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Membrane Technologies for Carbon Capture, Separation and Utilization (CCSU) – An Overview of Materials, Methods, Mechanisms, Merits and Challenges

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ABSTRACT

Membrane-based CO_2 capture, storage and utilization (CCSU) have become quite popular in the mitigation of climate change and reduce greenhouse gas emissions. In this article, a brief review of the need for capturing, storing & converting CO_2 is addressed and the various methods and technologies adopted for the same are discussed. Among them, the use of membranes is elaborated with its basic principle & mechanism. Various types of membranes used in general, their merits and demerits are deliberated. The scope for further development in this field of membranes for carbon capture are highlighted. For carbon capture, gas separation membranes selectively remove carbon dioxide (CO_2) from flue gases emitted by industrial sources such as power plants or factories. In carbon storage, membranes are employed to separate and compress the captured CO_2 for safe underground storage in geological formations, preventing its release into the atmosphere. Carbon utilization involves converting CO_2 into valuable products such as chemicals, fuels, or materials using catalytic and electrochemical membrane reactors. Membrane technologies offer a promising avenue for advancing CCSU efforts, providing energy-efficient, scalable, and versatile solutions for carbon capture, storage, and utilization.

Key words: Membrane technology, Carbon capture, Separation, Utilization, CCUS

1. Introduction

In the face of escalating global concerns over climate change and the urgent need to reduce greenhouse gas emissions, carbon capture technologies have emerged as a critical strategy to mitigate the impact of industrial processes and power generation on the environment [1]. The primary driver of climate change is the increase in greenhouse gases in the atmosphere, primarily CO_2, which results from the burning of fossil fuels (coal, oil, and natural gas). Carbon capture, storage & conversion (CCSC) technologies can capture and prevent large quantities of CO_2 from being released into the atmosphere, helping to reduce emissions and slow down global warming [2]. While efforts to transition to renewable energy sources and improve energy efficiency are crucial, it is challenging to eliminate all carbon emissions in the short term. CCSC allows us to continue using fossil fuels during the transition while capturing and storing the CO_2 emissions, making it an essential bridge technology.

Many countries rely heavily on fossil fuels for their energy needs. Carbon capture and conversion can help these nations reduce emissions from their existing fossil fuel infrastructure, allowing them to maintain energy security while working towards decarbonization. Some industrial processes, such as cement and steel production, are extremely carbon-intensive and challenging to decarbonize [3]. CCSC can play a vital role in capturing and reducing emissions from these sectors. In a globalized economy, if one country or region significantly reduces its emissions without, carbon-intensive industries may relocate to areas with lax emissions regulations, resulting in carbon leakage. Carbon capture technologies can help prevent this by capturing emissions regardless of where they occur.

There are several carbon capture and conversion technologies currently available or in development [4]. These technologies vary in their methods and applications. In post-combustion capture (PCC) technologies, Amine Scrubbing is one of the most mature carbon capture technologies [5]. It involves using liquid amine solutions to capture CO_2 from the flue gas of power plants and industrial facilities. Adsorption-based technologies use solid materials to capture CO_2. In the pre-combustion capture technologies, integrated gasification combined cycle (IGCC) is used where coal or biomass is gasified, and the CO_2 is captured before combustion, resulting in a cleaner syngas [6]. In oxy-fuel combustion, burning fossil fuels in pure oxygen is done rather than air, producing a flue gas predominantly composed of CO_2 and water vapor, which is easier to capture. Direct air capture (DAC) technology captures CO_2 directly from the atmosphere [7]. It typically involves large fans or filters that pass air through a chemical solution or sorbent material to capture

CO_2. Algae and certain microorganisms can be used to capture and convert CO_2 into biomass. This approach has potential applications in wastewater treatment and biofuel production.

Mineralization technologies involve converting CO_2 into stable carbonate minerals through a chemical reaction with alkaline materials like calcium or magnesium [8]. Various startups and research efforts are exploring ways to convert captured CO_2 into valuable products like synthetic fuels, chemicals, and building materials. In enhanced oil recovery (EOR), captured CO_2 is injected into oil reservoirs to increase oil production while storing the CO_2 underground [9]. Geological storage involves injecting captured CO_2 into geological formations deep underground, such as depleted oil and gas reservoirs or saline aquifers, where it can be stored securely. CO_2 can be chemically combined with minerals to form stable carbonates, effectively locking up the carbon in solid form. CCSC technologies focus on converting CO_2 into useful products, such as plastics, chemicals, or building materials.

