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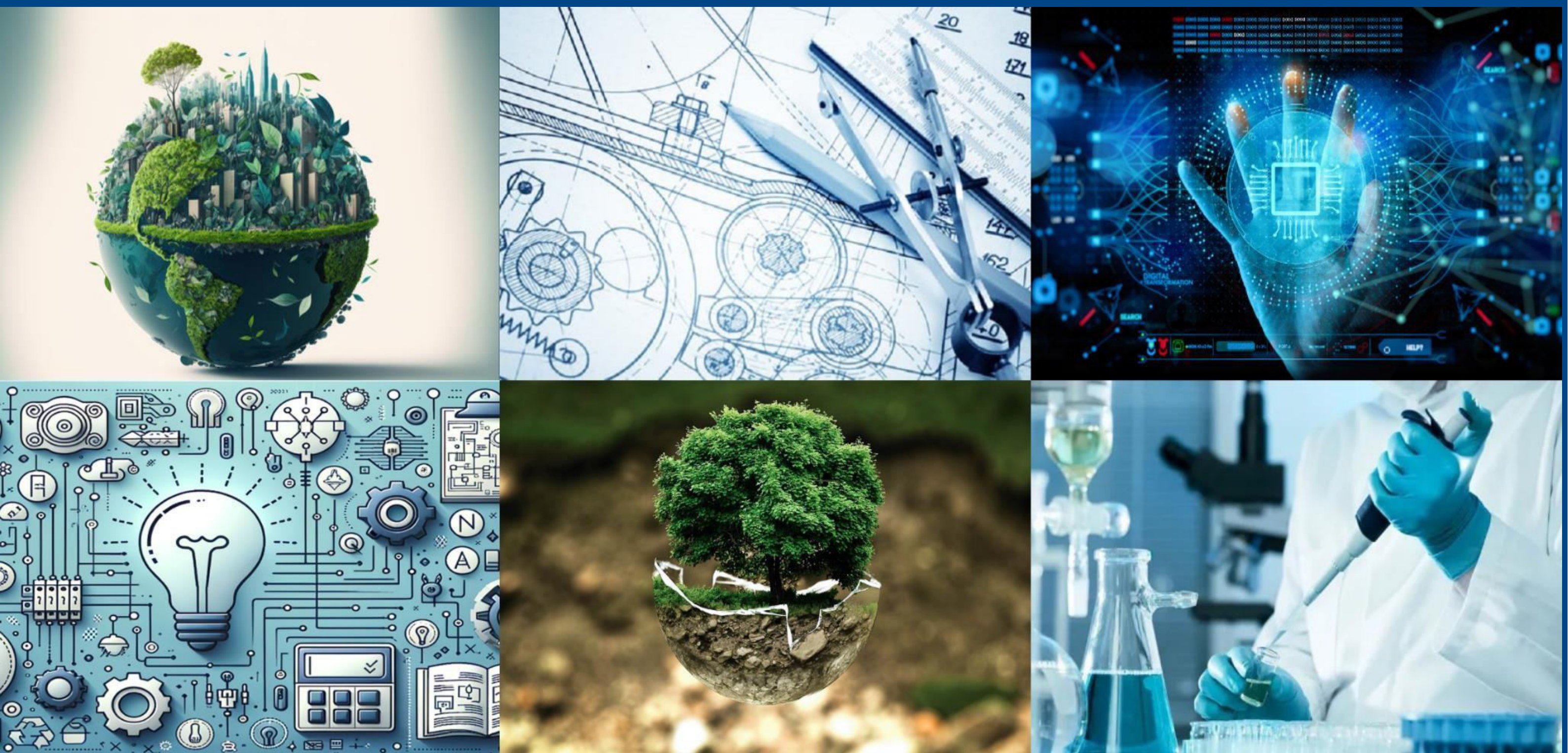

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Development of a Portable CO_2 Conversion System for Industrial Flue Gas and Solid Carbon Recovery

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ABSTRACT: This paper presents the development of a compact and autonomous system designed to capture carbon dioxide (CO_2) from industrial flue gas and convert it into solid carbon and oxygen through an electrochemical process. The proposed system integrates three functional units: a CO_2 capture chamber, an electrochemical conversion module, and a solid carbon storage tank. The flue gases pass through the capture chamber, where CO_2 is absorbed by specialized sorbent materials and then directed to the conversion module. Inside the module, CO_2 undergoes electrochemical reduction, forming fine solid carbon particles while releasing oxygen into the atmosphere. The resulting solid carbon is safely collected in a detachable tank for later reuse in pigment and composite manufacturing. The system operates autonomously with minimal human intervention, ensuring continuous emission treatment for industrial setups. With its compact structure, low maintenance needs, and ability to convert harmful emissions into reusable products, the system offers a sustainable and efficient solution for reducing industrial CO_2 emissions and promoting eco-friendly manufacturing practices.

