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Carbon Capture and Storage using DAC Technology

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Abstract: *Direct Air Capture (DAC) technology has attracted a lot of interest as a possible way to remove carbon dioxide (CO_2) directly from the atmosphere, thereby reducing the effects of climate change. This in depth study offers a thorough analysis of DAC technology, emphasizing its underlying ideas, most current developments, difficulties, and incorporation with carbon capture and storage (CCS) plans. In the context of global climate mitigation efforts, this study tries to clarify the current state of distributed agriculture (DAC), as well as its viability, limitations, and future possibilities, through a thorough analysis of scientific literature, technical advancements, and real-world applications.*
Keywords: *Solenoid valves, Signal Conditioning Unit, Arduino Mega, Sorbent Molecules, CO_2 sensors*

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I. INTRODUCTION

The undeniable threat that climate change poses to our planet is principally caused by the atmospheric build-up of greenhouse gases, most notably carbon dioxide (CO_2). These gases trap heat, raising global temperatures, upsetting weather patterns, and having an adverse effect on the environment and society. In addition to lowering greenhouse gas emissions, we also need to look at ways to remove the CO_2 that is already in the atmosphere. Here, Direct Air Capture (DAC) shows itself to be a technologically promising approach.

DAC technologies are designed to take CO_2 out of the air directly. While carbon capture and storage (CCS) systems concentrate on emissions from certain sources, such as power plants, distributed carbon dioxide (DAC) can target CO_2 that is diffused throughout the atmosphere. There is potential for using the CO_2 gathered in a number of different industrial areas. DAC facilities now function as experimental projects with constrained capture capacities.

There will need to be a great deal of research and development done if these technologies are to be scaled up to have a meaningful impact on atmospheric CO_2 levels. Even if DAC is now quite expensive, economies of scale and technological developments are essential to improving accessibility. Not withstanding these obstacles, research on DAC is moving forward quickly.

The on going development of materials, capture techniques, and integration with renewable energy sources underscore the promise of DAC as an effective weapon in the fight against climate change. In this study, a conceptual design of a DAC system using an Arduino Mega microcontroller is explored. We will examine its elements, features, and possible advantages while recognizing its current drawbacks and places in need of more study.

II. LITERATURE SURVEY

1. Research Theories

The literature study offers a thorough summary of pertinent studies and research on the current theories and procedures used in CCS DAC technology. The main conclusions and insights from a variety of sources are highlighted in this overview of the literature, highlighting the importance and potential influence of the aforementioned technologies in resolving the issues that current practitioners confront.

Source 1: Intergovernmental Panel on Climate Change (IPCC) of the World Meteorological Organization (WMO) "CARBON DIOXIDE CAPTURE AND STORAGE (2005)"
Results: Special Report outlining the origins, sequestration, transportation, and storage of CO_2. It also covers the technology's expenses, economic prospects, and societal concerns, such as regulatory and public perception.

Source 2: "A Knowledge Mapping-Based Study on the Development of Carbon Capture and Storage Technology," by Authors Hong-Hua Qiu and Lu-Ge Liu, Article MDPI, published in May 2018.

Results: Carbon emissions and environmental protection, research and development activities, and socially relevant issues are among the topics covered in detail. In the meantime, the main emerging trends in the field of CCS technology research are emerging materials, emerging techniques and processes, evaluation of technological performance, and socioeconomic analysis.

Source 3: Natalia Kulichenko and Eleanor Ereira's "Carbon Capture and Storage in Developing Countries: A Perspective on Barriers to Deployment", a study conducted by the World Bank.
Results: Project Financing for Carbon Capture and Storage Power Plants in Developing Nations (Ch-6, pp. 80–106)

Source 4: "Direct Capture of CO_2 from Ambient Air" Eloy S. Sanz-Perez, Christopher R. Murdock, Stephanie A. Didas, and Christopher W. Jones from the Department of Chemical and Environmental Technology, ESCET, Rey Juan Carlos University, C/Tulipan s/n, 28933 Mo Ástoles, Madrid, Spain, and the School of Chemical & Biomolecular Engineering, Georgia Institute of Technology, 311 Ferst Drive, Atlanta, Georgia 30332-0100, United States, contributed to this work.
Results: A thorough explanation of the chemical sorbents used in this application, including solvents and solid sorbents that interact strongly with CO_2, is provided, with the main chemical sorbent classes being metal-organic frameworks (MOFs), supported amine and ammonium materials, and basic solvents. The field of DAC has a lengthy history.

