Analysis of Carbon Dioxide Capture Technology and Resource Utilisation

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Abstract: Addressing the increasingly severe issues of carbon dioxide emissions pollution and intensified greenhouse effects, this paper focuses on a systematic analysis of carbon dioxide capture technologies and resource utilisation. It aims to explore synergistic optimisation pathways for carbon capture and subsequent resource conversion, filling a gap in existing research that predominantly concentrates on single domains or industries. The study primarily employs literature analysis, case studies, and inductive summarisation to systematically outline the types, characteristics, and core pathways for resource utilisation within carbon capture technologies. Results indicate that physical adsorption methods (utilising core materials such as MOFs and activated carbon), membrane separation techniques, and bioenzymatic approaches each possess distinct advantages and disadvantages, rendering them suitable for different operational scenarios. Resource utilisation can be achieved through chemical synthesis, biological applications (microalgal fixation, carbon-enriched agriculture), and enhanced oil recovery. Among these, chemical synthesis coupled with solid waste co-disposal technologies offer both environmental benefits and economic viability, demonstrating considerable application potential. This paper summarises current technological developments and application potential, noting existing research limitations such as insufficient case studies and limited sample sizes. It proposes that future research should expand sample scope through practical production cases to deepen understanding. This study provides technical guidance for synergistic optimisation of carbon capture and resource utilisation, holding practical significance for advancing low-carbon green development.

Keywords: CCUS; CO_2 Resource Utilisation; Carbon Capture; CO_2 Reduction Measures

1. Introduction

1.1 Research Background and Significance

The ongoing expansion of global industrial development and the intensification of environmental challenges present significant hurdles in addressing greenhouse gas emissions, particularly carbon dioxide. [3] Research into carbon dioxide capture technology primarily focuses on reducing emissions of this key greenhouse gas, thereby mitigating environmental pollution caused by substantial greenhouse gas discharges. By investigating carbon dioxide capture and resource utilisation techniques, this study explores the technical feasibility of synergistically optimising carbon capture processes with subsequent resource conversion pathways.

Its core theoretical value lies in: by closely integrating the capture process with resource conversion pathways, it simplifies carbon storage and transportation, enhances processing efficiency and technological benefits, and opens innovative avenues for resource recycling in carbon capture technology development, broadening research perspectives and possibilities.

1.2 Research Content and Framework

This study focuses on the concept, characteristics, and research achievements of carbon capture technology. It systematises the primary methods for carbon dioxide resource utilisation, categorising and briefly analysing them. It introduces and summarises key technologies for carbon capture and carbon dioxide resource utilisation, laying the groundwork for examining practical application cases of these technologies. It summarises and analyses primary application scenarios for carbon capture and C02 resource utilisation. By reviewing and analysing practical applications of resource utilisation technologies across industrial and domestic sectors, it evaluates their environmental benefits and economic advantages. This provides reference points and future prospects for ongoing research and practical implementation of carbon capture and resource utilisation technologies.

1.3 Research Methodology and Innovation Points

The primary methodologies employed include case studies, literature analysis, and inductive summarisation. This paper draws upon databases such as CNKI to comprehensively gather relevant literature on carbon capture and CO_2 resource utilisation,focusing primarily on technical analysis and applications. Through studying and reflecting upon the referenced case studies and literature, the theoretical foundation for this research is established. By summarising the development, application status, and achievements of existing technologies, reasonable projections for the future development and application trends of carboncapture and CO_2 resource utilisation technologies are proposed based on practical circumstances.

Current literature offering comprehensive reviews of carbon capture and resource utilisation remains scarce, with prior research predominantly focusing on analyses within specific aspects or industries of . Consequently, this paper aims to investigate and summarise key technologies within carbon capture and CO_2 utilisation alongside practical applicationsacross diverse industries. It further proposes reasonable projections for the development and application trends of these technologies, thereby providing a reference for subsequent research in carbon capture and CO_2 utilisation.

2. Overview of Carbon Capture Technologies

2.1 Physical Adsorption Methods

Physical adsorption techniques leverage the physical properties of materials to achieve the adsorption capture and desorption release of specific substances. The primary physical adsorption methods currently employed in carbon capture technology can be categorised into two types: pressure swing adsorption (PSA) and temperature swing adsorption (TSA). Technical descriptions and analyses of their respectiveadvantages and disadvantages are provided below.

