International Journal of Applied Science; Vol. 8, No. 4; 2025
ISSN 2576-7240 E-ISSN 2576-7259
https://doi.org/10.30560/ijas.v8n4p39

Integrated CO_2 Treatment in Offshore Gas Fields Using Membrane Separation and Ocean Storage

Lin Yiqi[1]

[1] Guangdong Ocean University, China

Correspondence: Lin Yiqi, Department of Horticulture and Landscape Architecture, Guangdong Ocean University, Zhanjiang, China. E-mail: lyq219@stu.gdou.edu.cn

Received: October 22, 2025; Accepted: November 12, 2025; Published: November 13, 2025

Abstract

The greenhouse effect has been increasingly aggravating. As the key to alleviating the emission of CO_2, carbon capture and storage (CCS) holds an important position on achieving the goal of carbon neutrality goal. However, CCS still face the challenge about high cost, high energy consumption and high risks and so on. The passage focuses on the collaborative optimization of gas membrane separation technology and ocean storage, and systematically illustrate their mechanism and efficiency in the technological integration. The result shows that by selecting membrane materials and integrating processing, the gas purity and pressure can meet the requirements of ocean storage can be achieved in the capture stages, which significantly reduce the intermediate processing links, thereby lowering system energy consumption and operating costs, and improving the efficiency and economy of the entire CCS chain. In the future, further research on the pressure resistant and stability of membrane materials should be strengthened to promote the development of collaborative technology toward large-scale and commercialization.

Keywords: membrane separation technology, ocean storage technology, collaborative optimization

1. Introduction

Human activities such as Industrial emission and deforestation, resulting in the continuous increase of greenhouse gas concentration, which is changing the global climate system at an unprecedented rate. The problems triggered by greenhouse effect such as frequent weather occurrence, glaciers melting acceleration and the rise of sea levels, have not only threatened the living environment of human beings, but also have a far-reaching influence on the stability of ocean ecosystems. The increase of ocean temperature and seawater acidification have led to large-scale of coral reefs bleaching, and marine biodiversity is facing a serious threat.

As the key method to alleviating greenhouse effect, carbon capture and storage (CCS) has been drawing global attention. CCS technology captures carbon dioxide (CO_2) from industrial emission sources or the atmosphere and safely stores it in geological structure or deep sea environment, thereby effectively reducing the content of greenhouse gases in the air. Currently, the technology has been applied on a large scale in many countries such as China, Canada, and the United States, and has shown great potential especially in carbon-intensive industries like coal-fired power generation and oil and gas exploitation. Noticeably, with the development of CCS technology, the combination of carbon storage and enhanced oil recovery (EOR) has become an important comprehensive utilization mode. This mode is usually called carbon capture, utilization, and storage (CCUS), and its core is injecting the captured CO_2 into depleted or inefficient oil reservoirs. On the one hand, CO_2 is used to effectively reduced the viscosity of crude oil and improve its fluidity, thereby increasing the oil recovery rate. On the other hand, it realizes the geological storage of CO_2, forming a virtuous circle of increasing production with carbon and promoting storage with production [1].

However, although the CCS technology has a significant effect on reducing emission, its extension and application still face many challenges about high cost, high energy consumption and high risk. Although carbon capture technology is already relatively mature, it still face significant issues of high energy consumption and high technological cost [2]. Then, the requirements for safety and long-term monitoring during storage are high, and the public concerns over the risk of CO_2 leakage should not be ignored either. Under this background, as the key links of CCS system, the gas membrane separation technology and ocean storage technology have received particular attention due to its unique technical features. The gas membrane separation technology has the advantages of flexible operation, relatively low energy consumption and environmental friendliness, and ocean storage is regarded as one of the most potential storage methods due to its large storage capacity and long duration [3]. Especially like China, which has an intensive coastal industrial and concentrated emission sources, developing efficient and low-cost membrane separation technologies, combined with marine storage pathways, is expected to provide a practical and feasible solution for regional carbon reduction.

This article aims to conduct an in-depth exploration of the potential and realization path of the collaborative optimization of gas membrane separation technology and ocean storage technology, focusing on analyzing the mechanism effects and comprehensive benefits of the collaboration between these two technologies. By studying the integrated CCS model, especially exploring innovative models such as carbon storage +EOR, look for feasible methods which can drop the cost of the CCS system and improve the running efficiency, and provide technical references and policy suggestions for promoting the low carbon transformation of the marine industry and facilitating the sustainable development of the green economy.

