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A Comparison of Carbon Dioxide Capture and Conversion Technologies

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Abstract. Large-scale carbon dioxide emissions are the primary cause of global warming: to achieve the 'dual carbon' targets, it is essential to develop carbon dioxide capture and conversion technologies and to advance their application and development. This paper provides a systematic review of the mainstream CO_2 separation technologies currently in use, including pre-combustion capture, post-combustion capture and direct air capture, as well as the technical principles, maturity and key bottlenecks of pathways for converting CO_2 into resources through thermocatalysis, electrocatalysis, photocatalysis and bioconversion. It also focuses on the cutting-edge coupled application technology of integrated capture and conversion. On this basis, a comparison is conducted across multiple aspects, including principles, energy consumption, efficiency, economic viability and the stage of industrialisation. The results indicate that chemical absorption is the mainstream method for post-combustion capture, but it has high energy consumption; physical adsorption offers significant advantages under the high-pressure conditions of pre-combustion capture; thermal catalytic technology is highly dependent on hydrogen supply; electrocatalytic and photocatalytic technologies hold great potential; and integrated capture-conversion technology is expected to transform traditional energy consumption patterns, although material stability remains a challenge.

Keywords: carbon dioxide capture,carbon dioxide conversion,chemical absorption,integrated capture and conversion

1. Introduction

With the increasingly pressing challenge of global warming looming large, how to effectively control and reduce anthropogenic greenhouse gas emissions—particularly carbon dioxide, which accounts for the largest share—has become a focal point of widespread international concern. On 22 September 2020, China made a commitment at the United Nations General Assembly to strive to reach peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Developing economically viable carbon capture and utilisation (CCU) technologies is not only crucial for the implementation of the objectives set out in the Paris Agreement, but also directly impacts the advancement of China's domestic 'dual carbon' strategy, whilst providing robust support for the global energy transition and sustainable development.

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The chemical absorption method, which is currently in widespread use, generally faces significant challenges in practical operation, such as high energy consumption, persistently high costs and limited capture efficiency. Coupled with the numerous technical bottlenecks still present in carbon sequestration, this creates considerable resistance to the overall development of the technology. Therefore, a systematic comparison of existing mainstream technologies and their operational performance, analysed from the perspectives of technical mechanisms, application characteristics, and strengths and weaknesses, is essential to provide more targeted and practical guidance for future research directions and policy formulation.

In the research on carbon dioxide capture technologies, early efforts were largely concentrated on the relatively mature chemical absorption method, with the organic amine solution method being the most typical technical route. Although this method offers good capture efficiency, the energy consumption associated with solvent regeneration is quite high, and long-term operating costs are also substantial. Physical adsorption performs well under high-pressure conditions, but its adsorption capacity declines significantly under low-pressure conditions, and no particularly mature solutions have yet been found for cost control. As for direct air capture, an emerging technological route, current research efforts are primarily focused on the development of high-efficiency adsorbents and the optimisation of low-energy-consumption process flows.

Regarding CO_2 conversion technologies, traditional research has centred on thermocatalysis, which remains the most mature technical route for industrial applications. In recent years, as the cost of renewable energy generation has continued to fall, electrocatalytic and photocatalytic conversion technologies have developed rapidly. These technologies utilise green electricity to drive CO_2 reduction reactions and are regarded by the industry as a development direction with long-term strategic value. Furthermore, biological conversion technologies, owing to their unique environmental benefits, have consistently received significant attention within the scientific research community.

However, judging by the research findings published to date, most relevant literature, both domestic and international, provides detailed reviews and summaries of only a single specific technology, or focuses its analysis on a particular type of scenario; few studies offer a comprehensive comparative analysis and integrated evaluation of multiple technological pathways.It is precisely in light of this research landscape that this paper will undertake a systematic review and comparison of the currently widely applied carbon dioxide capture and conversion technologies, clarifying one by one the basic principles, application characteristics, practical advantages, and existing shortcomings of each technology. At the same time, this paper will also discuss coupled capture and conversion technologies, analysing their development potential and the practical obstacles they face in real-world applications. Finally, by integrating current technological developments with trends in global energy demand, this paper will outline the future direction of carbon dioxide capture and utilisation technologies, aiming to provide valuable insights for both scientific research and engineering applications in this field.

2. Carbon dioxide capture technology

2.1. Pre-combustion capture

2.1.1. Physical adsorption

Physical adsorption is a technical method that can be applied for both pre-combustion and post-combustion capture; however, chemical adsorption offers greater advantages in post-combustion

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scenarios.