Among the diverse array of carbon capture methods, membrane-based carbon capture has gained significant attention and recognition for its potential to provide a more efficient, cost-effective, and environmentally sustainable solution [10]. Carbon capture with membranes represents an innovative approach that leverages selective permeability to separate and capture carbon dioxide (CO_2) from industrial emissions and power plant flue gases. This cutting-edge technology not only offers a promising avenue for reducing carbon emissions but also holds the potential to reshape our energy landscape, making strides towards a more sustainable and climate-conscious future.

2. Various membranes used for carbon capture:

Carbon capture with membranes relies on a diverse range of membrane materials, each tailored to specific applications and conditions. These membranes are designed to selectively separate carbon dioxide (CO_2) from gas mixtures such as flue gases, natural gas, or ambient air. Here are some of the various membranes used for carbon capture:

(a) Polymeric Membranes: Hollow Fiber Membranes - These are often used in post-combustion carbon capture. They consist of thin, porous polymer fibres that allow for the selective transport of CO_2 while blocking other gases. Flat Sheet Membranes - flat sheet membranes are used in both pre-combustion and post-combustion capture. They are made from various polymers like polyimides, cellulose acetate, and polyethylene [11,12].

(b) Mixed Matrix Membranes (MMMs): These membranes combine a polymer matrix with inorganic fillers like zeolites, metal-organic frameworks (MOFs), or nanoparticles. The addition of these fillers enhances the selectivity and permeability of the membrane [13].

(c) Inorganic Membranes: Silica Membranes - silica-based membranes are known for their high thermal stability and are suitable for pre-combustion capture in integrated gasification combined cycle (IGCC) systems. Zeolite Membranes - Zeolite-based membranes have excellent selectivity for CO_2 and are used in both pre-combustion and post-combustion applications [14,15].

(d) Mixed Gas Membranes: These membranes are designed to operate under mixed gas conditions typically found in industrial processes. They offer a practical solution for capturing CO_2 from flue gases in power plants and other high-temperature environments [16].

(e) Nanostructured & Ceramic membranes: These membranes incorporate nanomaterials like carbon nanotubes or graphene to enhance CO_2 selectivity and permeability. Ceramic membranes are known for their robustness and can withstand high temperatures and corrosive environments. They are suitable for pre-combustion and some post-combustion capture processes [17,18].

(f) Ionic liquid & Hybrid membranes: These specialized membranes use ionic liquids as the transport medium, which can offer high CO_2 selectivity in various carbon capture applications. Hybrid Membranes - These membranes combine two or more materials, such as polymers with inorganic components, to achieve a balance between selectivity and permeability [19].

The choice of membrane depends on the specific requirements of the carbon capture process, including the gas mixture composition, operating conditions, and economic considerations. Researchers and engineers continue to explore and develop new membrane materials and configurations to improve the efficiency and cost-effectiveness of carbon capture technologies, contributing to the global efforts to combat climate change.

3. Principle and mechanism of carbon capture by membranes:

Carbon capture by membranes is a promising technology used to capture carbon dioxide (CO_2) emissions from various industrial processes and power plants. The principle behind this technology is to selectively separate CO_2 from flue gases or other gas streams using specialized membrane materials. The primary mechanisms involved in carbon capture by membranes include selective permeation and diffusion:

(I) Selective Permeation: Membrane materials are chosen for their ability to selectively allow the passage of CO_2 while blocking other gases, such as nitrogen (N_2) or methane (CH_4). This selectivity is based on differences in the molecular size and solubility of gases in the membrane material. For example, in a typical polymeric membrane, the polymer matrix has pores or channels that are of a size and chemical nature that preferentially allow CO_2 molecules to pass through while hindering the passage of larger N_2 or CH_4 molecules. A representative image is shown in Figure 1 (a). This selectivity can be adjusted by choosing the appropriate membrane material or by modifying the membrane's properties.