The literature study concludes by highlighting the significance of pertinent studies and research on the current theory and procedures used in CCS DAC technology. It demonstrates how CCS DAC technology may significantly improve the environment and support sustainability objectives. These results provide a solid basis for the advancement and room-scale application of CCS DAC technology.

2. Provide feedback and practice

One of the main environmental issues and the cause of global climate change is carbon dioxide (CO_2). This overview covers numerous organizations, tactics, and policy bodies while examining current doctrine and practice on the avoidance and reduction of greenhouse gas emissions through September 2021. i.e., CCS, or carbon capture and storage: The idea is to store CO_2 emissions underground after they are captured at the source.
Use:
i. To keep CO_2 out of the atmosphere, CCS technology is applied in electrical and industrial facilities.
ii. Strategies for cutting greenhouse gas emissions: Every year, tens of billions of tons of greenhouse gas emissions are discharged into the atmosphere, despite all of the efforts made to cut them. Consequently, the IPCC suggested that, in order to stop the increase of CO_2 in the atmosphere, CO_2 capture technology is essential. The conventional focus of CO_2 collection has been on emissions from big stationary sources, like steel and metal industries, cement facilities, oil refineries, and fossil power plants.
These technologies are typically used in the production of synthesis gas (H_2) and natural gas (CO). Feedstocks appropriate for energy generation and CO_2 capture can be produced by a number of methods, such as gasification of coal (IGCC), coke, or oil wastes (reaction 2), or reforming oil (reaction 1). Reaction 3: A gas primarily consisting of CO_2 and hydrogen is produced when CO and water react, also known as the water gas reaction. Pure H_2 can be used to generate electricity by eliminating CO_2. Under these conditions, CO_2 concentrations range from 15 to 60%, making it easy to capture. However, the initial stage of fuel preparation for oil reforming and coal mining is costly and challenging.

$$CxHy + xH2O \rightarrow xCO + (x + y/2)H2 \quad ...(1)$$

$$CxHy + x/2\ O2 \rightarrow x\ CO + y/2\ H2 \quad ...(2)$$

$$CO + H2O \rightarrow CO2 + H2 \quad ...(3)$$

3. Received during combustion
CO_2 can also be retained in the flue gas released after combustion. A number of technologies can be used in this way, as there is no need to replace existing combustion equipment. Flue gas must normally be removed first, as required by law in most countries. The main effect of this approach is to reduce CO_2 emissions from 4% by volume for combined natural gas power plants to 13-15% for coal fired power plants. Average global temperature changes from 2006 to 2100 were determined by multimodal simulations. All changes relate to the period 1986-2005. This review describes advances in the direct removal of CO_2 from ambient air using

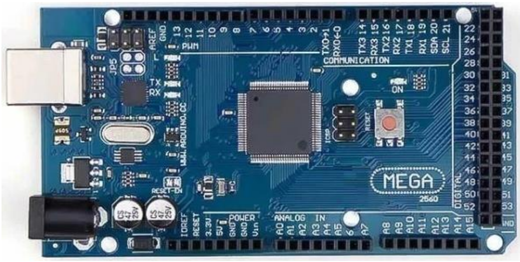
adsorbents or direct air capture (DAC), one of several potential "carbon technologies." The history of the DAC begins with the initial presentation of the atmosphere, followed by the assessed activities important for identifying the number of organisms and removing CO_2 from the atmosphere. A brief discussion of informal methods based on DAC is also included. Finally, an overview of the feasibility and cost performance of DAC is presented.

4. Send fire

The flue gas that is emitted after burning contains the ability to hold CO_2. This allows for the application of many different technologies without requiring the replacement of current combustion equipment. In most countries, it is legally required to remove flue gas first. This strategy's primary result is a decrease in CO_2 emissions, which go from 4% of total emissions from combined natural gas power plants to 13-15% from coal-fired power plants. Using multi-model simulations, the average global temperature increases from 2006 to 2100 were calculated. Every modification relates to the years 1986–2005. This article details developments in direct air capture (DAC), one of several possible "carbon technologies" or the removal of CO_2 directly from ambient air using adsorbents. The first presentation of the atmosphere in the history of the DAC is followed by an assessment of the activities crucial to determining the quantity of organisms and extracting CO_2 from the atmosphere. Included is a brief explanation of unofficial techniques based on DAC. Lastly, a summary of DAC's cost effectiveness and viability is given.

III. COMPONENTS SELECTION

1. Microcontroller Board: -



The following summarizes the main considerations that led us to choose the Arduino Mega 2560 for this project: There are a few main reasons why the Arduino Mega microcontroller board was selected.