2.1.1 Pressure Swing Adsorption (PSA) technology

Pressure Swing Adsorption (PSA) technology primarily exploits the differential adsorption capacities of adsorbent materials towards different gas molecules under varying pressure conditions to achieve targeted capture of carbon dioxide molecules. [11] When high-pressure waste gas enters the adsorption tower, carbon dioxide molecules are captured by the adsorbent material. After gas processing, pressure is released to desorb the carbon dioxide, thereby regenerating the adsorbent material.

2.1.2 Temperature swing adsorption technology

Temperature Swing Adsorption (TSA) harnesses the differing adsorption characteristics of adsorbents at varying temperatures to achieve efficient carbon dioxide capture. Most materials employed in this technology operate on a cyclic process involving low-temperature adsorption (approximately 50-60°C) and high-temperature desorption (approximately 150-200°C). TSA is primarily suited for treating large volumes of low-pressure flue gas.

2.1.3 Physical Adsorption Materials

Current materials utilised for physical adsorption include metal-organic frameworks (MOFs), activated carbon, and solid amines. [9]

As novel materials, MOFs exhibit diversity and design flexibility in both structure and chemical properties, increasingly finding application in gas storage and separation. [11] Precise engineering of the metal framework enables selective adsorption of carbon dioxide molecules.

Activated carbon, possessing a rich pore structure and capable of being regenerated for reuse, is a widely employed carbon-based adsorbent in industry. [12] It offers advantages including structural tunability, excellent regenerability, strong cycling stability, and high hydrophobicity. Furthermore, its raw materials are widely available, resulting in lower costs compared to other adsorbents.

Solid amines are composite materials utilising porous substrates with organically loaded amines on their surfaces. They exhibit outstanding adsorption capabilities under mild conditions while overcoming the drawbacks of liquid amines, such as their corrosive effect on equipment. Consequently, they represent one of the key research focuses in the development of novel CO_2 adsorbents. [12]

2.2 Membrane Separation Method

Membrane separation technology employs the selective permeability of membrane materials to isolate carbon dioxide from mixed gases. [4] Depending on the properties of the membrane material, it can be categorised into polymeric membranes and inorganic membranes. The advantages of membrane separation lie in the low energy consumption and minimal pollution associated with the membrane materials. [9] Additionally, the process features a simple structure, straightforward operation, and ease of maintenance.

However, membrane separation technology still has limitations. Current literature references indicate that membrane separation techniques based on CO_2 gas permeation remain in their nascent stages of development both domestically and internationally. Most research remains confined to theoretical numerical calculations, lacking practical experimental data to substantiate findings.

2.3 Biological Enzyme Method

Biological enzyme-based CO_2 capture primarily involves identifying enzymes capable of catalysing specific reactions.

Microbial cultures are cultivated and collected, then mixed with industrial flue gas or CO_2-containing waste products. The enzymes catalyse the conversion of CO_2 into usable products, thereby achieving targeted CO_2 capture.

Current literature indicates that mainstream enzymatic CO2 capture techniques involve either utilising carbonic anhydrase to hydrate CO_2 into HCO^{3-}, which is then further fixed as $CaCO_3$ with Ca^{2+} participation, or employing formate dehydrogenase (FDH) to catalyse the reduction of CO_2 into formic acid. [15] The bioenzymatic approach represents a promising CO_2 capture method. Its advantages include the production of carbon-containing compounds, facilitating subsequent resource utilisation, storage, and transportation of CO_2. Potential drawbacks may include challenges in obtaining bioenzyme raw materials and relatively stringent reaction conditions.

3. Overview of CO_2 Resource Utilisation Methods and Technologies

3.1 Chemical Synthesis

One of the primary current applications for carbon dioxide resource utilisation is chemical synthesis within industrial production. Common examples are analysed below.

3.1.1 Synthesis of Methanol from Carbon Dioxide and Hydrogen In the reaction system for hydrogenating CO_2 to produce methanol, the primary chemical reaction is as follows:

$$\mathrm{CO_2} + 3H_2 \rightleftharpoons \mathrm{C}H_3OH + H_2\mathrm{O} \quad (1)$$

$$CO + 2H_2 \rightleftharpoons \mathrm{C}H_3OH \quad (2)$$

$$\mathrm{CO_2} + H_2 \rightleftharpoons \mathrm{CO} + H_2O \quad (3)$$

Through a series of reactions between carbon dioxide and hydrogen, the final products are methanol and water.