(II) Diffusion: Once the gas mixture contacts the membrane, the CO_2 molecules diffuse through the membrane material. This diffusion process occurs because CO_2 molecules have a higher affinity for the membrane material due to their size and solubility characteristics. CO_2 molecules dissolve into the membrane, move through its structure, and then desorb on the other side as a concentrated CO_2 stream. A representative image is shown in Figure 1 (b).

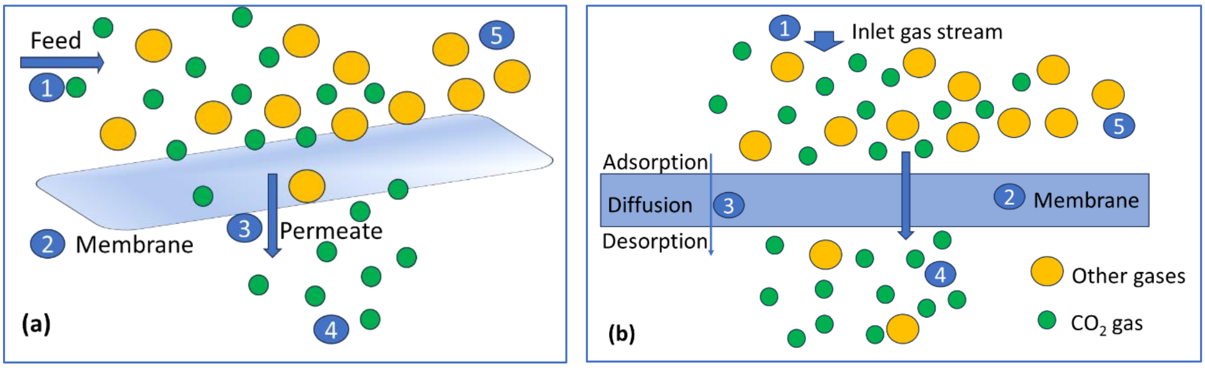

Figure 1: Mechanism of carbon capture by (a) Selective permeation (b) Diffusion

The key components and steps involved in carbon capture by membranes are as follows:

(1) Inlet Gas Stream: The gas stream containing CO_2 and other gases, such as N_2, CH_4, and trace impurities, is introduced into the membrane separation unit.

(2) Membrane Material: Specialized membrane materials are placed within the separation unit. These materials can be made of polymers, ceramics, or other advanced materials that possess the desired selective permeation properties.

(3) Selective Separation: The gas mixture comes into contact with the membrane material, and the selective permeation and diffusion processes take place. CO_2 molecules pass through the membrane material while other gases are largely rejected.

(4) CO_2 Enrichment: On the other side of the membrane, a concentrated CO_2 stream is collected. This enriched CO_2 stream can be further processed, compressed, and transported for storage or utilization.

(5) Reject Gas: The remaining gas, which is depleted in CO_2, exits the separation unit and can be released into the atmosphere or subjected to further treatment if necessary.

4. Various membranes and their carbon capture efficiencies:

Carbon capture efficiency values for membrane-based carbon capture technologies can vary widely depending on factors like the type of membrane, operating conditions, and the specific application. It's important to note that carbon capture efficiency can be influenced by factors such as temperature, pressure, gas composition, and the presence of impurities. Additionally, real-world efficiency may vary from laboratory-tested values due to operational and economic considerations. Additionally, efficiency values may change as technology continues to advance. Here are a few membrane-based carbon capture methods along with some general efficiency information:

Polymeric Membranes: Polymeric membranes are commonly used in post-combustion carbon capture. They have reported CO_2 capture efficiencies ranging from 20% to 90% or more, depending on the membrane material, design, and operating conditions. Examples of polymeric membranes include: Polyimide Membranes, Polyethylene Membranes, Polyvinyl amine Membranes, Polyetherimide Membranes.

Mixed Matrix Membranes (MMMs): Mixed matrix membranes incorporate solid particles or nanoparticles into a polymer matrix to enhance their separation properties. Their capture efficiency can vary widely, often falling in the range of 30% to 90%. Examples include: Zeolite-polymer MMMs; Metal-organic framework (MOF)-polymer MMMs.