- Wide Range of I/O Capabilities: With so many digital and analog input/output ports available, the Arduino Mega is a great choice for attaching and managing numerous sensors, actuators, and peripherals at once. This is important for a project like DAC technology, where a large number of sensors may be used for data collection, control, and environmental monitoring.

- Processing Capacity: The Arduino Mega has enough processing power and storage to manage intricate algorithms, data processing jobs, and control logic needed in DAC systems thanks to its ATmega2560 processor, which runs at 16 MHz, and large flash memory (256 KB). This is crucial for the system's decision-making, control, and real-time monitoring procedures.

- Community Support and Compatibility: A large developer, maker, and enthusiast community supports Arduino boards, including the Mega. This guarantees a large selection of suitable libraries, sample programs, tutorials, and community forums where you can ask questions, exchange ideas, and work through problems that arise while working on the project. This network of help can greatly accelerate development and lessen implementation difficulties.

- Expandability and Modularity: The Arduino Mega modular design facilitates effortless expansion via shields and modules, offering the opportunity to incorporate supplementary features or interact with external devices as required for your DAC technology endeavor. It is advantageous that the system can be scaled up or down in the future.

- Cost Effectiveness: The Arduino Mega offers a balance of functionality, performance, and price when compared to some other microcontroller boards with comparable capabilities. Because of this, it is an affordable option for projects like the development of Direct Air Capture technology that have rigorous I/O needs and processing duties.

In general, the Arduino Mega is a good and useful option for implementing the control and monitoring components of your DAC system because of its wide range of I/O capabilities, processing power, interoperability, community support, expandability, and affordability.

Specifications:

- Microcontroller: ATmega2560
- Operating Voltage: 5V
- Input Voltage (recommended): 7-12V
- Input Voltage (limits): 6-20V
- Digital I/O Pins: 54 (of which 15 provide PWM output)
- Analog Input Pins: 16
- DC Current per I/O Pin: 20 mA
- DC Current for 3.3V Pin: 50 mA
- Flash Memory: 256 KB (8 KB used by bootloader)
- SRAM: 8 KB
- EEPROM: 4 KB
- Clock Speed: 16 MHz

2. Pressure Sensor: -

Because the PT9544 pressure sensor is appropriate for measuring pressure in the setting of vacuum systems and atmospheric circumstances, it is utilized.

➢ Pressure Range: Typically, the PT9544 sensor can measure a wide range of pressures, from ambient pressure to vacuum levels. This range is crucial to DAC technology, as measurements of pressure might range from lower pressures in the capture and storage systems to ambient air pressure.

➢ Accuracy and Precision: The PT9544 sensor provides accurate and precise pressure measurements, which is necessary for DAC operations to record accurate data. Precise pressure measurements are essential for overseeing and managing the functioning of air collection systems, guaranteeing maximum effectiveness and productivity.

➢ Small and Adaptable: The PT9544 sensor's small size makes it simple to incorporate into your DAC system without taking up a lot of room. Because of its adaptability, installation options are diverse and precise pressure measurements may be made at strategic spots in the collection and storage infrastructure.

➢ Durability and Reliability: Equipped with characteristics that improve durability in a range of environmental situations, the PT9544 sensor is built for dependable long-term performance. This dependability adds to the overall efficacy and stability of the technology by enabling continuous and precise pressure monitoring in DAC systems.

Specifications:

- Pressure Range: Typically, 0 to 10 bar (other pressure ranges may be available)
- Output Signal: Analog (0-10V or 4-20 mA)
- Supply Voltage: 10-30 VDC
- Accuracy: ±0.5% of Full Scale (FS)
- Operating Temperature: -25°C to 85°C
- Process Connection: G1/4" male thread
- Electrical Connection: M12 connector or cable
- Material: Stainless steel (housing)
- Protection Rating: IP65/IP67 (depending on the variant)

3. CO_2 Sensor:-

There are a number of strong reasons why the Sensirion Non-Dispersive Infrared (NDIR) CO_2 sensor was chosen.

➢ Precise CO_2 Measurement: NDIR sensors are renowned for their exceptional precision in determining CO_2 levels. This is crucial for Direct Air Capture (DAC) systems, as accurate air level monitoring is necessary for efficient CO_2 capture and storage. The Sensirion NDIR CO_2 sensor is known for its broad measurement range, which enables it to precisely monitor CO_2 concentrations ranging from ambient levels to higher amounts encountered in DAC operations.

