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Progress in Carbon Dioxide Capture and Storage (CCS) and Conversion Utilization Research

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Abstract. The issue of climate change caused by excessive carbon dioxide (CO_2) emissions has garnered widespread attention. This paper reviews the current major technologies for CO_2 treatment, including carbon capture and storage (CCS) and CO_2 utilization. CCS technology effectively reduces atmospheric CO_2 concentrations by injecting captured CO_2 underground for long-term storage, thereby mitigating climate change. Additionally, improvements in technology can enhance oil recovery rates. CO_2 utilization transforms CO_2 into high-value chemicals such as methane and carbon monoxide (CO) through thermal catalysis, photocatalysis, and electrocatalysis. Despite challenges such as low energy efficiency and high costs, these technologies show significant potential in reducing carbon emissions and promoting carbon recycling.

1 Introduction

Climate change is the most serious global challenges, with the fundamental cause being the large-scale release of greenhouse gases, especially CO_2. Since the Industrial Revolution, with the widespread use of fossil fuels and the acceleration of industrialization, the amount of CO_2 emissions has increased rapidly. These excessive CO_2 emissions have led to a significant intensification of the greenhouse effect, causing profound changes in the Earth's natural climate system. The greenhouse effect not only causes a continuous rise in the global average temperature, but also triggers a series of chain reactions, such as the accelerated melting of polar glaciers, a significant rise in sea levels, and the frequent occurrence of extreme weather events. These changes seriously threaten the balance of the ecosystem, the stability of the global food supply chain, and the safety of human living environments. Therefore, reducing CO_2 emissions has become the primary environmental issue that the global community must urgently address.[*]

To meet this challenge, countries and research institutions around the world are actively exploring various technological means to mitigate or even reverse the impact of excessive CO_2 in the atmosphere. This article will explore in detail several major technological approaches to addressing the issue of excessive CO_2 in the atmosphere, including CCS and

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CO_2 utilization. CO_2 capture and storage technology can effectively reduce the concentration of CO_2 in the atmosphere and mitigate the process of climate change by capturing CO_2 from industrial emission sources and safely storing it underground. CO_2 utilization technology, on the other hand, can convert CO_2 into useful chemicals or fuels through advanced catalysis and chemical reactions, achieving efficient resource utilization.

2 Physical Methods for CO_2 Treatment

2.1 Carbon Dioxide Storage

CCS is a crucial technology for combating climate change, aimed at reducing greenhouse gas emissions, especially CO_2 concentrations, to mitigate global warming.

Deep geological storage is currently the most mature technology, achieving long-term storage by injecting CO_2 into abandoned oil and gas fields, salt cavern formations, or coal seams. Depleted oil fields are one of the preferred locations for geological CCS. These oil fields have stored large amounts of oil and gas throughout geological history, proving their good sealing and storage capabilities. Injecting CO_2 into depleted oil fields not only achieves long-term storage but can also enhance oil recovery (Enhanced Oil Recovery, EOR) to further extract residual oil and gas. EOR technologies mainly include three categories: water flooding, gas flooding, and chemical flooding. Water flooding increases oil recovery by injecting water into the reservoir, potentially improving oil recovery by 10%-20% [1]. Gas flooding improves reservoir displacement efficiency by injecting gases such as natural gas or CO_2, with CO_2 injection in EOR potentially increasing recovery by 10%-15% [1]. Chemical flooding alters the physical and chemical properties of oil by injecting surfactants, polymers, and other chemicals, which can enhance recovery by 8%-15% [1]. Each of these EOR technologies has its characteristics and can be selected based on specific reservoir conditions to improve recovery.

2.2 Advantages of Carbon Dioxide Storage

CCS technology has significant advantages as an important measure for greenhouse gas reduction. Its main advantage lies in effectively mitigating climate change. Permanently storing captured CO_2 rather than releasing it into the atmosphere can significantly reduce greenhouse gas emissions and is significant in combating climate change [2]. Additionally, injecting CO_2 into reservoirs can increase oil recovery and extend the lifespan of oil fields, as confirmed by research by Ampomah et al. [3]. Furthermore, the processes of capturing, transporting, and storing CO_2 can generate carbon offset credits, providing new business opportunities for companies participating in carbon trading markets and becoming an important means for companies to address climate change [4].

