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Design and Preliminary Experimental Evaluation of a Carbon Trapping Towered Chamber for Atmospheric CO_2 Mitigation

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ABSTRACT

The surge in the concentration of the carbon dioxide (CO_2) gas owing to urban growth, transport mechanisms and industry related activities urges us to conduct research on the ways to reduce atmospheric (CO_2). This study represents the design, construction & preliminary testing of a laboratory scale Carbon Trapping Tower Chamber (CTTC) designed to investigate the interaction of ambient air with carbon surfaces under an applied electric field. The prototype was fabricated from the vertical chamber, suction fan, carbon rods, and DC power supply. The last two elements are active parts where the fan creates the inflow of the air while carbon rods are the surface upon which it is found under the action of an electric current. The prototype was fabricated from readily available materials, and the fabrication process was kept as simple as possible; nevertheless, the prototype demonstrated good electrical insulation, airflow performance, internal access, and overall efficiency. Our tests related to prototype shows that the installed fan was able to provide enough airflow and the electric circuit was functioning well without significant problems and mechanical instability. Nevertheless, during the described tests, the (CO_2)

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concentrations at the inlet and outlet were not evaluated. Therefore, while the capacity of the prototype to remove (CO_2) from the air is evident, its efficiency and rates are not supported by the presented evidence. Future experiments should include calibrated inlet and outlet (CO_2) measurements, characterization of airflow, analysis of adsorption and controlled experiments to determine if the applied electric field has a measurable effect on (CO_2) capture.

Keywords: Carbon Dioxide, Direct Air Capture, Carbon Material, Electric Field, Forced Convection, Adsorption, Prototype, Atmospheric Mitigation.

Introduction

Carbon dioxide (CO_2) is a foremost greenhouse gas that is accountable for the long-term warming of the Earth's climate. It is much less abundant in the atmosphere than nitrogen and oxygen, but its contribution to the greenhouse effect makes it a concern from an environmental standpoint. Reducing the emission of (CO_2) at their sources is therefore an important component of efforts to limit its continuing build-up in the atmosphere. Measures that may help include improving fuel efficiency, expanding the usage of electric automobiles, growing the usage of renewable energy sources and reducing emissions from industrial activities. But applying these measures is not always easy. Their wider uptake may depend on existing infrastructure, investment, government policy and broader changes in energy use over time.

Reducing new (CO_2) emissions does not address the carbon dioxide already accumulated in the atmosphere. This has sparked interest in carbon-capture and carbon-removal techniques, including technologies that aim to pull (CO_2) directly from the ambient air. In the past, carbon-capture systems were developed for industrial gas streams that contain a much higher concentration of the target gas. Direct air capture is more difficult because the (CO_2) concentration in the atmosphere is much lower and the capture system must process a fairly large volume of air [1, 2].

The situation becomes significantly more complex when the system is used in the form described for distributed or urban applications. In this case, the working device should ensure that a significant fraction of the flow through the capture region interacts with the gas to be captured. Meanwhile, the power required to drive the air circulation system and the additional capture mechanism should not be too large. Thus, the control of airflow, residence time, and consequently flow rate and pressure losses as well as power consumption, are critical factors in consideration of such a small-scale system.

The present research deals with the concept of a small-scale Carbon Trapping Tower chamber (CTTC). The system uses forced air flow through carbon surfaces with a DC electric field applied vertically in a chamber, with air being sucked by a suction fan. The electric field is introduced as an alternative variable that may influence the interaction between the air and the carbon surfaces.

The current study aims to construct and analyze the first working prototype of the CTTC system, so that future experiments can be carried out to test the efficiency of (CO_2) removal. Therefore, this paragraph should demonstrate whether the suggested system can ensure the necessary airflow and be mechanically and electrically reliable, so that future experiments can be conducted.

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Theoretical Background

Carbon Dioxide in Ambient Air

The molecule of carbon dioxide comprises of one atom of carbon and two atoms of oxygen. The bonds between the atoms are strong; as a result, (CO_2) is a stable molecule. That is why it is not easy to detach carbon dioxide from the air. A molecule of (CO_2) does not interact actively with other substances, which is why it is difficult to remove it from the composition of air in normal conditions.