➢ Stability and Long-Term Performance: NDIR technology is appropriate for continuous monitoring and control applications in DAC systems because it offers steady and trustworthy CO_2 measurements over long periods of time. Maintaining the efficacy and efficiency of CO_2 capture and storage operations requires consistent performance.

➢ little Power Consumption: Sensirion's CO_2 sensors, among others, are made to function with little power consumption. This is helpful for energy efficient operation, particularly in off grid or remote distributed air conditioner installations where power conservation is a top concern.

Specifications:

- Measurement Principle: Non-Dispersive Infrared (NDIR)
- Carbon Dioxide (CO_2) Measurement Range: 0-40,000 parts per million (ppm)
- Accuracy: ± (30 ppm + 3% of measured value) within 400-10,000 ppm
- Response Time: <2 minutes (for 63% step change)
- Temperature Range (Operating): 0°C to 50°C
- Humidity Range (Operating): 0% to 100% RH (non-condensing)
- Supply Voltage: 3.3 V to 5.5 V
- Communication Interface: I2C (up to 400 kHz) and UART (up to 115200 bps)
- Dimensions: 35.6 mm x 23.3 mm x 3 mm (L x W x H)
- Digital Output Resolution: 16-bit
- Power Consumption (Average): 19 mA @ 3.3 V (continuous operation)
- Warm-up Time: <30 seconds

4. Molecular Sieves:-

Because of its numerous uses, 13x molecular sieves were specifically taken into consideration.

- Selective Adsorption: Molecular sieves are engineered to adsorb molecules of particular sizes in a selective manner. The capacity of 13x sieves to specifically adsorb CO_2 from air while permitting other gases, such as oxygen and nitrogen, to flow through, is well recognized.

- High Capacity: 13x molecular sieves can absorb a large amount of CO_2 per unit weight or volume of the sieves thanks to their high CO_2 adsorption capacity. This large capacity is essential for effective digital audio converters.

- Regenerability: Molecular sieves can be utilized again and again by desorbing the CO_2 that has been absorbed. As a result, they are more economical and eco-friendly than one-time use adsorbents.

- Stability: 13x molecular sieves remain stable in a variety of working environments, such as those with fluctuating pressures and temperatures that are typical of DAC systems.

- Commercial Availability: Due to their vast commercial availability, these sieves are easily accessible for large-scale DAC projects. Details: Molecular sieves of type 13x (Type x) with a pellet diameter of 1.6 mm (other diameters may also be offered)

Specificaions:

- Adsorbate: primarily used for CO_2 adsorption from air;
- Pore Size: approximately 10 angstroms (1 nanometer), suitable for capturing CO_2 molecules while allowing smaller molecules like nitrogen and oxygen to pass through;
- Surface Area: typically ranges from 600 to 800 square meters per gram (m2/g), providing a large surface area for CO_2 adsorption;
- Adsorption Capacity: can adsorb a significant amount of CO_2 per unit weight of molecular sieves, depending on the particular conditions and activation level;
- Regenerability: molecular sieves are regenerable by desorbing the captured CO_2, making them economical and environmentally friendly;
- Material: typically composed of zeolite materials such as sodium aluminosilicate

5. Temperature sensor:-

For several reasons, Direct Air Capture (DAC) projects frequently use PT100 sensors, usually referred to as platinum resistance temperature detectors (RTDs).

- Accuracy: Temperature-sensitive operations in DAC systems require constant monitoring and control, and PT100 sensors provide this critical accuracy. Accurate temperature regulation is frequently required for maximum effectiveness and performance.

- Stability: The stability and little drift over time of PT100 sensors are well-known. This guarantees that temperature readings stay accurate and consistent for the duration of the DAC system's operation, which results in consistent process performance.

- Linear reaction: The PT100 sensors provide a linear reaction to temperature variations, which facilitates precise calibration and interpretation of temperature measurements. In DAC processes, this linear response helps to preserve particular temperature setpoints.

- Broad Temperature Range: PT100 sensors are capable of functioning in a broad temperature range, which encompasses the high temperatures that might be encountered in DAC systems during specific procedures like as CO_2 desorption or adsorbent renewal.

- Compatibility: The PT100 sensors may be easily integrated into DAC technology projects since they are compatible with conventional measurement and control systems that are frequently used in industrial settings.

- Industry Standard: Because of their accuracy, stability, and dependability, PT100 sensors are widely utilized and well established in a variety of sectors for temperature sensing applications. For many DAC technology projects where accurate temperature control and monitoring are crucial, this makes them the preferable option.