I. INTRODUCTION

Industrial sectors such as power generation, cement manufacturing, steel production, and chemical processing are among the largest sources of carbon dioxide emissions. Most industrial chimneys continuously discharge flue gases containing high levels of carbon dioxide, which directly contribute to global warming and air pollution. Although several carbon capture and storage methods have been developed, most of them require large infrastructure, high energy consumption, and expensive maintenance, making them unsuitable for small and medium-scale industries.

Conventional carbon capture systems mainly focus on capturing and storing carbon dioxide in liquid or compressed form, which increases operational complexity and long-term safety risks. These systems also fail to utilize the captured carbon effectively, resulting in waste management challenges. Therefore, there is a strong need for a compact, efficient, and self-operating system that can directly capture carbon dioxide from industrial exhaust and convert it into a reusable and stable form.

The proposed study introduces a portable carbon dioxide conversion system for industrial flue gas and solid carbon recovery. The system is designed to capture carbon dioxide from chimney emissions and convert it into solid carbon and oxygen through an electrochemical process. The produced carbon is stored safely and can be reused in various

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industrial applications, while the released oxygen improves local air quality. The modular and lightweight design allows easy installation on existing chimneys without requiring major structural changes.

This system provides an environmentally sustainable approach to reducing industrial emissions by converting harmful carbon dioxide into a valuable resource. It can help industries minimize their carbon footprint and move toward greener manufacturing operations.

II. LITERATURE REVIEW

The problem of industrial carbon dioxide emissions has been widely studied in recent years, leading to the development of various carbon capture and utilization technologies. Conventional carbon capture and storage methods such as absorption using amine-based solvents, adsorption on solid materials, and membrane separation have shown effectiveness but often require large infrastructure and high operational costs. These systems are mainly suitable for large industries with continuous operations and available space for storage and processing units.

Zhang and Li (2023) discussed the use of electrochemical methods for converting carbon dioxide into solid carbon and fuels. Their research indicated that electrochemical reduction could serve as a promising approach for transforming waste carbon dioxide into useful materials. Similarly, Kumar and Mehta (2022) emphasized the potential of small-scale carbon capture systems that could be installed near the emission sources to make the process more efficient and cost-effective.

Patel (2023) studied metal-organic frameworks as sorbent materials for efficient carbon dioxide absorption at industrial temperatures. These materials have high surface areas and strong selectivity, making them suitable for flue gas treatment. In another study, Das and Gupta (2022) focused on recycling captured carbon for industrial use, highlighting the growing interest in transforming waste emissions into valuable by-products instead of storing them underground.

Despite these advancements, most existing technologies are either large, non-portable, or dependent on centralized infrastructure. There is limited research on compact and autonomous systems capable of capturing and converting carbon dioxide directly at the chimney outlet. Therefore, the proposed system aims to fill this gap by combining portable design, electrochemical conversion, and solid carbon recovery to achieve sustainable emission control.

III. RESEARCH GAP

Most existing carbon capture technologies are designed for large-scale operations that require heavy infrastructure, large storage areas, and continuous monitoring systems. Such setups are impractical for small and medium-sized industries that operate with limited space and budget. Conventional systems capture carbon dioxide and store it in liquid or gaseous form, which increases the risk of leakage and long-term maintenance issues.

In addition, very few studies have focused on compact and autonomous systems capable of functioning directly on industrial chimneys. Current approaches mainly emphasize carbon storage rather than conversion into a stable and reusable form. The lack of small-scale, continuous, and self-operating systems limits the adoption of carbon capture technologies in local industries.

To overcome these limitations, the present study focuses on developing a portable and self-sustaining carbon dioxide conversion system that captures carbon dioxide from flue gas and converts it into solid carbon and oxygen. This research bridges the existing gap between large-scale capture systems and small, efficient emission control technologies suitable for decentralized industrial applications.

IV. PROBLEM STATEMENT

The increasing concentration of carbon dioxide in the atmosphere due to industrial emissions has become one of the most serious environmental concerns of the present era. Industrial chimneys continuously release flue gases containing large amounts of carbon dioxide, which directly contribute to climate change, air pollution, and global warming. Despite the growing awareness about the need for emission control, most industries still lack effective systems to capture or reduce the amount of carbon dioxide being emitted.

