

Carbon Capture and Absorption Tower

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Abstract –

The growing concentration of carbon dioxide (CO₂) in the atmosphere, primarily from fossil fuel combustion, industrial activities, and deforestation, has become one of the main drivers of global climate change. Carbon Capture and Storage (CCS) is a promising technology aimed at reducing CO₂ emissions by capturing carbon directly from major sources before it reaches the atmosphere and securely storing it underground. This project investigates the fundamental principles, techniques, and effectiveness of CCS as a climate mitigation strategy. It explores the three main stages of the process-capture, transport, and storage-and analyzes various capture methods such as pre-combustion, post-combustion, and oxy-fuel combustion.

The study also examines potential storage options, including depleted oil and gas reservoirs, deep saline aquifers, and unmineable coal seams, focusing on their capacity, safety, and long-term stability. Attention is given to the technological, economic, and environmental challenges associated with large-scale CCS deployment, such as high energy requirements, potential leakage risks, and the need for effective monitoring systems.

Additionally, the project highlights ongoing research and innovations aimed at improving the efficiency and cost-effectiveness of CCS technologies, including the integration of renewable energy sources and the development of carbon utilization pathways. The findings emphasize that while CCS alone cannot solve the climate crisis, it represents a crucial component of a comprehensive global strategy to achieve net-zero emissions and ensure a sustainable energy future.

Keywords:

Carbon, adsorption towers, zeolites, MOFs, amines, activated carbon, physisorption,

1. INTRODUCTION

The rapid increase in atmospheric carbon dioxide (CO₂) concentrations due to industrialization, fossil fuel combustion, deforestation, and other human activities has emerged as one of the most pressing environmental challenges of the 21st century. Elevated CO₂ levels intensify the greenhouse effect, leading to global warming, rising sea levels, ocean acidification, and extreme weather events, all of which threaten ecosystems, human health, and socio-economic stability. Mitigating these impacts requires not only the transition to renewable energy sources but also the implementation of technologies capable of capturing and managing carbon emissions.

Carbon Capture and Storage (CCS) is a key technological solution that addresses this need.

CCS involves three critical stages: capturing CO₂ from major emission sources such as power plants, cement factories, and refineries; transporting the captured CO₂ safely via pipelines or ships; and storing it securely in suitable geological formations deep underground. Common storage options include depleted oil and gas reservoirs, deep saline aquifers, and unmineable coal seams, each offering different capacities, risks, and monitoring requirements.

The importance of CCS lies not only in its potential to reduce emissions from existing infrastructure but also in its role as a transitional strategy toward a low-carbon economy. While renewable energy adoption is crucial, immediate global energy demands still rely heavily on fossil fuels, making CCS a practical solution to bridge the gap. Moreover, innovations in CCS technology, such as chemical absorption, membrane separation, and carbon utilization for industrial products, are continually improving efficiency and reducing costs, enhancing its feasibility for large-scale deployment.

This project aims to provide a comprehensive overview of CCS, exploring its working principles, technological advancements, environmental benefits, economic considerations, challenges, and future prospects. By analyzing these aspects, the study highlights CCS as a vital component of global strategies aimed at achieving net-zero emissions and mitigating the adverse effects of climate change.

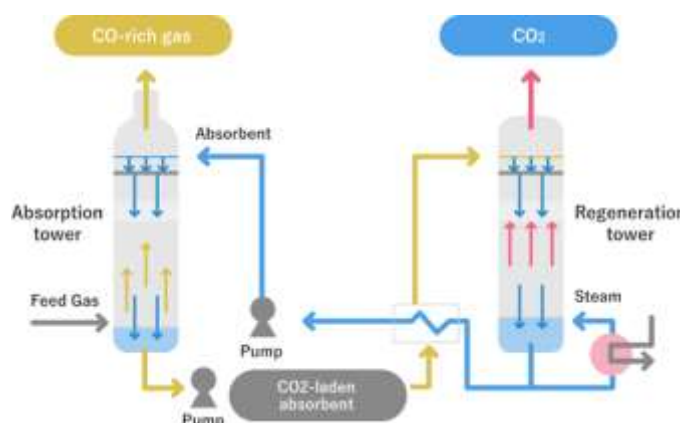


Fig1.1- Carbon Capture And Absorption Tower

A carbon capture absorption tower is a tall column in carbon capture technology where CO₂ from industrial flue gas chemically reacts with a liquid solvent (like an amine solution) to remove it, with gas flowing up and solvent flowing down counter-current, resulting in purified gas exiting the top and a CO₂-rich solvent exiting the bottom for regeneration in a separate stripper tower, a process crucial for reducing greenhouse gas emissions.

1.1 Key Characteristics:

Carbon capture absorption towers are characterized by their ability to facilitate a high-efficiency **gas-liquid mass transfer** process, typically in a **counter-current flow** configuration, utilizing specific **chemical solvents** (like amines) to selectively remove CO₂ from industrial flue gas.