Specifications:

An example of a platinum resistance temperature detector (RTD) is the PT100 temperature sensor, which comes with the following specifications:

Type: PT100 (Platinum RTD)

- Temperature Range: -200°C to 850°C (-328°F to 1562°F) is the temperature range that standard PT100 sensors can measure. It's possible that PT100 sensors with extended range can measure temperatures more broadly.
- Precision: PT100 sensors have a high degree of precision; depending on the grade and calibration, they can often measure within ±0.1°C to ±1°C.
- Resistance at 0°C: A PT100 sensor's resistance, which increases linearly with temperature changes, is 100 ohms at 0°C, hence the designation PT100.
- Temperature Coefficient: PT100 sensors temperature coefficient of resistance, which is utilized in computations to translate resistance variations into temperature readings, is roughly 0.00385 ohms/ohm/°C.
- Construction: To create a resistance element, platinum wire is usually coiled around a ceramic or glass core in PT100 sensors. 14

- Response Time: For the majority of applications, PT100 sensors respond rather quickly within a few seconds, on average. Depending on the PT100 sensors manufacturer, model, and grade, these specs may change slightly. It's crucial to consult the datasheet supplied by the sensor manufacturer to find the details pertaining to a particular PT100 sensor model

6. Solenoid Valve:-

24 volt DC solenoid valves:

➢ Controlled Gas Flow: In DAC systems, solenoid valves regulate the flow of gases like air and CO_2. Their ability to precisely regulate gas flow rates is essential for preserving ideal process conditions throughout the CO_2 capture, release, and storage stages.

➢ Automation: Gas flow regulation can be automated with solenoid valves, eliminating the need for human modifications. Because this automation can be linked into control systems and designed to work according to preset parameters, it enhances system efficiency, consistency, and reliability.

➢ Response Time: The quick response times of solenoid valves allow for quick opening and closing of the valve. This fast reaction is useful for making quick changes to gas flow rates, particularly when there are dynamic process circumstances or when the system calls for it.

➢ Compatibility: 24V DC solenoid valves are easily integrated into DAC technology projects since they work with standard power sources and industrial control systems.

Specifications:

- Voltage: Direct Current, 24 V DC
- Type of Valve: Normally Closed (NC), which means that when the solenoid coil is not receiving any power, the valve is closed and opens when it is.
- Operating Pressure Range: Depending on the particular model and application requirements, solenoid valves for industrial usage may often withstand pressures ranging from 0 to several hundred pounds per square inch (psi).
- Flow Rate: Depending on the size and design of the valve, the solenoid valves flow rate is expressed in liters per minute (LPM) or gallons per minute (GPM). A few GPM to several tens of GPM are typical flow rates.
- Valve Size: Solenoid valves are available in a range of sizes, including 1/4-inch, 1/2-inch, 3/4-inch, and 1 inch