Another difficulty is its relatively low concentration in ambient air. Only a small fraction of atmospheric air consists of (CO_2). Consequently, a system designed to remove a measurable amount of the gas must process a comparatively large volume of air.

Several approaches have been investigated for (CO_2) capture. Chemical absorption uses reactive liquids that interact with (CO_2), while adsorption involves the attachment of gas molecules to the surface of a solid material. Materials with relatively high surface areas, containing activated carbon and zeolites, have been considered for adsorption-based capture. Other approaches use electrochemical or catalytic processes in which (CO_2) is converted into other chemical products [3-9].

The CTTC is based on the simpler concept of bringing ambient air into contact with a solid carbon surface. In the present prototype, carbon rods provide the main internal surfaces. The applied electric field is introduced as an additional experimental parameter whose possible influence on the gas-surface interaction can be examined separately.

Electric-Field and Electrostatic Effects

The response of a gas to an applied electric field depends on the field strength as well as on the nature of the particles or molecules within the gas. When a neutral molecule is placed in an external electric field, its charge distribution can become slightly distorted, producing polarization. Charged particles behave differently because the electric field acts on them directly and exerts an electrical force [10-12].

The mere appearance of an electric field does not indicate than (CO_2) molecules will split. Bonds in (CO_2) are strong, requiring far different conditions to be broken than are needed to form an electric field inside a lab chamber. The CTTC does not propose to be a system that directly splits (CO_2) into carbon and oxygen. In this design, the electric field has a more limited and testable role. It provides a controlled electrostatic environment in which the interaction between the moving air and the carbon surface can be studied. Can the field improve the adsorption or some other interaction? We can't assume that the mere fact that there is a field will have an effect, it needs to be measured. The reason for this caution is that while electrostatic collection of ions is straightforward, the interactions of neutral gas molecules with an electric field are more complex. Here controlled experiments are crucial to determine and effect of the applied electric field on the carbon dioxide capture.

Forced Airflow and Residence Time

In the CTTC a suction fan creates the pressure difference sufficient to pull the ambient air into the chamber and make it flow through the region of treatment. The quantity of air flowing through the chamber per unit time is defined by the quantity

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which is known as volumetric flow rate and is represented by Q. It is given by the following ratio:

$$Q = \frac{dV}{dt}$$

The term V from the above mentioned relation represents the volume of air flowing through the system or chamber on the other hand, t is the corresponding time. After this volumetric flow rate there is another parameter which is crucial to define the complete phenomenon. That parameter or we can that quantity is known as residence time. It provides an approximate measure of the time available for the air to remain inside the treatment chamber before it exits. For a simplified chamber model, the residence time may be expressed by the following equation:

$$t_r = \frac{V_c}{Q}$$

Here$t_r$is the residence time, V_c is the effective volume of the chamber and Q is the volumetric flow rate.

In general, we can say that, increasing the airflow rate allows more air to pass through the chamber in a given period, but it also reduces the time available for interaction between the air and the carbon surfaces. Conversely, a lower flow rate increases the residence time but reduces the volume of air treated per unit time. Therefore, the airflow rate must be considered together with the chamber volume when evaluating the operating conditions of the CTTC [12-15].

The increased flow rate allows more gas to pass through the system in a certain period. However, it will reduce the contact time between the air and the carbon surfaces. Hence, a small flow rate is needed in order to allow the gas to stay inside the chamber for a longer time, but it will reduce the amount of gas that can be treated. Considering the trade-off between airflow rate and residence time, pressure loss and required power should also be taken into account.

The available surface of the carbon material is essential. Increasing it might allow more gas molecules to find and occupy the available adsorption sites on its surface. Thus, the size and arrangement of the carbon rods, and their placement in the chamber might impact the performance of the system.

Design of the Carbon Trapping Tower Chamber

System Overview

The CTTC consists of multiple functional parts that together define a specific path for the incoming air. Ambient air flows in through the intake and is drawn into the chamber by a suction fan, goes into the region that contains the carbon rods and electrical assembly, and ascends through the vertical section and leaves through the outlet. The collaboration of mechanical air transport and the treatment region allows for the study of the interaction of the moving air with the carbon surfaces.