Key characteristics of these absorption towers include:

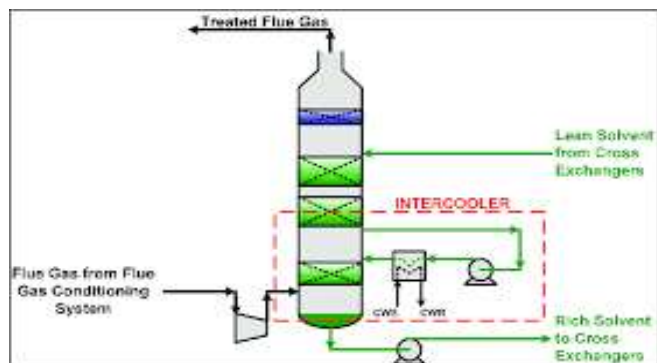


Fig1.2 Operational Design and Flow

- **Counter-current flow:** Flue gas enters the bottom and flows upward, while the liquid absorbent (e.g., amine solution) is pumped to the top and flows downward, maximizing contact efficiency.
- **Mass Transfer:** The design is centered on facilitating efficient mass transfer from the gas phase to the liquid phase, where the CO₂ is absorbed through a chemical reaction.
- **Internal Components:** Towers utilize various internals like packing materials (e.g., structured packing, random packing) or trays (e.g., bubble-cap, valve trays) to provide a large surface area for the gas and liquid to interact effectively.
- **Operating Pressure:** They typically operate at or near atmospheric pressure, particularly in post-combustion applications, which makes them suitable for retrofitting existing power plants.

Performance and Efficiency

- **High Capture Efficiency:** The technology is mature and highly effective, with the ability to achieve a CO₂ recovery rate of 90-95% or more.
- **Solvent Regeneration:** The process is part of a closed-loop system where the "rich" solvent (containing CO₂) is sent to a regeneration (stripping) tower and heated to release a high-purity CO₂ stream (typically >99.9%), allowing the "lean" solvent to be recycled back to the absorber.
- **Selectivity:** The chosen solvent is highly selective for CO₂, allowing other gases (like nitrogen) to pass through.

Physical and Chemical Properties

- **Large Footprint:** Due to the large volume of flue gas processed (especially from power plants), the absorption towers can be quite large.
- **Materials of Construction:** Materials must be corrosion-resistant (e.g., stainless steel, alloy steel) due to the corrosive nature of the amine solutions and the acidic gases they capture.

- **Temperature Profile:** Absorption occurs at a relatively low temperature (around 30–50 °C), while desorption requires high temperatures (around 110–130 °C) in the regeneration section.

- **Energy Consumption:** A key challenge is the signic regeneration) which impacts overall operating costs and the efficiency of the power plant.

1.2 Principle

The fundamental principle of Carbon Capture and Storage (CCS) is based on the separation, transport, and long-term isolation of carbon dioxide (CO₂) from the atmosphere or industrial emissions to reduce its contribution to climate change. The process is designed to prevent CO₂ from entering the atmosphere, thereby mitigating the greenhouse effect and global warming. CCS operates on three interconnected stages:

1. Carbon Capture

The first step involves separating CO₂ from the emissions produced by power plants, industrial facilities, or other major sources. The principle behind carbon capture relies on the physical or chemical separation of CO₂ from other gases, primarily using one of the following techniques

Post-combustion capture: CO₂ is removed from flue gases after fuel combustion using solvents, membranes, or adsorption techniques.

Pre-combustion capture: Fuel is partially oxidized to produce a gas mixture from which CO₂ is separated before combustion. Oxy-fuel combustion: Fuel is burned in pure oxygen rather than air, producing a flue gas that is mainly CO₂ and water, simplifying CO₂ separation.

The underlying principle is selective separation: isolating CO₂ based on its chemical or physical properties, such as solubility, affinity for a solvent, or membrane permeability..

2. Transport

Once captured, CO₂ is compressed into a dense or supercritical state to facilitate safe and efficient transport. The principle here is minimizing volume and maintaining stability to allow transport via pipelines, ships, or trucks to storage locations without leakage or hazards.

3. Storage

The final stage involves injecting CO₂ into deep geological formations, where it can remain trapped for hundreds to thousands of years. The principle of storage is based on physical and chemical containment, including

Structural trapping: CO₂ is trapped beneath impermeable rock layers. Residual trapping: CO₂ gets trapped in the pores of the rock. Solubility trapping: CO₂ dissolves into underground fluids. Mineral trapping: CO₂ reacts with minerals to form stable carbonates.

By combining these principles, CCS effectively removes CO₂ from the atmosphere or prevents its emission, contributing to climate change mitigation and offering a transitional pathway toward a low-carbon future.

1.3 Construction and Components of A carbon capture and Storage

1. Overview of Carbon Capture and Storage (CCS is a technology designed to capture carbon dioxide (CO₂) emissions

from industrial sources (like power plants or factories) and store it underground to prevent it from entering the atmosphere. It is a key tool in reducing greenhouse gas emissions. CCS typically involves three main stages:

1. Capture-Separating CO₂ from other gases.
 2. Transport-Moving captured CO₂ to storage sites.
 3. Storage Injecting CO₂ into deep geological formations.
2. Components of CCS

A. Carbon Capture

Carbon capture is the first and most energy-intensive step. There are three main approaches:

1. Post-Combustion Capture: Captures CO₂ from flue gases after fuel combustion.

Uses chemical solvents (e.g., amines) that absorb CO
Components: Flue gas absorber column: CO₂ reacts with solvent.