2. Overview of Membrane Separation Technology

2.1 Basic Principle and Mechanisms

Gas membrane separation technology is based on the difference in the dissolution rates of different gas molecules in the membrane material and the selectivity of the membrane, and achieve the separation of mixed gases under the pressure and other driving forces [4]. In principle, the transport mechanism in gas membrane separation involves factors such as gas type, diffusion rate, and solubility, and its essence is a kind of permeation, formed by molecules with different diameter passing through different membrane gaps in the membranes [5]. For example, compared to other gases, in a mixed gases of H_2, N_2, and CO_2, in a particular membrane material, the solubility of CO_2 is greater, and the membrane allows CO_2 to pass through preferentially, thereby achieving the separation of CO_2.

This separation process involves complex gas-membrane interaction mechanisms, including adsorption, dissolution, diffusion, and desorption and so on. The selectivity of membrane materials is usually determined by both solubility selectivity and diffusion rate selectivity. An ideal separation membrane should possess high permeability and high selectivity at the same time, but these two characteristics often have a trade-off relationship. In recent years, with the development of material science, new membrane materials such as mixed-mechanism membrane, facilitated transport membrane have emerged continuously. By introducing specific functional groups or nanostructures, the separation performance of the membrane has been significantly improved.

2.2 The Application in CO_2 Capture

In the field of offshore oil and gas recovery, the treatment of high-concentration CO_2 in associated natural gas has always been a technical challenge. Although the traditional amine absorption process has good separation effects, it also has problems such as large equipment, high energy consumption, and high consumption of chemical reagents. In contrast, membrane separation technology, due to its modular design and simple operation, is particularly suitable for application on offshore platforms with limitation space.

Some studies have focused the issues of high gas-oil ratios in deep-sea environments and the treatment of natural gas with high CO_2. The study proposed that the gas stream undergoes compression and dehydration treatment, and sent to a Hydrocarbon Dew Point Adjustment (HCDPA). Then, a combined process of Membrane Permeation (MP) technology and Chemical Absorption (CP) is employed to initially separate the refine the CO_2. The separated CO_2, under certain purity and pressure conditions, can be utilized to EOR [3]. This indicates that the membrane separation technology can be efficiently mixed with other crafts, and the gases can reach a certain purity under reasonable cost conditions.

2.3 Advantages and Limitation

Membrane separation technology has the advantages of high reliability, low environment impact, low energy consumption and convenient operation. Currently, it is widely used in industry, most for carbon production, oxygen enrichment, decarburization, and gas dehumidification and so on [6]. In addition, gas membrane separation technology has also created new opportunities for the research and development of new membranes in new fields [7]. In the previous industrial stage, the commonly used polymer membrane materials include Polyolefin (PO) and Polyimide (PI), but their permeability was poor. Therefore, nowadays, inorganic membranes are more commonly used. Contrast to organic membranes, the inorganic one has thermal stability, stable chemical properties, uniform void distribution, and is more convenient to operate [8].

However, membrane separation technology still faces some significant challenges. At the beginning, the production cost of high-performance membrane materials is relatively high. Especially those advanced membrane materials which possess high selectivity and high permeability in the meanwhile. Secondly, the membrane materials are easily being polluted and aging during use, which lead to the drop of separation performance. Moreover, with the condition of high pressure or complex gas components, the separation efficiency and service life of the membrane will be significantly affected [9]. To address these obstacles, the interdisciplinary cooperation among multiple fields such as material science and chemical engineering are required, through various efforts such as the opening of new materials, optimization of membrane component structure, and innovation in crafts, diligently promote the technological progress.

3. Overview of Ocean Sequestration Technology

3.1 Basic Principles and Storage Types

CO_2 storage is a means of carbon emission reduction. Currently, the ocean storage technology is able to capture approximately 15% of the global CO_2 emission each year [10]. It holds the characteristics of large storage capacity, great potential and high security, which can promote the construction of a low-carbon society.

At present, ocean storage has three forms: marine geological sequestration, seabed sequestration, and ocean water column sequestration. Marine geological sequestration involves injecting CO_2 into seabed formation such as depleted oil and gas layers, saline aquifers, and then sequestering it through physical barriers or chemical reactions with certain minerals to form stable carbonates. Seabed sequestration, also known as marine sediment sequestration, involves injecting CO_2 into sedimentary layers and storing it below the pore water. In the low-temperature and high-pressure environment, it forms crystalline hydrates, and storage on the seabed is achieved based on the property that crystalline hydrates are hardly soluble seawater. Ocean water column sequestration is to directly inject compressed CO_2 into the deep sea below 1500m. It will form different states in different depths and seawater densities [11]. For example, in relatively shallow sea areas, CO_2 is generally stored in gaseous or liquid form, while in deeper sea areas, it is stored in liquid form.