The principal advantage of this reaction system lies in methanol being a vital chemical feedstock and fuel with extensive application potential. [19] It holds significant importance for advancing renewable energy and green chemical processes within CCUS,

thereby aiding carbon emission reduction.

The primary drawback lies in thermodynamic limitations, resulting in relatively low single-pass conversion rates for carbon dioxide. However, developing highly efficient reaction catalysts can effectively reduce overall process energy consumption. [21] At present, the high cost of hydrogen and the lack of suitable, high-efficiency reactioncatalysts remain the principal reasons why carbon dioxide hydrogenation to methanoltechnology is not yet suitable for widespread adoption.

3.1.2 Methane-CO_2 Reforming and CO_2-Methanation

The primary chemical reactions in methane-CO_2 reforming are as follows:

$$\mathrm{CH_4} + CO_2 \rightleftharpoons 2CO + 2H_2 \quad (4)$$

The primary chemical reactions for carbon dioxide methanation are as follows:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (5)$$

The advantage of this series of reactions lies in simultaneously converting the two most abundant greenhouse gases, carbon dioxide and methane. [23] This holds significant importance and value for effectively reducing carbon emissions, mitigating environmental issues, and promoting green development.

A common drawback of both utilisation methods is the substantial consumption of reaction feedstocks (CH4 or H2) required to convert industrially captured CO_2, entailing considerable costs. Furthermore, the development and application of highly efficient reaction catalysts remain limited, resulting in suboptimal conversion rates and reaction speeds. [23]

3.1.3 CO_2 Mineralisation of Calcium Carbide Residue to Produce Calcium Carbonate Micropowder

Calcium carbide residue contains abundant $Ca(OH)_2$, extensively utilised domestically Iacross building materials, chemical industries, and other sectors for brick manufacturing when blended with other raw materials. [16] Given its over 80% CaO content, multiphase reaction technology enables efficient extraction of calcium-rich components, such as producing high-value calcium carbonate products via CO_2 mineralisation.

This approach simultaneously purifies CO_2 from industrial waste gases and efficiently utilises impurities within calcium carbide residue, achieving synergistic disposal of CO_2 and solid waste. It fulfils dual requirements for carbon capture and solid waste resource utilisation, demonstrating promising development prospects and offering valuable reference for enhancing production efficiency.

3.2 Biological Utilisation

Biological utilisation of CO_2 involves the resource recovery of carbon dioxide through biological fixation and conversion, primarily encompassing microalgal fixation technology and carbon-enriched agricultural applications. [20] Microalgal fixation technology primarily employs concentrated microalgal cultures for photosynthesis, utilising CO_2 as a raw material to synthesise biofuels through photosynthesis, demonstrating considerable development and application potential. In carbon-enriched agriculture, CO_2 functions as a gaseous fertiliser to accelerate crop growth, offering significant commercial value and broad applicability for greenhouse agriculture and emerging agricultural industries. However, biological utilisation technologies face challenges due to inherent biological instability factors, making large-scale conversion and utilisation difficult.

3.3 Enhanced Oil Recovery

CO_2 enhanced oil recovery represents a more traditional approach to CO_2 resource utilisation. This involves injecting CO_2 into reservoirs to dissolve it within crude oil, thereby reducing oil viscosity and increasing reservoir pressure, significantly boosting oil recovery rates. Furthermore, upon completion of oil extraction, the CO_2 can be sequestered in situ, simultaneously achieving resource utilisation and carbon storage reduction objectives. CO_2 enhanced oil recovery is currently deployed at scale globally. By the end of 2020, the United States alone utilised over 10 million tonnes of CO_2 for this purpose. [3]

4. Summary and Outlook

This study collates and summarises the fundamental principles and application pathways of carbon capture technologies and CO_2 resource utilisation techniques, providing an initial analysis of their current developmental status. Through examination of diverse literature and case studies, it systematically organises, analyses, and synthesises the progress, applications, and achievements of existing technologies. It explores and projects the feasibility of integrating carbon capture processes with resource conversion pathways, offering potential references for investigating synergistic optimisation between CO_2 capture and subsequent resource utilisation technologies.

This study is subject to limitations including a scarcity of case analyses and restricted sample scope. Future research may integrate practical production cases, appropriately expand sample coverage, and propose novel methodologies to deepen investigations.

5. References

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