Mechanical Structure

Final version of the project was selected as a vertical tower type to keeping the device somewhat less compact but maintain a specific airflow trajectory. The prototype was designed considering the practical aspects of the device’s creation. The local materials

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were used wherever it was possible to assure that the device can be fabricated without the use of exotic or expensive materials. The design also considers the maintenance and service and all the elements and parts are made accessible to the inspections, cleaning, adjustments, or replacements as necessary. The design can also be expanded or modified in the future to allow greater treatment areas or sections for treatment addition. However, it would require further analyses as additional length of the chamber or additional carbon rods would impact the pressure, airflow, and thus the fan performance, as well as voltage requirements of the device.

Airflow Mechanism

The suction fan is installed at the inlet of the system. Once activated, it creates a pressure difference that draws in the surrounding air into the treatment chamber. The incoming air then passes through the internal treatment area before heading towards the outlet.

Forced convection provides more control over the movement of air than natural airflow. It is useful to use in situations where the external wind conditions are weak or unstable as the fan can maintain a continuous flow of air through the chamber.

The presence of a specific inlet and outlet also provide a suitable opportunity for future measurements. With appropriate instruments, the airflow rate and CO_2 concentration can be determined at selected locations before and after the treatment region.

Electro-Assisted Trapping Region

The treatment region consists of the carbon rods, and the electrical connections required to set up the applied electric field. The rods are placed in a way that the air can pass through the spaces among them.

Electrical field here is considered as an experimental variable and is not an inherent characteristic of a given capture process. The electric environment could impact the polarized species, the charged particles or the interactions occurring at the carbon surface however its contribution to such a phenomenon and its relevance should be experimentally addressed. The prototype is therefore a tool to probe electro assisted gas/surface interaction. It is not presented as an electrochemical system for CO_2 conversion in other chemical species.

Operational Concept

The operating process is simple. Ambient air, first, enters through the intake and is drawn into the chamber by the suction fan. The airflow then passes through the spaces between the carbon rods within the region where the electric field is applied. After going through this treatment region, the air ascends and is discharged through the outlet.

In order to determine whether the chamber produces any measurable change in CO_2 concentration, the air entering and leaving the treatment region has to be analyzed. By comparing the two concentrations, a simple estimate of the system's performance can be made. The percentage change in CO_2 concentration can be calculated by the following expression:

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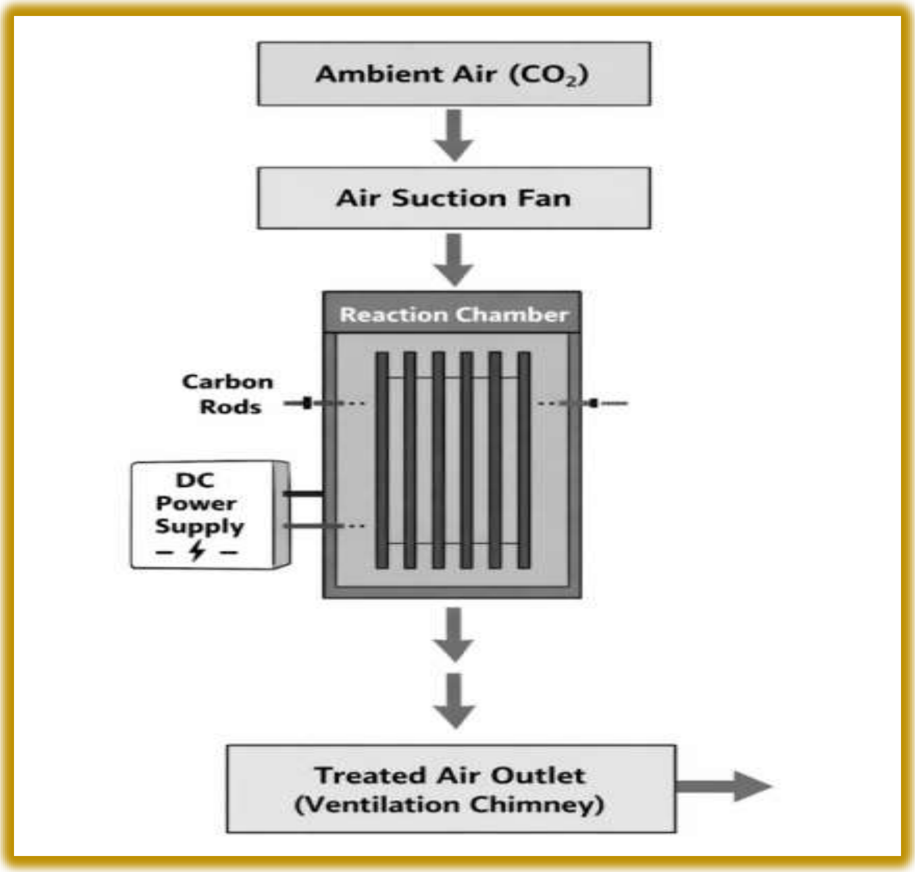
$$\eta = \left(\frac{C_{in} - C_{out}}{C_{in}}\right) \times 100\%$$