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Existing carbon capture and storage technologies are mainly developed for large-scale industries or centralized plants. These systems involve complex setups, high maintenance costs, and heavy equipment that require significant space and technical supervision. As a result, they cannot be practically implemented in small and medium-scale industries, which together form a large portion of total industrial emissions. Moreover, most available systems only store the captured carbon dioxide in gaseous or liquid form, which poses potential risks of leakage and long-term environmental hazards. They do not provide any mechanism for converting the captured gas into a stable and reusable form.

Therefore, there is a need for an alternative technology that is compact, affordable, and capable of functioning autonomously without continuous human supervision. Such a system should be able to capture carbon dioxide directly from industrial flue gas, convert it into a stable solid material, and store it safely for further reuse.

The proposed study focuses on developing a portable and autonomous carbon dioxide conversion system that addresses these issues. The system captures carbon dioxide from chimney exhausts and converts it into solid carbon and oxygen through an electrochemical process. The produced solid carbon can be reused in manufacturing industries, while the released oxygen improves the surrounding air quality. This approach offers a practical and sustainable solution for emission reduction in small and medium industrial setups.

V. BBJECTIVES

The main objective of the project is:

- To design a compact and efficient system capable of capturing carbon dioxide directly from industrial flue gas.
- To develop an electrochemical conversion process that transforms captured carbon dioxide into solid carbon and oxygen.
- To achieve autonomous and continuous operation with minimal human supervision and maintenance.
- To enable safe collection and reuse of the produced solid carbon for various industrial applications, promoting sustainable manufacturing practices.

VI. DESIGN AND METHODOLOGY

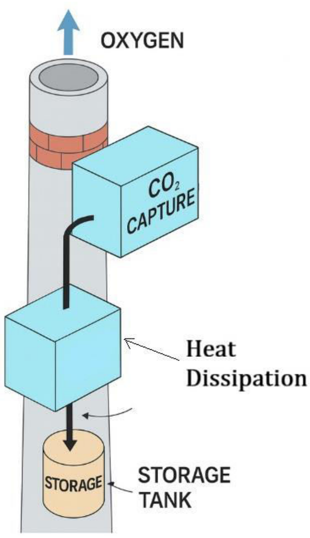

Fig: The System Structure

The proposed system is designed to capture carbon dioxide directly from industrial flue gas and convert it into solid carbon and oxygen using an electrochemical process. The overall setup consists of three major components: a carbon dioxide capture chamber, an electrochemical conversion module, and a solid carbon storage unit. The entire system is compact, modular, and capable of continuous operation with minimal human control.

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Carbon Dioxide Capture Chamber: The flue gas coming out of the industrial chimney first passes through the capture chamber, where it comes into contact with advanced sorbent materials such as metal-organic frameworks or amine-coated filters. These materials selectively absorb carbon dioxide while allowing other gases to pass through. The design of the chamber ensures maximum surface contact between the exhaust gas and the absorbent material to enhance capture efficiency. The temperature and flow rate of the gas are monitored using sensors to maintain optimal conditions for carbon dioxide absorption.

Electrochemical Conversion Module: The absorbed carbon dioxide is then transferred into the electrochemical conversion module. Inside this unit, the captured carbon dioxide undergoes an electrochemical reduction process using a catalyst-coated electrode system. When a suitable electrical potential is applied, the carbon dioxide molecules are split into solid carbon and oxygen according to the reaction:
$CO_2 \rightarrow C \text{ (solid)} + O_2$

The solid carbon produced is in the form of fine, powder-like particles. The oxygen gas generated during this reaction is released safely into the atmosphere, improving local air quality.

Solid Carbon Storage Unit: The solid carbon particles formed in the electrochemical cell are collected in a sealed storage tank placed at the base of the system. The tank is detachable and designed for easy handling, allowing the collected carbon to be removed and reused in various applications such as pigment, rubber, or composite material production. The storage unit is insulated to maintain safety and stability under different operating conditions.

Autonomous Operation and Control: The entire system operates automatically through a control unit that monitors temperature, gas flow rate, pressure, and carbon dioxide concentration. The control system adjusts the flow and conversion rates based on the exhaust gas composition, ensuring continuous and efficient performance. The setup requires minimal maintenance and can function continuously for long operational hours.

This design provides a practical and sustainable approach for reducing industrial carbon emissions while generating a reusable by-product. It can be easily integrated into existing industrial setups without significant structural changes.