Inorganic Membranes: Inorganic membranes, such as ceramic or silica-based membranes, are known for their high thermal and chemical stability. They can achieve high CO_2 capture efficiencies, often exceeding 90%. Examples include: Silica Membranes, Zirconia Membranes, Pebax Membranes (a hybrid polymer-inorganic membrane)

Ionic Liquid Membranes: Ionic liquid-based membranes can be highly efficient for CO_2 capture and have reported capture efficiencies of 90% or higher in some cases.

Composite Membranes: Composite membranes combine multiple materials, such as polymers, ceramics, and metals, to optimize CO_2 capture efficiency. These membranes can achieve efficiencies in the range of 50% to 90% or more.

It's important to note that no single membrane material or technology is universally efficient for all carbon capture scenarios. The choice of membrane technology and its associated efficiency will depend on the specific application, cost considerations, and the desired level of CO_2 capture, composition of the gas stream being treated. It often involves a trade-off between selectivity (the ability to capture CO_2) and permeability (the rate at which gases can pass through the membrane). Membranes with high selectivity for CO_2 typically have lower permeability and vice versa. Continuous research and development efforts aim to optimize membrane materials and system designs to achieve higher efficiencies while minimizing energy consumption and operational costs.

5. Advantages of using membranes over other methods

Using membranes for carbon capture offers several advantages compared to other methods, making it an attractive option for mitigating greenhouse gas emissions. Here are some key advantages of membrane-based carbon capture [20-22]:

(i) Energy Efficiency: Membrane processes generally require lower energy inputs compared to traditional solvent-based carbon capture methods such as amine scrubbing. This results in reduced operational costs and lower energy consumption, making it a more efficient option.

(ii) Reduced Environmental Impact: Membrane-based carbon capture produces fewer waste byproducts and uses fewer chemicals compared to some other capture technologies. This can lead to a lower environmental footprint and reduced risks associated with chemical handling and disposal.

(iii) Modularity and Scalability: Membrane systems can be designed to be modular and scalable, making them adaptable to a wide range of applications and industries. They can be easily integrated into existing processes and can be expanded or downsized as needed.

(iv) High Selectivity: Membranes can be engineered to have high selectivity for CO_2, allowing them to effectively separate and capture carbon dioxide from gas mixtures while minimizing the co-capture of other gases, such as nitrogen.

(v) Space Efficiency: Membrane systems typically have a smaller footprint compared to traditional absorption or adsorption columns, making them suitable for installations with space constraints.

(vi) Lower Capital Costs: Depending on the specific application and scale, membrane-based carbon capture systems can have lower capital costs compared to alternative technologies, especially in cases where retrofitting is required.

(vii) Rapid Start-Up and Shutdown: Membrane systems can be quickly started and stopped without the extended ramp-up and ramp-down times associated with some solvent-based capture systems. This flexibility can be advantageous for intermittent carbon capture needs.

(viii) Reduced Corrosion and Maintenance: Membranes are less susceptible to corrosion and fouling compared to some chemical solvents, leading to reduced maintenance requirements and longer system lifetimes.

(ix) Lower Water Usage: In some cases, membrane-based carbon capture can operate with reduced water usage compared to traditional solvent-based systems, which can be important in water-scarce regions.

(x) Integration with Other Technologies: Membrane-based carbon capture can be integrated with other processes, such as gas separation or natural gas purification, allowing for greater flexibility and efficiency in overall industrial operations.

Though membrane-based carbon capture offers these advantages, it's important to note that no single carbon capture method is universally applicable. The choice of technology depends on the specific application, gas composition, and economic considerations. Membrane-based carbon capture is particularly well-suited for certain industrial processes and applications where its unique advantages can be maximized. The advantages of using membranes for CCUS, over other methods are shown in Figure 2.