2.3 Disadvantages of Carbon Dioxide Storage

CCS technology also faces potential drawbacks and challenges. Its construction and operational costs are relatively high, which may impose certain pressures and obstacles on the project's economic viability [5]. Moreover, long-term storage of CO_2 may lead to accidental leaks, posing potential safety risks to the environment and surrounding residents, necessitating strict monitoring and management measures [6]. The processes of capturing, compressing, and transporting CO_2 also require significant energy, which can reduce the overall energy efficiency of power plants or factories, necessitating further advancements in technology to improve efficiency [7]. Overall, governments and enterprises need to continuously optimize technologies and improve policies and regulations to further promote the development and application of CCS technologies, achieving the goal of greenhouse gas reduction.

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3 Chemical Conversion of CO_2

3.1 Carbon Dioxide to Methane

3.1.1 Thermocatalytically Conversion of Carbon Dioxide to Methane

The Sabatier reaction is a thermocatalytic method for converting CO_2 to methane. This reaction can be represented as: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. In the study by Li et al. [8], Ni/Al_2O_3 was used as a catalyst for the hydrogenation of CO_2 to produce methane. According to their research [8], at higher reaction temperatures, CO_2 molecules first adsorb on the surface of the Ni/Al_2O_3 catalyst and are thermally activated. The activated CO_2 reacts with hydrogen in the reaction atmosphere to generate methane and water. The produced methane desorbs from the catalyst surface, and water also desorbs, exposing the active sites on the catalyst surface again. Although this reaction efficiently converts CO_2 into the clean fuel methane, achieving both capture and utilization of greenhouse gases, the required hydrogen can come from clean hydrogen production technologies, providing a renewable source of raw materials for the process. However, the Sabatier reaction requires high temperature and pressure conditions, which increases equipment and energy consumption, raising the cost of the process. Additionally, the preparation process of composite catalysts like Ni/Al_2O_3 is relatively complex, making large-scale production and commercialization difficult.

3.1.2 Photocatalytic Conversion of Carbon Dioxide to Methane

Photocatalysis is another method for converting CO_2 into methane. Under visible light or sunlight, various semiconductor photocatalysts, such as TiO_2 or cadmium sulfide (CdS), are excited to generate electron-hole pairs. These photo-generated charge carriers can activate CO_2 molecules adsorbed on the catalyst surface and undergo a series of reduction reactions with water molecules or hydrogen, ultimately producing fuels such as methane, methanol, and ethanol [9]. This method has the advantages of utilizing renewable solar energy resources, not consuming fossil fuels, and having a relatively simple process. However, the activity and selectivity of existing photocatalysts are low, and production efficiency needs improvement.

3.1.3 Electrocatalytic Conversion of Carbon Dioxide to Methane

Electrocatalytic conversion of CO_2 to methane is another method that has attracted attention. Hori et al. [10] indicated that in the electrocatalytic process, an electric current drives CO_2 to be reduced to CH_4 on the surface of the electrocatalyst. Birdja et al. [11] noted that electrochemical CO_2 reduction has advantages such as high energy density and high flexibility for storing renewable electricity, allowing for low overpotential and efficient reversible conversion of CO_2 into useful products through suitable electrocatalysts. However, this technology still faces challenges such as low energy efficiency, the need for improved product selectivity, low overall conversion rates, and insufficient technological maturity.