3.2 Security Mechanism and Long-term Stability

The safety mechanism of ocean sequestration is mainly achieved through two method: physical isolation and chemical fixation. The aim is to stably store CO_2 at the bottom of the sea and prevent leakage.

Physical isolation refers to placing CO_2 in a specific marine environment, using high-pressure and low-temperature conditions to stabilize its existence or form a barrier structure, preventing the release of CO_2 into the atmosphere. The typical methods includes ocean water column sequestration and seabed sequestration. The former one mixes CO_2 with seawater under high pressure and low temperature conditions in order to form a high density solution that naturally sinks to the deep sea, and the latter effectively prevent gas migration by storing CO_2 in the hydrate layer to form a low-permeability layer [12]. Chemical fixation involves injecting CO_2 into the ocean and allowing it to react with seawater to form carbonate ions. These ions combine with calcium(Ca2+) , magnesium(Mg2+) and other positive ion to form insoluble carbonates, achieving long-term storage.

In aspect of long-term stability, different storage style leads to different performance. Marine water column sequestration ultimately stores CO_2 in the form of carbonates, but its dissolved state is affected by environmental factors such as temperature and water depth, resulting in moderate stability. Seabed sequestration, relying on the physical and chemical properties of CO_2 hydrate being insoluble in water and the sealed barrier it forms, can significantly limit gas migration and thus has higher long-term stability.

3.3 Gas Purity and Pressure Requirements

Generally speaking, there is no a specific numerical standard for the purity of gases in marine storage. It is mainly determined by the storage technology and the application system. However, in order to prevent the impurity gases from polluting seawater, it is also necessary to separate high purity gases. A study has proposed a system which is called Gas Lift Advanced Dissolution (GLAD), in order to store deep-sea CO_2. Nevertheless, the system requires a large amount of energy consumption to directly release CO_2 into deep sea. In order to realize the low-budget and environmental-friendly CO_2 ocean storage, the system has been improved to Progressive Gas Lift Advanced Dissolution (P-GLAD). This is a type of J-shape pipe arranged at a depth of 200-3000 meters in the deep sea. It can dissolve low-purity CO_2 in seawater, use the buoyancy of the CO_2 gas to drive the flow of seawater, and transport it to a depth of 1000 to 3000 meters in the deep sea for storage, which save the step of purifying the gas, enhancing the efficiency of CCS process [13].

CO_2 can be safely stored at the bottom of the sea, which is benefited from the low-temperature and high-pressure environment, as well as the crystalline hydrates formed by the gas in this circumstance [12]. In the ocean, the pressure of seawater increases with depth. High pressure can cause CO_2 to change from a gaseous state to a fluid, reducing the volume of its internal molecules. This not only provides more space to store CO_2 but also keeps it in a stable state, preventing leakage. Moreover, low temperature can weaken the thermal motion of molecules, reducing the molecular spacing, increasing the number molecules per unit volume, raise the density of CO_2, and make it more stably stored at the bottom of the sea.

4. Coordination Mechanisms and Collaborative Benefits

4.1 The Coordination Mechanisms

To store CO_2 in the ocean, the purity of the gas needs to be as high as possible. Achieving this result depends on the membrane materials selected in membrane separation technology. Polyimide films are commonly used in industry for CO_2 capture. Although the molecular chains of polyimide films have good regularity and strong intermolecular interaction force, their gas permeability is relatively low. Therefore, some studies have introduced fluorine microporous units for application in this membrane [14]. The fluorine groups in Polymers of Intrinsic Microporosity-Polyimide (PIM-PI) have an aromatic ring structure that can combine with CO_2, enabling CO_2 to be preferentially absorbed on the film surface and enter the interior of the film. In addition, the pore size of microporous structure is larger than that of CO_2 molecules. If in a mixed gas of CO_2, CH_4 and N_2, due to the molecular diameters of CH_4 and N_2 being closer to the pore size of fluorine micropores, the diffusion resistance will increase, leading to the preferred separation of CO_2.

The requirements for gas pressure in marine storage can also be met by choosing appropriate membrane materials. Asymmetric membrane have been invented through a phase separation process under environmental conditions of 100-120 bar pressure, which indicated that the dense layer and porous layer in this membrane are suitable for high-pressure environments and no structural damage will occur [15]. Meanwhile, this research focuses on the separation of CO_2 and CH_4, and its separation environment is under high pressure, which indicates that asymmetric membrane can be used to separate high-pressure gases.

4.2 The Collaborative Benefits

Membrane separation technology and marine storage reduce the compression steps by choosing asymmetric membrane to increase the pressure of the separated gas. This not only reduces energy consumption but also better promotes the collaborative optimization of the two technologies, enhancing the efficiency of carbon capture and storage. Compare to other traditional CCS technology, it does not need to use a compressor for pressurization on the permeation side after separating CO_2, which greatly reduces energy consumption.