Physical adsorption generally employs substances such as water, methanol and activated carbon as adsorbents. Common methods include pressure swing adsorption (PSA) and temperature swing adsorption (TSA), with PSA being the more competitive of the two. The principle works as follows: the feed gas first enters a high-pressure adsorption tower; as carbon dioxide has a larger dipole moment and smaller molecular volume, it is more readily adsorbed and is therefore captured by the adsorbent first. The pressure inside the tower is then reduced to atmospheric pressure or slightly lower, allowing gases with lower adsorption affinity to be vented first, thereby increasing the concentration of carbon dioxide within the tower. Subsequently, a vacuum pump is used to create a negative pressure, desorbing the carbon dioxide from the adsorbent, after which the pressure inside the tower is raised back to operating conditions in preparation for the next adsorption cycle. The advantages of physical adsorption technology are quite evident: overall energy consumption is low, the equipment is resistant to corrosion, and the adsorbent can be reused repeatedly. However, there are several drawbacks: commonly used adsorbents are relatively expensive, and the adsorption capacity decreases significantly when the partial pressure of carbon dioxide is low. Furthermore, water vapour in the flue gas tends to compete with carbon dioxide for adsorption sites, resulting in moisture being adsorbed alongside the CO_2; therefore, the flue gas must undergo thorough pre-treatment before entering the system. At present, research efforts are primarily focused on developing new adsorption materials with high adsorption capacity, high selectivity and lower costs.

2.1.2. Coal gasification combined cycle

Following gasification, coal produces a synthesis gas consisting of carbon monoxide and hydrogen. Through the water-gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$), the carbon monoxide in the system can be converted into carbon dioxide, ultimately yielding a mixture of carbon dioxide and hydrogen. The mixed gas can then be separated using pressure swing adsorption (PSA) technology; this method, which essentially involves physical adsorption, effectively removes carbon dioxide from the mixture. The purified hydrogen can be used directly in power generation equipment such as gas turbines; the entire process is not only flexible but also offers considerable overall operational efficiency. Researchers have employed steady-state modelling to analyse the process of carbon dioxide capture from synthesis gas using low-temperature separation methods within integrated gasification combined cycle systems [1].

2.2. Post-combustion capture

2.2.1. Chemical adsorption

The operational process of the chemical absorption method typically consists of two core stages: absorption and regeneration. First, the carbon-containing mixed gas undergoes pre-treatment steps such as drying, desulphurisation, and dust removal; once impurities have been removed, it enters the absorption tower for counter-current mass transfer with the absorption liquid. Once the absorbent solution is fully saturated and has adsorbed the carbon dioxide, it is transferred to the desorption tower. At this stage, the carbon dioxide is released from the absorbent solution through high-temperature heating, thereby completing the regeneration process [2]. Taking organic amines as an example, within the absorption tower, the organic amine absorbs the pre-treated carbon dioxide flue gas ($CO_2 + 2RNH_2 \rightarrow RNHCOO^- + RNH_3^+$), after which it flows out of the absorption tower and into the desorption tower. The organic amine solution that has absorbed carbon dioxide is referred to

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as the rich solution; it flows downwards from the top of the desorption tower whilst coming into contact with counter-flowing heated steam. Heating causes the above absorption reaction to proceed in the reverse direction, releasing high-purity carbon dioxide and converting the amine solution, from which the carbon dioxide has been removed, back into a lean solution. After cooling in a heat exchanger, it returns to the absorption tower to await recirculation. The organic amine absorption method is currently the most mature and widely applied dominant technology among post-combustion capture techniques, offering the advantages of high absorption capacity and selectivity. However, the high energy consumption associated with the regeneration process represents a fundamental technical and economic bottleneck. To overcome this limitation, efforts are currently underway to optimise performance by flexibly adjusting the concentration and ratio of the amine solution.

2.2.2. Membrane separation

This is a highly promising separation method, which involves the design of a material that utilises differences in the solubility and diffusion rates of various gas components within a gas separation membrane to achieve selective separation. This method is often divided into three stages: adsorption, diffusion and desorption. During the adsorption stage, molecules from the mixed gas are dissolved onto the membrane surface; in the second diffusion stage, the gas components already dissolved in the membrane move from high pressure to low pressure within the membrane; in the third desorption stage, the gas molecules reach the low-pressure side and are released in gaseous form.

The primary energy consumption of this method lies in gas compression; compared to other methods, it has lower energy consumption and is environmentally friendly.

Current innovation is primarily focused on membrane materials; existing research utilises bacterial cellulose (BC) derived from coconut water wastewater and cellulose acetate (CA) membranes to produce a bio-based membrane capable of enhancing CO_2 separation efficiency. In a two-stage configuration, with a cellulose acetate membrane thickness of 0.04 mm and an operating pressure of 0.28 MPa, the selectivity of CO_2 in methane reached 35.52, significantly outperforming the single-stage system (19.72) , representing an improvement of approximately 80%. This research has not only made significant advances in CO_2 membrane separation but has also made outstanding contributions to the utilisation of agricultural waste [3].

2.3. Direct air capture

Direct air capture, as the name suggests, involves capturing CO_2 directly from the ambient atmosphere. Its advantages include location independence and the theoretical potential to achieve zero emissions. However, due to the extremely low concentration and partial pressure of CO_2 in the atmosphere, this is extremely difficult to achieve.