IV. BLOCK DIAGRAM

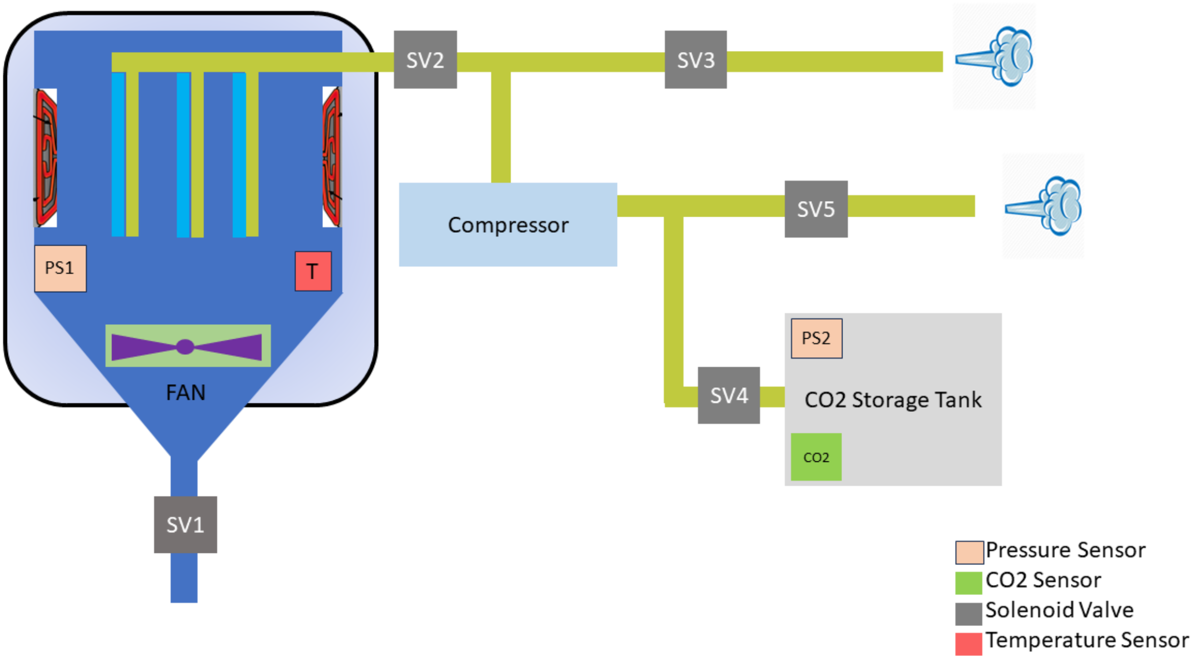


Fig. Carbon Capture and Storage using DAC Technology

The system's needed flow capacity is taken into consideration while choosing the valve size. Block Schematic The functional architecture of our DAC Technology is shown in the block diagram above.

1. Solenoid Valves

Valves with solenoids A solenoid valve is a crucial component of Direct Air Capture (DAC) technology, performing functions like controlling gas flow, purging and ventilating, regulating pressure, ensuring safety shutdown, and automating processes. Think about things like valve type, material compatibility, pressure and temperature ratings, and electrical compatibility with your control system when choosing a solenoid valve. 16

2. Nichrome Wire

Nichrome Wire Because of its high electrical resistance, nichrome wire is used in DAC systems to provide controlled and consistent heating, which is necessary for thermal operations. It is perfect for heating elements in our project, helping to ensure effective carbon capture operations. Its temperature stability, corrosion resistance, and compatibility with electrical systems, including microcontrollers like the Arduino Mega, further contribute to its advantages.

3. Fan

A fan Fans are necessary for ventilation, pressure management, temperature regulation, air circulation, and cooling electronic components. Efficient CO_2 capture and processing while preserving system reliability and performance can be achieved by selecting a fan that meets your control system's requirements for size, power consumption, noise level, airflow capacity, and compatibility.

4. CO_2 sensor

A CO_2 detector When it comes to tracking and detecting carbon dioxide (CO_2) concentrations, the CO_2 sensor is essential. The sensor gives accurate control and optimization of DAC processes by providing real-time data on CO_2 levels. This information is essential for guaranteeing proper CO_2 collecting, storage, and processing, which enhances the DAC system overall efficacy and environmental impact.

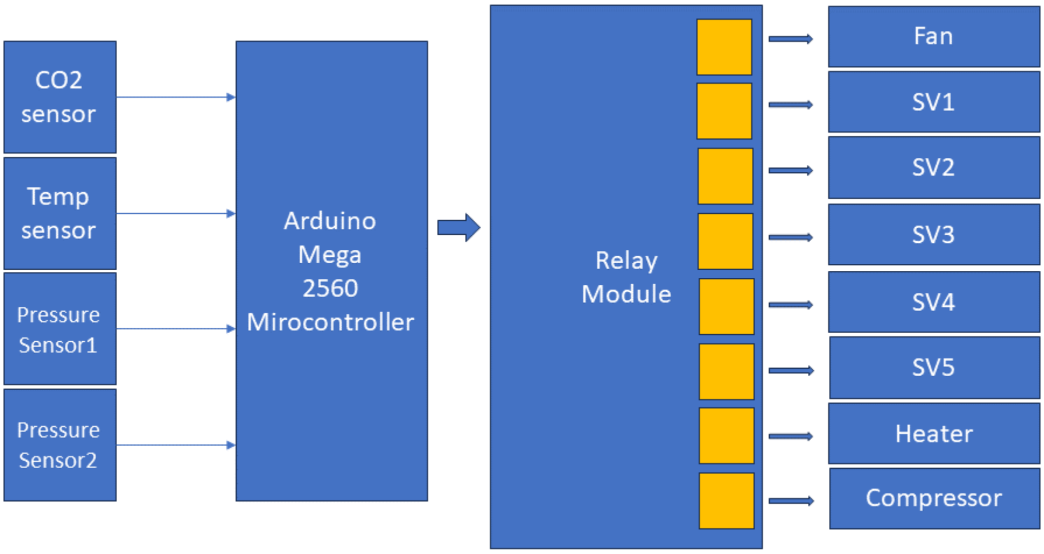
5. Pressure Sensor

Sensor of Pressure The system pressure levels are measured and observed using the PT9544 pressure sensor. In order to maintain proper pressures for gas flow, regulate pressure changes throughout processes, and improve overall system performance and efficiency, this sensor is essential to guaranteeing ideal operating conditions.

