power rating for sensors and micro-controllers. Figure 1 presents the device's mechanical design.

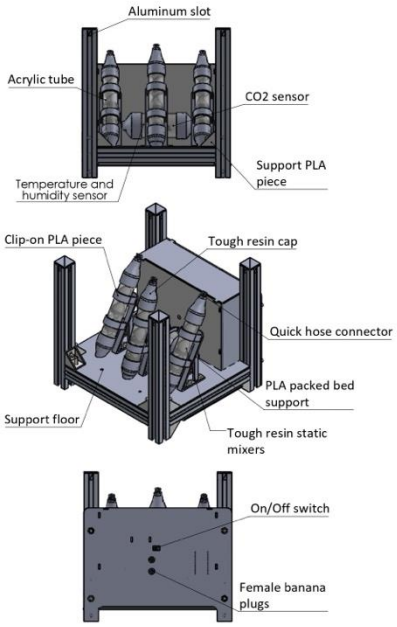

Fig. 1. Isometric drawing of the direct air capture unit.

2.1 Printed Circuit Board

The main objective of the device electronics is to ensure power efficiency, data accessibility for all users and long-term functionality.

Power efficiency is obtained by manipulating the voltage delivered to the air pump, which is the most power consuming component. Through experimentation it was found that the air pump can achieve the lowest air flow setting (1.5 L/min) with a voltage supply of 5 V. Nonetheless, the device's power supply is 12 V. The supply voltage is stepped down to the desired voltage by combining the TIP120 transistor and a custom PWM signal delivered by the Teensy 4.1 micro-controller. Overall, the device consumes an average of 3.5 W when set to its minimum air flow (1.5 L/min) and 5.2 W) when set to its maximum air flow (3.4 L/min). Thus, by employing a custom PWM signal, the device can reach up to a 32.7% reduction in power consumption when it's in the minimum air flow setting.

Data accessibility is delivered by the ESP32 microcontroller which allows Bluetooth communication with any portable device. A pair of SHT31-D sensors monitor outlet humidity and temperature, while two MH-Z19 sensors measure CO_2 concentration at the outlet. The data recovered by the sensors is processed by the Teensy 4.1 micro-controller. Then it is sent to the ESP32 micro-controller. Finally, the ESP32 microcontroller transmits the data via Bluetooth for the user to monitor de device performance.

Long-term functionality is achieved by easily dismountable components. The PCB was designed solely for through-hole soldering. This allowed to solder female headers instead of the actual components. Thus, in case of malfunction, all sensors and micro-controllers can be swiftly removed and replaced from the device.

The PCB was designed using EasyEDA (version 6.5.34), with the complete electrical diagram detailed in figure 2. Figure 3 shows the final product mounted within the device The main objective of the device electronics is to ensure energetic efficiency, data accessibility for all users and long-term functionality.

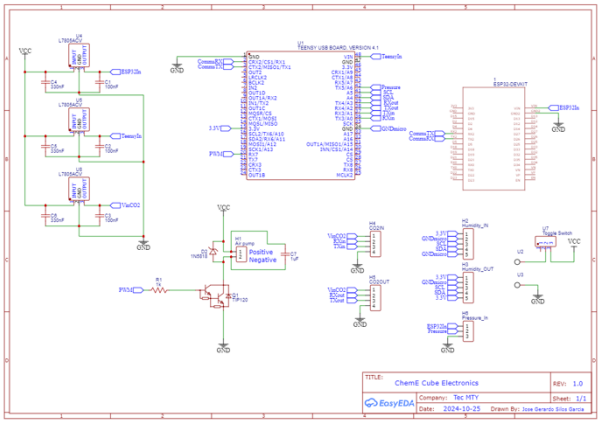

Fig. 2. PCB electrical schematic and wiring.

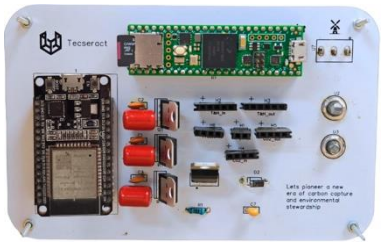

Fig. 3. Assembled PCB for device control and monitoring.

2.2 Static mixers design and manufacturing

Static mixers are introduced in the zeolite 13X packed beds to improve CO_2 adsorption efficiency by reducing channelling effects. Its design employs a helical shape to continuously recombine and divide the fluid flow. Figure 4 presents the design blueprint, which includes measurements in millimetres.