Here C_{in} stands for the CO_2 concentration at the chamber inlet and C_{out} that of the concentration measured at the outlet.
In the present study, this expression is presented as a measure for evaluating the system in future experiments. No removal efficiency is reported here as CO_2 concentrations were not measured at the inlet and outlet during preliminary testing.

Block Diagram of the Carbon Trapping Tower Chamber for CO_2 Mitigation
The block diagram of the Carbon Trapping Tower Chamber (CTTC) indicates the basic route followed by ambient air as it passes through the proposed system. Air that comprises atmospheric CO_2 enters into the ambient-air inlet and is drawn into the chamber by a suction fan. The fan maintains a continuous airflow and directs the incoming air towards the internal treatment region. After passing through this region, the air ascends through the chamber and leaves through the treated-air outlet or ventilation chimney.



Inside the treatment chamber there are several carbon rods placed in parallel with the incoming air stream. This can be seen in the figure representing the final design of the chamber, and it should be noted that it is different to the simpler configuration used in the first prototype. The carbon rods are connected to a DC power supply in order to

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provide the electrical conditions needed to impose the desired electric field in the treatment zone. The air then flows through the spaces in between the rods, making contact with the carbon surfaces and getting subjected to the imposed field.

The treatment region is the main part of the system in which the interaction between the flowing air, carbon surfaces, and electric field is investigated. The electric field is included as an experimental variable to examine whether it can influence the interaction of CO_2 with the carbon surfaces. At this stage, however, the specific contribution of the electric field to CO_2 capture has not been established experimentally and therefore is not assumed in the present study.

After passing through the carbon-rod region, the air continues upward through the vertical chamber and is discharged through the outlet. In this way, the CTTC combines controlled airflow with a carbon-based treatment region and provides a simple arrangement for studying the possible electro-assisted interaction of ambient CO_2 with carbon surfaces.

The block diagram describes the proposed operating arrangement of the system rather than a measured CO_2 removal process. To determine whether the chamber actually reduces CO_2 concentration, the CO_2 levels at the inlet and outlet would need to be measured under controlled experimental conditions. Such measurements would also allow the influence of the electric field and other operating parameters to be evaluated quantitatively.

Experimental Setup

Prototype Fabrication

A laboratory model of the proposed CTTC was assembled using available materials. A transparent polymer casing took the shape of a pressure chamber which served as a transparent casing providing the required isolation with the possibility to see inside by looking at the transparent walls. Carbon rods were placed inside the chamber in a specific manner. The necessary parts were provided with electric insulation in order to avoid unwanted contact and to ensure safety.

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The prototype was designed so that it allows to perform inspection and maintenance easily. Inspection of the fan, carbon rods, electrical parts and the chamber itself was possible at any time. This stage of the research aimed at designing an assembling of a working laboratory prototype and not a CO_2 capture unit on a large scale.