6. 16x2 LCD Display

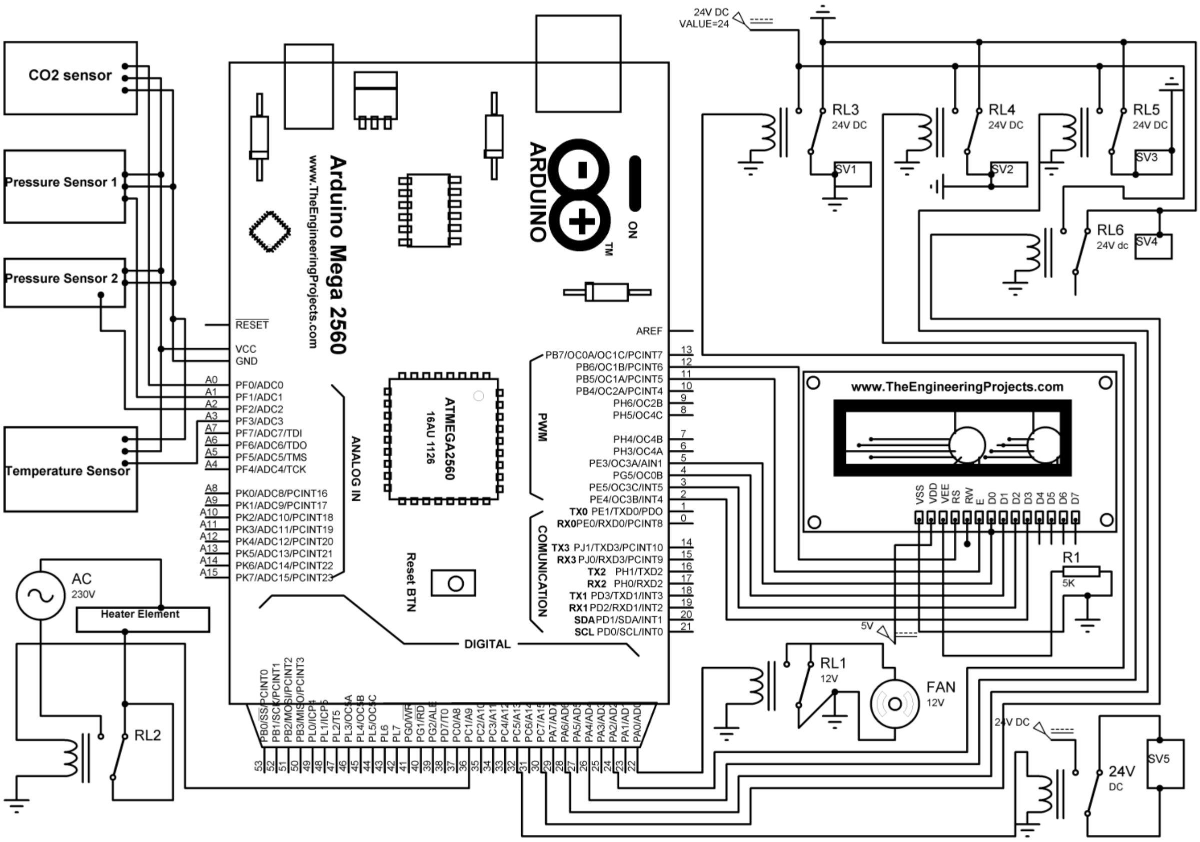
16X2 LCD Display Real time data, system status, and operational parameters can all be shown using an LCD display as a user interface. It gives temperature, pressure, and CO_2 levels a visual representation.

7. Temperature Sensor



Thermostat For precise temperature monitoring and control during the CO_2 collecting and storage procedures, PT100 sensors are necessary. By keeping temperatures within the necessary range, enabling automated control, facilitating data analysis, and promoting adsorbent material regeneration cycles, they ensure optimal operation, safety, and process efficiency. PT100 sensors are vital instruments for optimizing the efficiency of DAC systems in the fight against climate change since they interface with control systems in a fluid manner.

V. CIRCUIT DIAGRAM



VI. EXPERIMENTAL PROCEDURE

1. Inserting Molecules in Chamber
Placing Molecules into the Chamber. There are three distinct sorbent panels that make up the chamber. Each had the ability to store 500 grams of 13x molecular sieves.