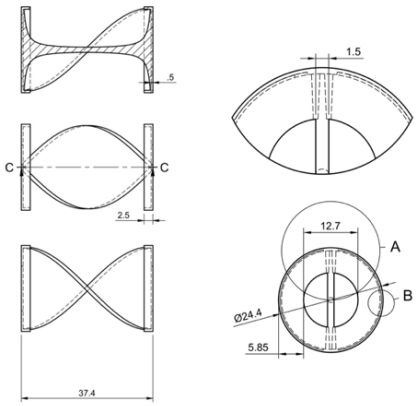

Fig. 4. Static mixers blueprint.

The static mixers were designed using Autodesk Fusion 360 (version 2.0.20970), with the dimensions detailed in Figure 4. The model was processed in Chitubox Basic (version 2.2.0) to prepare it for printing. The segments were printed using an Elegoo Saturn 2 3D printer with Anycubic Tough Resin 2.0. Post-processing involved curing the segments by submerging them in distilled water for 10 minutes, followed by 15 minutes of UV light exposure. Finally, supports were removed, and the segments were sanded to eliminate imperfections.

3 Methodology

3.1 Static mixers operational test

To assess the effect of static mixers on CO_2 adsorption by zeolite, the device was tested under two conditions: with and without static mixers. All other experimental variables were held constant, including the mass of silica and zeolite. In both setups, 40 grams of silica were placed in the first tube, followed by 30 grams of zeolite in each subsequent tube. Both, the silica gel and zeolites, were procured from Fisher Scientific.

The experiment consisted in measuring the concentration of CO_2 in ppm at the outlet of the device until the zeolite reached saturation. Due to compatibility issues between the Teensy 4.1 micro-controller and Excel's "Data Streamer" tool, used for real-time data logging, an Arduino UNO board was employed to collect data from the CO_2 sensor. Figure 5 presents a visual representation of the experimental setup.

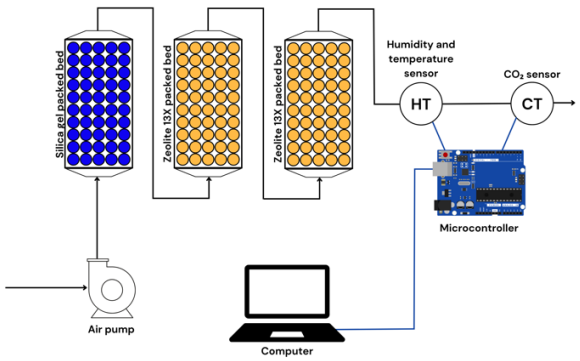

Fig. 5. Experimental set up to test the effectiveness of the mixers.

The collected data was used to develop breakthrough curves for each scenario. These curves illustrate how the dimensionless concentration of the adsorbate (CO_2) varies over time. The dimensionless concentration is defined as the ratio of the instantaneous concentration to the initial concentration, the later represents the maximum concentration of the experiment.

From the breakthrough curves, the percentage utilization of the packed bed was calculated. This parameter quantifies the extent to which the adsorption capacity of the packed bed was effectively utilized during the experiment based on the breakthrough time.

The percentage of utilization of the packed bed can be calculated with the following equation [12]:

$$\eta = \frac{t_b}{t_t} \times 100 \quad (1)$$

Where:

- η is the percentage of utilization of the packed bed.
- t_b is the breakthrough time (s).
- t_t is the exhaustion time (s).

The breakthrough time is defined as the duration from the beginning of the experiment until the CO_2 concentration at the outlet begins to rise, indicating the onset of breakthrough. This parameter represents the time during which complete removal of the adsorbate is achieved.

Moreover, the exhaustion time is calculated as seen in equation 2 [13].

$$t_t = \int_{t=0}^{t=t_{total}} \left(1 - \frac{C_t}{C_o}\right) dt \qquad (2)$$

Where:

- t_{total} is the time of the experiment.
- C_t is the concentration of CO_2 at a given time
- C_o is the initial CO_2 concentration.

The exhaustion time can also be determined by calculating the total area under the breakthrough curve and subtracting it from the total area of the graph. This represents the time during which the adsorbent is fully utilized before reaching saturation. This time was determined using polynomial regression, allowing for an accurate integration of the breakthrough curve.

The amount of CO_2 captured up to the breakthrough and exhaustion time was calculated using the following equation, obtaining the density of air calculated with the ideal gas law at experimental conditions which were 26°C and 1 atm:

$$m_{CO_2} = \frac{\dot{V} \cdot \rho_{air} \cdot y_{CO_2} \cdot MW_{CO_2} \cdot t_b}{MW_{air}} \qquad (3)$$

Where:

- m_{CO_2} is the mass of carbon dioxide captured (g).
- ρ_{air} is the density of the air $\left(\frac{g}{mL}\right)$.
- MW_{air} is the molecular weight of the air $\left(\frac{g}{mol}\right)$.
- y_{CO_2} is the mole composition of carbon dioxide in the air.
- MW_{CO_2} is the molecular weight of carbon dioxide $\left(\frac{g}{mol}\right)$.