Regenerator: Solvent is heated to release concentrated CO₂.
Heat exchangers: Recover energy from the process.

2. Pre-Combustion Capture Fuel is converted into a mixture of hydrogen (H₂) and CO₂ before combustion. CO₂ is separated, and H₂ is used as fuel.

Components: Gasifier: Converts fuel into syngas (CO+H₂).

Shift reactor: Converts CO to CO₂ and H₂. CO₂ separation unit: Removes CO₂ from H₂

3. Oxy-Fuel Combustion Fuel burns in pure oxygen instead of air, producing mostly CO₂ and H₂O. H₂O is condensed, leaving concentrated CO₂.

Components: Air separation unit: Produces oxygen.

Oxy-fuel boiler: Burns fuel with O₂. CO₂ purification unit: Condenses water, isolates CO₂.

B. CO₂ Compression and Transport

After capture, CO₂ must be transported to storage sites.

1. Compression CO₂ is compressed to a supercritical state (dense fluid, like liquid) Equipment: Compressors, pumps, and heat exchangers.

2. Transport

Usually via pipelines (most common), ships, or trucks.

Safety components:

Pressure sensors

Flow meters

Leak detection systems.

C. CO₂ Storage

Captured CO₂ is stored in geological formations for long-term isolation. Types of storage:

1. Depleted Oil and Gas Fields

Former oil/gas reservoirs are sealed with caprock. CO₂ can also enhance oil recovery (EOR).

2. Deep Saline Aquifers

Porous rock filled with salty water. CO₂ is injected into pores, trapped by caprock and chemical reactions.

3. Basalt Formations CO₂ reacts with minerals to form stable carbonates. Storage components Injection wells Monitoring wells Sealing layers (caprock). Monitoring and verification equipment (for leaks or migration)

D. Monitoring, Verification, and Safety

Key for ensuring CO₂ remains trapped safely:

Seismic surveys: Detect CO₂ plume movement underground.

Pressure and temperature sensors: Monitor storage conditions.

Groundwater monitoring: Ensure no contamination.

Leak detection systems: Alert if CO₂ escapes.

1.4 Limitations:

1. High Cost

Capture, compression, transport, and storage are energy-intensive and expensive

The cost per ton of CO₂ captured can be very high, making CCS less economically attractive without government incentives. Retrofitting existing plants with CCS is more expensive than designing new plants with integrated capture.

2. Energy Requirement

CCS systems consume a significant portion of the plant's energy output (known as the "energy penalty") Post-combustion capture can reduce plant efficiency by 20-30% This may require burning more fuel to maintain energy output, somewhat offsetting the emission reduction benefits.

3. Risk of CO₂ Leakage

Stored CO₂ could potentially leak from underground reservoirs, contaminating groundwater or escaping to the atmosphere. Requires continuous monitoring and well maintained geological sites. Leakage could negate environmental benefits and pose safety hazards.

4. Limited Storage Capacity

Not all regions have suitable geological formations for CO₂ storage. Long-term capacity may be limited in some countries, constraining large-scale deployment.

5. Not a Complete Solution

CCS does not eliminate all emissions; it only captures CO₂.

Other greenhouse gases (like methane or nitrous oxide) are not addressed by CCS. Should be combined with renewable energy, efficiency measures, and emission reduction strategies.

6. Technological and Regulatory Challenges

Requires advanced technology for capture, compression, and storage Complex regulations are needed for transport, injection, and monitoring. Public acceptance can be an issue due to perceived safety risks.

3. CONCLUSIONS

Carbon Capture and Storage (CCS) is a critical technology for mitigating climate change and achieving global net-zero emission targets. By capturing CO₂ emissions from large industrial sources and power plants, transporting it safely, and storing it in deep geological formations, CCS prevents significant amounts of greenhouse gases from entering the atmosphere.

CCS serves as a bridge technology: it allows continued use of fossil fuels in the short term while renewable energy and low-carbon technologies are scaled up. Its applications span multiple sectors, including power generation, cement and steel production, chemical industries, hydrogen fuel production, and enhanced oil recovery. This versatility makes CCS an indispensable tool for industries that are hard to decarbonize.

Despite its advantages such as reducing emissions by up to 90%, enabling negative emissions with bioenergy, and

providing economic opportunities through carbon utilization-CCS has notable challenges. High costs, energy-intensive operations, potential leakage risks, and limited suitable storage sites mean that CCS cannot replace the need for renewable energy and sustainable practices. Instead, it is most effective as part of a comprehensive climate strategy that combines emission reductions, energy efficiency, and green technologies.

In essence: CCS is a powerful, but complementary, solution. It plays a vital role in reducing industrial carbon emissions, supporting a transition to a low-carbon economy, and helping the world move closer to sustainable development and climate resilience. Its successful implementation depends on technological innovation, supportive policies, and careful monitoring

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