The technical cost of CCS mainly comes from the purification of gases. If use the PIM-PI, the high-purity gas can be directly separated during the membrane separation stage, reducing the step of purification, and does not need to use a series of equipment such as adsorption towers to remove impurities, reducing the technological cost. What’s more, the purified CO_2 can be used in the recovery of offshore crude oil, directly promoting economic benefits.

Furthermore, high purity CO_2 can prevent pipeline corrosion during transportation, prevent phase state instability during storage which may lead to gas leakage and environmental pollution, and also avoid introducing impurities into seawater, reducing harm to the marine ecosystem.

5. Case Study: Huizhou 32-5 Offshore Platform Project

5.1 Project Background and Implementation Process

The release of associated gas during offshore oil and gas extraction is significant, with CO_2 reaching over 80%, and traditional solutions are energy-intensive and inefficient [16]. The membrane decarbonization project implemented on the Huizhou 32-5 platform is the first project in China to capture and reinject CO_2 from associated gas at sea based on independent membrane technology. This project is based on domestic polyimide membrane components and established an integrated carbon removal and storage system.

The implementation of the project mainly includes three stages: Firstly, pre-treat the associated gas to stabilize the gas composition and pressure. Subsequently, a membrane separation unit is adopted to achieve efficient separation of CO_2 and hydrocarbon gases. Ultimately, the high purity CO_2 is pressurize and directly reinjected into the seabed strata for storage. The project has achieved the effective removal and resourceful storage of CO_2 from associated gas, providing a technical standard for the low-carbon development of offshore oil and gas fields.

5.2 Performance Evaluation: Gas purity and Storage Effect

The membrane separation system in the project has achieved a hydrocarbon recovery rate of no less than 90%. At the same time, it successfully purifies CO_2 to a level that can be directly stored [17]. High purity CO_2 not only reduces the risk of phase instability during the injection and storage process, but also significantly alleviates the corrosion tendency of the delivery pipeline, enhancing the system safety. Moreover, this project takes advantage of its high pressure and low temperature environment of the seabed strata to achieve CO_2 stable storage. The annual storage volume can reach 60,000 tons. While achieving emission reduction, it also has excellent economic benefits.

5.3 Experience Summary and Scalability

The successful implementation of the Huizhou 32-5 project indicates that the collaborative integration of gas membrane separation and marine storage technologies can significantly enhance the overall efficiency of the CCUS process, especially suitable for carbon reduction in coastal and offshore areas with dense emission sources. The pattern omits the independent gas purification and compression steps in traditional CCS, and has the advantages of energy conservation, consumption reduction and modularization. Whereas, at present, the compressive resistance and durability of membrane material in continuous high-pressure environments remain the bottleneck in engineering promotion. In the future, further research on membrane material structure optimization and real-time detection technology is needed to support the application of this model in a wider range of industrial occasions.

6. Conclusion and Outlook

6.1 Conclusion

The passage systematically reviews the mechanism, benefits and practical paths of the collaborative optimization of gas membrane separation technology and marine storage technology. The result shows that this collaborative pattern can effectively overcome the challenges of fragmented steps, high energy consumption and high cost in the traditional CCS process. Based on the matching of membrane material properties with storage requirements, the optimization of CO_2 purity and pressure parameters can be directly achieved in the capture stage, significantly eliminating the middle steps such as recompression and refining, reducing the overall energy consumption costs of the process. The case further verifies that this collaborative model is particularly suitable for the occasions such as offshore oil and gas platforms and coastal industrial. It combines the advantages of modular deployment with excellent environmental adaptability, providing a technically feasible and economically viable implementation path for promoting regional carbon reduction.

6.2 Outlook

Although the collaborative technology of gas membrane separation and marine storage has displayed obvious advantages, there is still room for improvement in the long-term stability of membrane materials, their tolerance to high-pressure environments, and real-time monitoring of storage systems. Future work can focus on the following tasks: First, develop high-performance composite membranes materials, such as mixed matrix membranes and enhanced asymmetric membranes, to enhance their mechanical strength and separation stability in high pressure and highly polluted environments. Secondly, establish a multi-scale monitoring and risk evaluation system to achieve dynamic and precise perception and warning of the seabed storage status. Third, promote policy and market mechanism innovation, enhance cross-departmental collaboration and support for demonstration projects, and move the collaborative model from pilot applications to large-scale and commercial deployment. Through continuous technological iteration and system optimization, this collaborative path is expected to become an important technological support for coastal areas to achieve green and low-carbon transformation, and provide a Chinese case and solution for the development of the global CCS technology system.

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