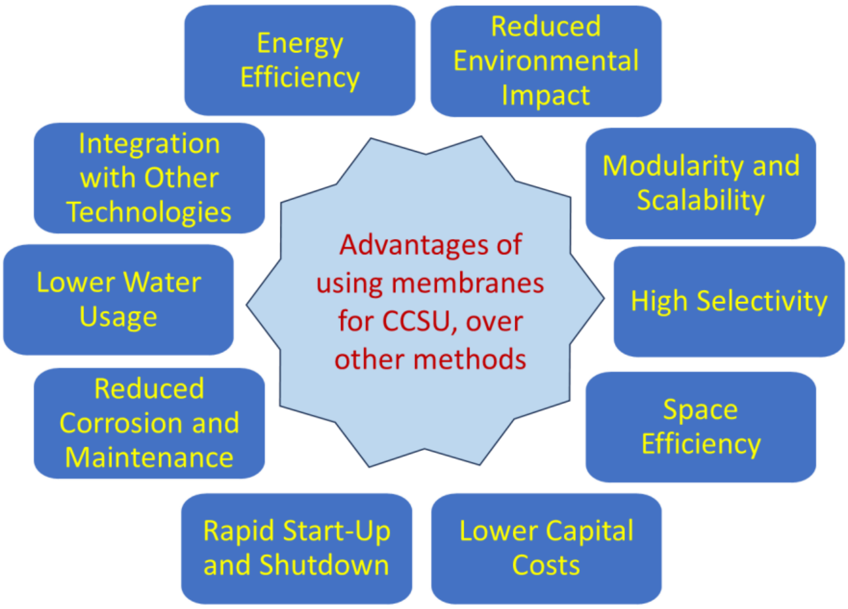

Figure 2: Advantages of using membranes for CCSU, over other methods

6. Drawbacks of using membrane technology for carbon capture:

While membrane technology for carbon capture offers several advantages, it also has some drawbacks and challenges that need to be considered. Here are some of the drawbacks of using membrane technology for carbon capture [2,10]:

(i) Limited CO_2 Concentration: Membrane systems are generally more effective at separating CO_2 from high-concentration sources. They may be less efficient when dealing with flue gases or gas streams with lower CO_2 concentrations, requiring additional pre-treatment steps.

(ii) Membrane Degradation & Fouling: Membranes can degrade over time due to exposure to harsh operating conditions, such as high temperatures, chemical contaminants, or fouling. This can lead to reduced performance and increased maintenance costs. Membranes can become fouled or blocked by impurities present in the gas stream, reducing their effectiveness. Regular cleaning or replacement may be necessary to maintain performance.

(iii) Selectivity vs. Permeability Trade-off: Achieving a high level of CO_2 selectivity often comes at the expense of permeability. This trade-off can affect the overall efficiency of the carbon capture process.

(iv) Capital Costs: While membrane systems can have lower capital costs in some cases, the initial investment can still be substantial, especially for large-scale applications.

(v) Pressure Requirements: Membrane systems may require high pressures to achieve efficient separation, which can increase energy consumption and infrastructure costs.

(vi) Gas Stream Impurities: Membranes can be sensitive to impurities in the gas stream, which may need to be removed or reduced through pre-treatment processes.

(vii) Membrane Material Compatibility: The choice of membrane material is critical, as it must be compatible with the specific gas composition and operating conditions. Finding suitable materials for all applications can be challenging.

(viii) Scalability Challenges: Scaling up membrane systems for large industrial applications can pose engineering challenges, particularly in terms of maintaining uniform gas flow and pressure distribution.

(ix) Environmental Impact: The production and disposal of membranes can have environmental impacts, including the use of energy and resources in their manufacturing.

(x) Space Requirements: While membranes have a smaller footprint compared to some other carbon capture technologies, they may still require significant space for installation, especially in crowded industrial facilities.

It's important to note that the extent of these drawbacks can vary depending on the specific membrane technology, the application, and the operating conditions. Researchers and engineers continue to work on improving membrane materials, designs, and processes to address these challenges and make membrane-based carbon capture more efficient and practical for a wider range of applications. Figure 3 gives the summary of drawbacks of using membrane technology for carbon capture.