2. Air Flow
Movement of Air Activate the compressor and fan. Solenoid valves 1,2 and 3 should be opened, while solenoid valves 4 and 5 should be closed. As a result, air will be able to flow between the molecules.

3. Creating vacuum in chamber
Producing a vacuum inside the container Now shut off solenoid valve 1 and the fan. Sorbent molecules will absorb CO_2 from the air at room temperature, and any leftover airborne particles will be drawn up by a compressor and expelled through Solenoid Valve 2 and 5. This procedure will continue until the vacuum pressure reaches a predetermined limit. The PT9544 pressure sensor measures this pressure. The compressor will then cause solenoid valves 2 and 5 to shut off.

4. Giving heat to the Molecular Sieves
Increasing the Molecular Sieves temperature Right now With the use of a heating element made of nichrome wire, warm the molecules to a steady temperature of $75^{o}\pm 4^{o}C$. Here, the microcontroller is configured to function as a thermostat. If the temperature rises over 75^{o}, it will cut off the supply to the Nichrome Wire. If the temperature falls below 75^{o}, it will turn on the supply. For thirty minutes, this process will continue

5. Storing CO_2 in Tank and displaying its Concentration
Holding CO_2 and showing its concentration in a tank To store the released CO_2 from molecules in the tank, open Solenoid Valve 2 and 4 and turn on the compressor. The compressor and solenoid valves 2 and 4 will turn off when the designated level is reached. The CO_2 concentration in parts per million will then be shown on a 16x2 LCD screen.

VII. FUTURE SCOPE

When considering the potential applications of direct air capture (DAC) technology for carbon capture and storage (CCS), a number of fascinating research and development opportunities arise that have the potential to completely transform how we tackle climate change.

1. Enhanced Carbon Capture Efficiency: By investigating new materials, cutting edge sorbents, and creative capture strategies, future research may concentrate on improving the effectiveness of DAC systems. DAC technology can be rendered more economical and expandable by increasing the rate of CO_2 removal and decreasing energy usage through the optimization of the capture process.

2. Carbon Negative Solutions: Building on the success of the DAC, further research may focus on creating carbon negative solutions that eliminate carbon emissions now in place in addition to removing CO_2 from the environment. This could entail using natural processes like increased weathering to trap carbon in soils or minerals, or it could entail combining DAC with bioenergy with carbon capture and storage (BECCS).

3. Hybrid Approaches: There is a great deal of potential for synergistic effects when hybrid approaches, like point source capture from industrial sites or power plants, combine DAC with other carbon capture technologies. To construct integrated carbon capture and storage (CCS) systems that maximize carbon removal capacities while minimizing costs and environmental concerns, research might investigate the integration of DAC with currently in place infrastructure.

4. Carbon Utilization and the Circular Economy: In addition to storage, further study may concentrate on using collected carbon as a useful resource in the creation of sustainable materials, chemicals, and fuels. By adopting the circular economy's tenets, DAC technology can help build closed loop systems that recycle and reuse CO_2, lessening dependency on finite resources and lessening environmental effects.

5. Community Engagement and Social Acceptance: Given the significance of including stakeholders, community involvement and social acceptance in the implementation of DAC technology might be given priority in future studies. Researchers can make sure that DAC initiatives are carried out in a way that benefits

all stakeholders and advances sustainable development by encouraging communication, establishing trust, and addressing concerns about environmental justice and equity.

6. International Collaboration and Knowledge Sharing: To advance DAC technology and hasten its global application, international collaboration is crucial. Future studies should concentrate on developing international collaborations, exchanging best practices, and promoting the flow of knowledge in order to get over financial, legal, and technical obstacles and encourage the broad use of DAC as a vital weapon in the battle against climate change. All things considered, research on direct air capture technology for carbon capture and storage has a bright future full of potential for creativity, teamwork, and good deeds.

Researchers can fully realize the potential of DAC as a game changing tool in our joint efforts to create a future that is more robust and sustainable by embracing these new lines of inquiry.

VIII. CONCLUSION

The potential of Direct Air Capture (DAC) in conjunction with Carbon Capture and Storage (CCS) to reduce CO_2 emissions is highlighted in the conclusion. It highlights the technical features of DAC, such as 13x molecular sieves, sophisticated materials, and energy efficient operations, as well as its scalability and efficiency. In order to advance research, cut costs, and implement CCS DAC solutions globally and contribute to a sustainable, carbon-neutral future, collaboration is essential

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