3.2 Regeneration technique test

To continuously capture CO2 with this device, the desorption or regeneration process must be considered, that is when the adsorbate is separated from the adsorbent. Desorption is crucial for reusing the zeolite 13X and silica. The silica gel was regenerated at 110 °C, following a regeneration temperature recommendation from a silica manufacturer (Ringchaowei), although their silica was not used in this study. While Avelino et al. employed temperatures ranging from 150 °C to 200 °C in their experiments [13] to regenerate zeolite 13X, it was experimentally tested how well 10 grams of zeolite 13X performed after being regenerated at 140 °C and 200 °C for 45 minutes. The device used for heating was a mechanical convection Heratherm™ Advanced Protocol Security Oven from ThermoFisher.

4 Cost analysis

4.1 Performance of zeolite 13X and silica after regeneration

Both zeolite and silica can be reused thousands of times. zeolite 13X retains 31% of its adsorption capacity after 5,000 temperature swing adsorption cycles at a regeneration temperature of 150°C [14], which is slightly higher than the working conditions in this study. This data was derived from a study focused on regenerating zeolite after being saturated with water. However, it is likely that in the case of CO2, the loss in adsorption capacity would be lower, as the bonds between water and zeolite are stronger than those between CO2 and zeolite. Water and zeolite interact through hydrogen bonds and van der Waal's forces, whereas CO2 interacts only through van der Waal's forces.

Similarly, at a regeneration temperature of 250°C, silica with 22 Å, 30 Å, and 60 Å pore sizes lost 6%, 52%, 33%, and 19% of their adsorption capacity, respectively, after 5,000 temperature swing adsorption cycles [14]. Al though the pore size of the silica used in this study is not specified, it is worth noting that, like zeolite, the regeneration temperature of 250°C is significantly higher than the temperature used in this study. Therefore, it can be inferred that the performance losses would likely be lower under the operating regeneration temperature.

4.2 Democratization of carbon capture

The construction costs for the prototype are 180 USD, with nearly 50% of the expenses attributed to the device electronics. The remaining costs are primarily associated with mechanical components and 3D printing materials such as poly-lactic acid (PLA) and resin.

Although the cost to manufacture the device may seem high, modifications to the prototype design could significantly reduce these expenses. For example, smaller aluminium profiles or alternative support materials could be employed, along with substituting acrylic tubes and certain 3D-printed parts, as this is the initial prototype. Additionally, with the widespread adoption of additive manufacturing, printing static mixers or other parts has never been more affordable.

This low-cost DAC solution enables the democratization of carbon capture by fitting Beaumont's description of Decentralized-DAC technology (DDAC). DDAC refers to carbon capture infrastructure that operates without the need for subsidies or carbon credits, it often makes a more convenient CO2 removal tool for users located in areas without massive nearby sources of CO2 [15]. Furthermore, by applying DDAC technology to indoor settings the removal process is exposed to higher concentrations of CO2 (1,500– 3,000 ppm) compared to those found outdoors (400 ppm), allowing the system to

be smaller and more energy efficient [15]. Thus, the proposed device empowers individuals to adopt carbon capture technologies without the need for significant financial investment.

5 Results and discussion

5.1 Static mixers operational test

Figure 6 presents a comparison of breakthrough curves and times when using or not using static mixers.

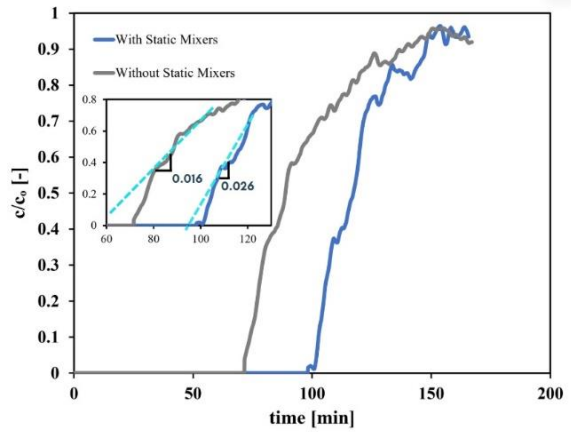

Fig. 6. Breakthrough curves of packed beds with and without mixers.

As shown in Figure 6, the total CO_2 removal time is notably longer, increasing by nearly 27 minutes when static mixers are used. This represents a significant improvement, particularly considering that only 100 grams of sorbent were used in this test. Additionally, the slope of the breakthrough curve for the test with static mixers is approximately 62.5% steeper compared to tests without them. A steeper slope indicates that the point at which the outlet concentration rises from zero coincides more closely with the moment when the sorbent reaches complete saturation, thereby maximizing adsorption efficiency.