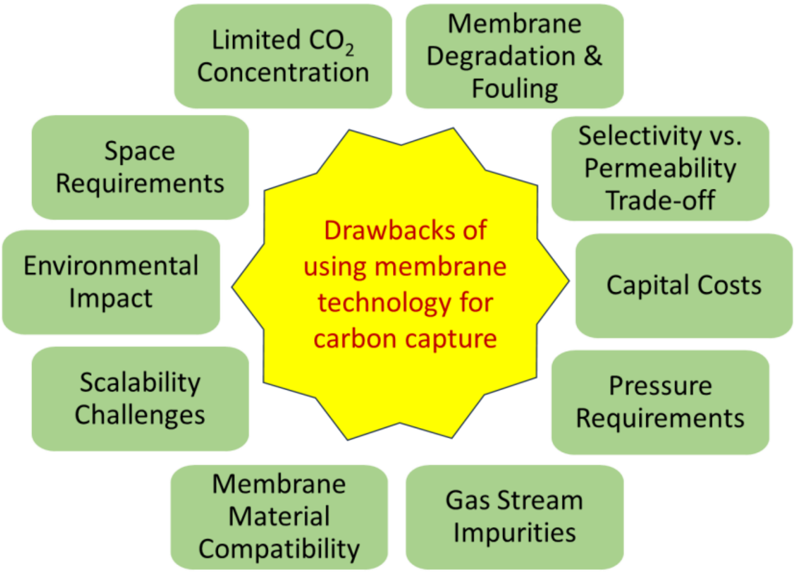

Figure 3: Drawbacks of using membrane technology for carbon capture

7. Future scope of using membrane technology for carbon capture:

The future scope of using membrane technology for carbon capture is promising and holds significant potential in the ongoing efforts to combat climate change. As technology advances and research progresses, several key areas of development and expansion can be anticipated [23-25]:

(a) Advancements in Membrane Materials: Ongoing research into advanced materials, including nanostructured membranes and mixed matrix membranes, may lead to breakthroughs in membrane performance, selectivity, and durability. Integration of nanomaterials, such as carbon nanotubes and graphene, to boost membrane performance. Exploration of advanced polymer blends and mixed matrix membranes for improved gas separation.

(b) Increased efficiency & lower costs: Researchers are continually working to enhance the efficiency of membrane systems for carbon capture. This includes improving the selectivity of membranes to capture CO_2 from various gas mixtures and reducing energy consumption during the separation process. Efforts are underway to reduce the capital and operational costs associated with membrane-based carbon capture. Innovations in membrane materials, manufacturing processes, and system designs aim to make this technology more cost-competitive with other carbon capture methods.

(d) Scale-Up & Integration with Renewable Energy: Membrane-based carbon capture systems are expected to be scaled up for use in large industrial applications, such as power plants and refineries. This will require the development of high-performance membranes and efficient system designs that can handle high volumes of CO_2 emissions. Integration with renewable energy sources, such as wind and solar power, holds promise. This could enable the capture of CO_2 emissions from renewable energy generation processes, further reducing the carbon footprint of clean energy technologies.

(f) Hybrid Approaches & Real-World Testing: Hybrid systems that combine membrane technology with other carbon capture methods, such as solvent-based capture or adsorption, may become more common. These hybrid approaches can take advantage of the strengths of each technology to improve overall efficiency and cost-effectiveness. Increased deployment of pilot-scale and commercial-scale membrane-based carbon capture projects to validate the technology's viability in real-world applications.

Membrane technologies for carbon capture is poised to play a vital role in the transition to a more sustainable and low-carbon future. As research and development efforts continue, membrane-based carbon capture is likely to become more efficient, cost-effective, and widely adopted, contributing to the global goals of mitigating climate change and reducing greenhouse gas emissions.

8. Conclusions

Membrane technology holds significant promise as an efficient, cost-effective, and environmentally sustainable method for carbon capture. It has the potential to play a crucial role in reducing greenhouse gas emissions from various industrial processes and power generation. It can be applied to a wide range of industrial sectors, including power plants, natural gas processing, and industrial emissions, making it a versatile solution for addressing emissions from diverse sources. The high efficiency, selectivity, environmental benefits are key elements for its adoption in future, though challenges remain in terms of membrane durability under harsh conditions, and cost competitiveness at a large scale. Membrane-based carbon capture can be integrated with renewable energy sources and other carbon capture methods to create hybrid systems that maximize efficiency and reduce emissions. As governments and industries worldwide increase incentives for the adoption of carbon capture technologies, including membrane-based systems. In conclusion, membrane technology represents a promising and evolving approach to carbon capture that can contribute significantly to reducing greenhouse gas emissions. While challenges exist, ongoing research and development are expected to lead to further improvements and wider adoption of this technology in the fight against climate change and sustainable future of mankind.

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