VII. WORKING PRINCIPLE

The system works by capturing carbon dioxide directly from the industrial flue gas and converting it into solid carbon and oxygen through an electrochemical reaction. The process is continuous and fully automated, ensuring efficient emission treatment with minimal human intervention.

Step 1 – Gas Collection: The flue gas exiting the industrial chimney is directed into the carbon dioxide capture chamber. Inside the chamber, the gas passes through filters coated with absorbent materials such as amine-based compounds or metal-organic frameworks. These materials selectively trap carbon dioxide molecules while allowing other gases to pass through.

Step 2 – Carbon Dioxide Absorption: As the exhaust gas flows through the chamber, the carbon dioxide is absorbed and temporarily stored within the absorbent layer. Temperature and flow sensors maintain optimal conditions to ensure maximum capture efficiency. Once the absorbent material reaches saturation, the captured carbon dioxide is released and sent to the electrochemical module for processing.

Step 3 – Electrochemical Conversion: In the electrochemical conversion module, the absorbed carbon dioxide is subjected to an electrical potential across catalyst-coated electrodes. This triggers a reduction reaction where carbon dioxide is split into solid carbon and oxygen. The overall reaction is:
$CO_2 \rightarrow C \text{ (solid)} + O_2$

The solid carbon is formed as fine black powder, while the oxygen gas is vented out safely into the atmosphere.

Step 4 – Carbon Collection and Storage: The solid carbon particles produced during the reaction are collected and transferred into a sealed storage tank placed at the base of the setup. The collected carbon is non-toxic and stable, allowing for safe handling and reuse. The tank can be periodically detached and emptied for recycling or industrial use.

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Step 5 – Autonomous Control: Throughout the process, sensors monitor gas composition, pressure, and temperature. A microcontroller-based control system regulates the operation automatically, ensuring continuous performance without manual adjustment.

This working process allows the system to efficiently capture and convert carbon dioxide from industrial emissions into valuable solid carbon, significantly reducing the environmental impact of industrial operations.

ADVANTAGES

The main advantages of the project will be:

- Reduces carbon dioxide emissions directly from industrial chimneys, minimizing environmental pollution.
- Converts harmful carbon dioxide into solid carbon, which can be reused in pigment, rubber, and composite industries.
- Operates continuously and autonomously with minimal human supervision.
- Compact and modular design allows easy installation on existing industrial chimneys without major modifications.
- Improves local air quality by releasing oxygen as a by-product of the electrochemical process.
- Low maintenance requirements and simple operation make it suitable for small and medium-scale industries.
- Supports sustainable industrial growth by turning waste emissions into valuable resources.

APPLICATIONS

The applications of this project are:

- Can be used in thermal power plants, cement factories, steel plants, and chemical industries to reduce flue gas emissions.
- Suitable for small and medium-scale industries that cannot afford large carbon capture systems.
- Useful in research and development setups for studying carbon conversion and utilization processes.
- Can be applied in continuous emission monitoring systems for cleaner industrial operations.
- Provides a base technology for future large-scale carbon recycling and industrial sustainability projects.

FUTURE SCOPE

The Future Scope of this project will be:

- The system can be further optimized by developing more efficient and durable absorbent materials to improve carbon dioxide capture efficiency.
- Integration of waste heat recovery from industrial chimneys can reduce the overall energy consumption of the system.
- Advanced catalysts and electrode materials can be designed to enhance the electrochemical conversion rate.
- Incorporation of smart sensors and artificial intelligence can enable automatic control, performance tracking, and predictive maintenance.
- Large-scale testing and optimization across different industrial sectors can help in standardizing this technology for commercial use.
- The collected solid carbon can be explored for use in advanced material manufacturing, energy storage, and filtration applications.

VIII. CONCLUSION

The development of a portable carbon dioxide conversion system for industrial flue gas and solid carbon recovery provides a practical and sustainable solution for reducing industrial emissions. The system captures carbon dioxide directly from chimney exhaust gases and converts it into solid carbon and oxygen through an electrochemical process. The compact and modular design allows easy installation on existing chimneys without major structural changes, making it suitable for both large and small industries.

The system operates autonomously with minimal maintenance and transforms harmful emissions into a reusable carbon product, contributing to environmental protection and resource utilization. Although there are challenges related to energy consumption and material optimization, the overall concept offers a promising step toward cleaner industrial production and long-term carbon management. With further improvements in material efficiency and system

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integration, this technology can significantly contribute to global emission reduction efforts and sustainable industrial development.

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