Using Equations 1 and 2, Figure 7 was generated to compare the percentage of packed-bed utilization with and without static mixers.

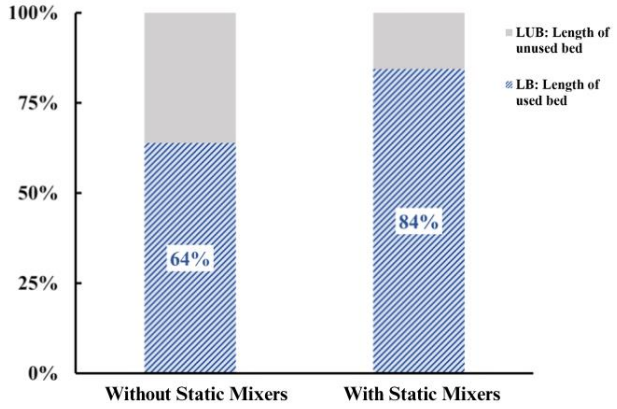

Fig. 7. Percentage of bed efficiency with and without mixers.

This figure supports the findings from Figure 6, demonstrating that bed utilization increased from 64% to 84% with the use of static mixers.

Table 1 presents a comparison between the CO_2 captured with and without static mixers up to the breakthrough time.

Table 1. Breakthrough times and percentage of bed used.

Static mixers	CO_2 captured (g) until t_b
Without static mixers	0.147
With static mixers	0.194

As shown in Table 1, a 32.1% increase in CO_2 capture is achieved as a result of using static mixers. This improvement in efficiency can be attributed to the fact that static mixers reduce channelling, which occurs when CO_2 molecules bypass the available adsorption sites on the zeolite surface, forming channels through which they flow in and out without being captured, even before the sorbent becomes saturated. The mixers achieve this by redirecting the air both tangentially and radially, thereby increasing the likelihood of CO_2 molecules adhering to the surface of zeolite 13X, which enhances CO_2 adsorption.

In contrast, without static mixers, as the zeolite becomes saturated, air can flow through gaps that lack adsorption material or static mixers, leading to inefficient CO_2 capture. These gaps arise from voids between particles and the intrinsic molecular-level porosity of zeolites [16] and silica [17].

5.2 Regeneration technique test

Figure 8 shows the breakthrough curves after regenerating zeolite 13X at 140 °C and 200 °C.

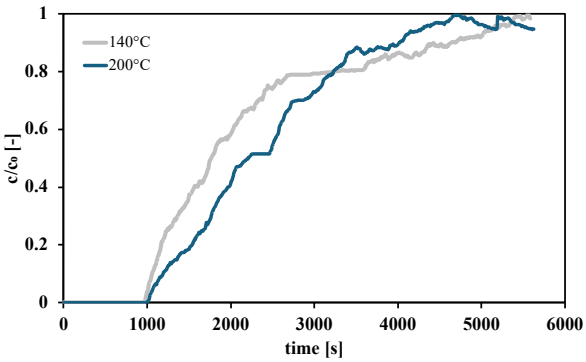

Fig. 8. Breakthrough curves for 10 g of zeolite 13X saturated with CO_2 at varying regeneration temperatures.

Figure 8 illustrates that regenerating zeolite 13X at 200 °C is unnecessary. To enhance the durability of the zeolite and reduce the associated regeneration energy costs, it is recommended that the zeolite be regenerated at 140 °C.

6 Conclusions

This study presents an affordable and modular alternative to achieve carbon capture. Experimental testing demonstrates that the proposed DAC unit using, only 100 grams of sorbent, can successfully remove all CO_2 from ambient air for approximately 98 minutes when employing additive-manufactured static mixers, compared to around 72 minutes without them. Even when taking into consideration fluctuations in ambient CO_2 concentration, this represents a 32.1% increase in captured mass. This intensification technique significantly enhances the economic viability of adsorption with zeolites, as it allows for greater carbon dioxide capture throughout the sorbent's useful lifespan.

Furthermore, the system's energy consumption of 3.5 watts during operation, while enabling real-time control and monitoring of the carbon removal process, highlights the well-engineered design of the electronic system, which can be easily adapted to similar DAC systems.

Although the prototype's initial cost is 180 USD, cost reduction can be achieved through design improvements, cheaper materials by leveraging additive manufacturing. These changes are fundamental for democratizing DAC technology, as it offers an accessible solution for all users and industries.

This study focuses solely on physical adsorption as a carbon removal method. Further research should examine the implementation of different carbon removal methods and intensification techniques.

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