Electrical Configuration

A DC power supply was used to obtain the desired level of electric field applied to the carbon-rod assembly. Nevertheless, the connections were made in such a way as to ensure stable operations.

The electrical properties of the system were held to limit hazardous surges and overheating during the experiments. The electric-field distribution was not depicted in this study, would be interesting to see such a plot in the referenced paper or see changes in the plot due to different electrode configurations or voltage levels.

Operating Procedure

The prototype was tested several times in the indoor laboratory in order to check some of the general properties of the machine. It was confirmed that the airflow is enough to guarantee that the fan can provide a continuous airflow with minor differences. Mechanical vibrations of the fan and other parts were taken into account in order to be sure that there are no serious problems. The electricity characteristics were analyzed to be certain that the input voltage can be stable and not vary.

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Thermal characteristics were studied in order to define if the temperature can increase significantly during a continuous work and lead to heating issues. The general idea of this reliability test was to guarantee that the prototype can work continuously without any malfunctions. As there were no calibrated CO_2 sensors at the inlet and outlet, the main idea of the tests was to study general mechanical and electrical properties and not the ability to decrease the level of carbon dioxide.

Results and Observations

The lab prototype was running constantly at the time of the observations without any mechanical issues. The suction fan provided a constant airflow in the vertical chamber while not failing itself at the test operation. Mechanical vibrations common for the functioning prototype were not apparent. Airflow path was not obstructed. Electric components of the prototype, namely the carbon rods and the DC power-supply circuit, were functioning at the tests. In general, we can say that the mechanical design was sufficient to provide a continuous airflow while ensuring proper operation of the electrical equipment. Nevertheless, the results need to be put in the context of limitations of the current test environment. Since no quantitative analysis of CO2 concentration was made before and after the treatment chamber, the current study cannot report any CO2 capture rate, removal efficiency, adsorption capacity or percentage of atmospheric CO2 reduction. Current findings only describe preliminary operational characteristics of the apparatus. They cannot confirm whether the prototype can remove CO2 from ambient air at a practically significant rate.

Discussion

The CTTC seems like a relatively simple system for examining the coupled influence of forced airflow, carbon surfaces, and applied electric field. This is a good thing, as while the prototype is still being worked on, alterations to the system are much easier made before a specific fabrication process begins. The vertical orientation of the chamber dictates the course of the flow, but alternative designs could easily be imagined in which the cross-section of the chamber, the number, size, or arrangement of the carbon elements are varied to optimize surface interaction. Another possibility for alteration would be the distance between the rods, for observing the effects of spacing on airflow patterns. The most pressing matters to be examined would be whether an applied electric field would have a demonstrable effect on the amount of CO2 absorbed by the carbon surfaces. The observations reported here are insufficient to address this issue as CO_2 concentrations were not measured at the inlet and outlet of the setup.

A more comprehensive investigation would require measurements of the inlet and outlet CO_2 concentration, airflow rate, residence time, temperature, relative humidity, applied voltage, electric-field configuration, carbon surface area, and pressure drop. Together, such measurements would enable the operational characteristics of the apparatus to be connected to its actual capture performance.

A calibrated CO_2 analyzer or NDIR sensor should be installed at both the inlet and outlet in future experiments, and tests should be performed with the electric field on and off while maintaining the other operating conditions as similar as possible. Such a comparison would help to disentangle any contribution from the imposed electrical

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environment from the ordinary gas-surface adsorption processes.
A useful experimental design would involve the comparison of at least three operating conditions: airflow through the carbon material without an imposed electric field, airflow through the carbon material with an applied electric field, and an appropriate control condition. If one could take several reads, this would make the probability that an observed change would be significantly different from an expected value from a normal fluctuation in the experiment more likely. To study the properties of the carbon material used would also be of interest. Typical carbon rods have a relatively small surface area available for adsorption, and materials such as activated carbon or metal-organic frameworks should be considered for later works, but their applicability to the proposed setup would need to be tested experimentally. The issue of energy consumption is also of considerable importance.
A practical CO_2 capture system must be evaluated not only in terms of the amount of CO_2 removed, but also in terms of the energy required to achieve that removal. The electrical power consumed by the fan and the field-generation system should therefore be measured in future experiments alongside the corresponding CO_2 removal data.