3.2 Carbon Dioxide to Carbon Monoxide

Converting CO_2 to CO is an important carbon capture and utilization technology. The target product of this process is the more reactive CO, which can be used as a chemical raw material and fuel. One of the main methods for converting CO_2 to CO is the reverse water-gas shift (RWGS) reaction. The RWGS reaction is the opposite of the water-gas shift reaction, which is typically used in industrial processes to produce hydrogen (H_2) from CO and water (H_2O) [12]. The RWGS reaction can be expressed by the following chemical equation: $CO_2 + H_2 \rightleftharpoons CO + H_2O$. In this reaction, CO_2 and H_2 are converted into CO and H_2O. This is an endothermic reaction that requires input of thermal energy to proceed. The typical working temperature range for the RWGS reaction is 600 °C to 900 °C, depending on the specific catalyst and reactor design. The conversion of CO_2 to methane mainly uses metals as catalysts, primarily consisting of Cu, Pt, and Rh fixed on various supports [12]. The choice of catalyst materials and supports very impact on the activity, selectivity, and stability of the RWGS reaction. The RWGS reaction can be conducted at lower temperatures (~165 °C) [12] with minimal production of by-products such as methane [13]. A promising method to enhance the performance of the RWGS reaction is the use of nanostructured catalysts. For example, MD Porosoff et al. developed a RWGS catalyst based on platinum nanoparticles that achieved 95% CO selectivity and approximately 50% CO_2 conversion rate at 550 °C. They found that compared to traditional bulk platinum catalysts, nanoscale platinum particles could better activate CO_2 molecules and selectively generate CO [14]. Overall, converting CO_2 to CO through the RWGS reaction is a promising method for utilizing CO_2 as a valuable chemical feedstock. However, research and development of catalyst design, reactor engineering, and process optimization remain key to improving the efficiency and cost-effectiveness of this technology.

3.3 Conversion of Carbon Dioxide to Other Chemicals

Converting CO_2 to other products, such as alcohols or alkenes, is an effective way to reduce carbon emissions and achieve carbon neutrality. Ethylene is a product that can be obtained by catalytically converting CO_2. The electrochemical method is a way to convert CO_2 to ethylene through electrolysis. This general reaction can be represented as: $2CO_2 + 4H_2 \rightarrow C_2H_4 + 2H_2O$. The electrochemical reduction of CO_2 to ethylene is a complex process involving multiple steps and intermediates. First, CO_2 adsorbs on the copper surface, then it is reduced to CO as an intermediate, and finally further reduced to products like CH_4 and C_2H_4 [15]. Converting CO_2 to ethanol is also a feasible method. The electrochemical reduction of CO_2 to ethanol is a multi-electron, multi-proton reaction, which can be represented as: $2\ CO_2 + 6\ H^+ + 6\ e^- \rightarrow CH_3CH_2OH + 2H_2O$. A class of promising catalysts is based on Cu materials. Research shows that a single copper catalyst can produce ethanol and other C^{2+} products. Optimizing the surface structure and active sites of copper is key to improving ethanol selectivity. For example, controlling the orientation of copper crystal planes can significantly impact product distribution [16]. Introducing a second metal element into copper-based bimetallic electrocatalysts can further enhance the yield and selectivity of ethanol. For instance, bimetallic catalysts such as Cu-Pd and Cu-Sn benefit from the introduction of a second metal to modulate electronic structure and catalytic active sites [16]. Furthermore, in the study by Jiang et al. [17], they developed a Cu-based electrocatalyst that achieved high Faradaic efficiency (>60%) for the selective reduction of CO_2 to C^{2+} products, including ethanol. They attributed this performance enhancement to the metal-ion battery cycling method that exposes more favorable (100) and (211) crystal planes for C-C coupling.

4 Conclusion

The technologies for capturing, storing, and converting CO_2 play a crucial role in addressing global climate change. CCS technologies effectively reduce the concentration of CO_2 by capturing CO_2 produced during industrial and energy generation processes and safely storing it underground, thereby mitigating the negative impacts of the greenhouse effect and climate change. In addition, CCS technology can be combined with enhanced oil recovery to achieve a win-win situation for energy production and environmental protection. Meanwhile, the conversion and utilization of CO_2 technologies provide new solutions for reducing carbon emissions. Through thermal catalysis, photocatalysis, and electrocatalysis, CO_2 can be converted into fuels such as methane and CO or other high-value-added chemicals, which not only helps to reduce CO_2 emissions but also provides raw materials for the chemical industry, achieving carbon recycling. However, these technologies still face challenges in energy efficiency, cost, and catalyst stability, requiring further research and technological breakthroughs. In the future, to achieve the global carbon neutrality goal, it is necessary to promote the development of CO_2 treatment technologies at multiple levels. It is hoped that this article can contribute to the development of CO_2 capture, storage, and conversion technologies, reduce global carbon emissions, and address climate change.

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