Economic Significance and Potential Application in Pakistan

The use of locally available materials gives the CTTC concept a potentially useful starting point for low-cost experimental development in Pakistan. A relatively simple construction can make prototype fabrication and modification more accessible in university laboratories and research environments.
The broader economic significance of the system, however, cannot yet be established from the present experiment. No measured CO_2 removal capacity, operating cost, carbon-storage quantity, or commercial operating lifetime has been determined.
The possible conversion of captured CO_2 into useful carbon-based products must also be considered separately. Adsorption of CO_2 does not, by itself, produce solid carbon. The production of carbon-containing materials from captured CO_2 would require an additional chemical or electrochemical conversion process.
The economic significance of the present work should therefore be viewed primarily as a research and development opportunity. Before any large-scale economic benefit can be claimed, a future version of the system would need to demonstrate measurable CO_2 removal, acceptable energy consumption, manageable maintenance requirements, suitable material lifetime, and an economically viable operating cost.

Limitations

Main limitation of the present study remains the lack of quantitative measurements of the CO_2 concentration. The prototype was evaluated on airflow observations, mechanical behavior, electrical stability and thermal performance. Thus, the actual capacity of the chamber for removing CO_2 from the atmosphere is still unknown. The electric-field structure inside the chamber was not experimentally characterized. Neither was the surface property of the carbon rods determined nor any adsorption isotherm or capacity established.
Another limitation is the lab-scale of the prototype. Its observed performance does not directly translate into an outdoor machine or a complete atmospheric treatment system. Variations in ambient temperature, humidity, dust load, external airflow and

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carbon surface contamination could affect the performance of a large-scale equivalent.
These limitations also point to the main requirements for the next stage of the work. They do not detract from the value of the prototype as an experimental platform for controlled investigation.

Future Work

The further experimental work would be focused on obtaining quantitative data about the change in CO_2 concentration at the inlet and outlet of the chamber. The reading could be taken using a sensor or NDIR analyzer that would provide information about the concentration changes inside the treated flow.
The quantitative analysis would require the measurement of the volumetric airflow rate instead of its theoretical value. The amount of CO_2 removed from the air per unit of time could be calculated using the inlet and outlet concentrations and airflow rates.
Effect of electric field on the described process should also be separately investigated. It would be achieved by conducting the experiments at different voltages with a constant airflow and other conditions. It is necessary to perform the measurements with the ionizer turned off to use these results as a reference.
The application of different materials and geometry is also worth considering. My primary task to make the surface of the adsorbent as large as possible, to optimize the distance between the rods, and to ensure the uniform airflow with minimal pressure loss. The temperature and air humidity should be determined during the experiments since they considerably impact the adsorption process and the performance of the instrument. Finally, to scale the experiment, the most critical factors in obtaining a maximal amount of CO_2 per unit of time with a minimal expenditure of energy and resources should be identified. Thus, the efficiency of the setup and its feasibility for practical implementation would be evaluated.

Conclusion

This study described the design, fabrication, and preliminary operation of a laboratory-scale Carbon Trapping Tower Chamber. The prototype was capable of continuous forced airflow through the vertical chamber and demonstrated satisfactory mechanical and electrical performance during the tests. The suction fan was operating satisfactorily, the chamber was stable, and there was no appreciable overheating observed during tests.
Measurements of CO_2 concentrations at the inlet and outlet of the chamber were not obtained, and thus it is not possible to report a measured CO_2 removal efficiency or assess whether the applied electric field would increase CO_2 capture.
The main finding of this study is the growth of a simplified laboratory prototype that could be used as a basis for controlled future experiments. The following research should be focused on obtaining calibrated CO_2 measurements, airflow characterization, controlled comparison of electric-field conditions, characterization of the carbon material, and measurement of energy consumption. These measurements are needed to verify if the CTTC concept could be taken from a preliminary laboratory apparatus to a technically viable carbon-capture system.

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