Lacarra-Etxarri and colleagues have now synthesised polyethylenimine-functionalised SBA-15 mesoporous silica (PEI/SBA-15) for solid-state adsorption in a simulated environment with air composition closely resembling that of the real atmosphere [4]. Through optimisation, they have successfully achieved a significant increase in CO_2 conversion rate and methane selectivity.

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3. Technologies for the conversion and utilisation of carbon dioxide

3.1. Thermocatalytic conversion

Using an external heat source and hydrogen, the efficient hydrogenation of CO_2 is achieved on the surface of a catalyst. The reaction exhibits greater reactivity than photocatalysis and electrocatalysis. Depending on the products, the reaction can be categorised as follows: the production of methanol or methane, or conversion to CO and H_2O.

In methanol production, pressure and temperature influence the reaction; ideally, the reaction pressure should be increased, with the reaction occurring at 200°C. Regarding catalysts, metal oxide systems are generally employed, particularly copper-based catalysts [5]. Methanation, $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$, is a strongly exothermic reaction that can be carried out at 200–400°C. Nickel-based catalysts are frequently employed due to their low cost and high activity.

Reverse water-gas shift reaction: $CO_2 + H_2 \rightarrow CO + H_2$, which is an endothermic reaction requiring high temperatures (>700 K) to achieve high conversion rates; current research focuses on maintaining catalyst activity under such high-temperature conditions.

Although thermal catalytic conversion is generally well-established, it is highly dependent on green hydrogen supply and is constrained by thermodynamic equilibrium.

3.2. Electrocatalytic conversion

By applying an external electric field to drive electron transfer at the catalyst cathode, electrical energy is converted into chemical energy, thereby enabling CO_2 conversion. In a system comprising a cathode, an anode and an electrolyte, the synergistic transfer of electrons and protons leads to the cleavage of the C=O bond, forming intermediates such as COOH and CO, which are subsequently converted into various products via hydrogenation or carbon–carbon coupling.

Zhang Mengmeng categorises the electrocatalysts currently used for CO_2-to-CO conversion into three main types: noble metals such as Ag, single-atom catalysts such as Ni-N-C, and molecular catalysts, and provides an analysis and summary of these [6].

3.3. Photocatalytic conversion

The principle behind this method is to utilise solar energy directly to drive CO_2 reduction and water oxidation, mimicking the process of photosynthesis in nature; however, due to complex reaction mechanisms and issues with catalyst stability, it remains a long way from industrial application.

Regarding how to enhance photocatalytic performance, graphitic carbon nitride (g-C_3N_4) has become a research focus due to its low cost and good response to visible light; however, it suffers from a small specific surface area, rapid electron recombination and weak CO_2 adsorption. Mekkat et al. addressed these shortcomings by combining nitrogen-doped porous carbon with g-C_3N_4 [7].

3.4. Bioconversion

Bioconversion is a method of utilising CO_2 through biological carbon sequestration [8].

For example, it primarily utilises the photosynthesis of microalgae to convert CO_2 into biomass energy; a key feature is its high carbon sequestration efficiency, with approximately 0.55 tonnes of microalgae produced for every 1 tonne of CO_2 sequestered [8]. This process can yield biodiesel, methane, syngas and other products.

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Although the bioconversion method is environmentally friendly, its inevitable limitations include a slow process and a large land footprint.

4. Integrated conversion and capture

4.1. In-situ coupled co₂capture and conversion technology

The key challenge of this technology lies in developing a material capable of performing two functions: efficiently capturing carbon dioxide and directly converting it into other substances. Such materials typically consist of three components: the capture agent, which is an alkali metal oxide substrate (calcium oxide or sodium oxide); the transition metal active sites, which are responsible for the catalytic reaction; and the support framework, which serves to immobilise these components [2]. In practice, this technology involves two steps. Firstly, industrial flue gas enters the reactor, where carbon dioxide reacts rapidly with the adsorbent and is adsorbed. The reaction equation for this process is $CaO(s) + CO_2(g) \rightarrow CaCO_3(s) + heat$. The flue gas is then purified and discharged via the outlet; once the adsorbent reaches saturation, the capture stage is complete. The second step is described below. In this step, reducing gases such as hydrogen or methane are introduced into the reactor. These gases react with the carbon dioxide accumulated on the surface of the adsorbent and at the catalyst sites, for example: $CO_2(g) + CH_4(g) \rightarrow 2CO(g) + 2H_2(g)$. It is worth noting that whilst the conversion reaction is taking place, the adsorbent is also regenerated, restoring its adsorption capacity, and the system simultaneously produces synthesis gas. Once the regeneration process is complete, the reactor switches back to adsorption mode, and the cycle repeats.

Compared with other methods, this technology simplifies equipment and operational procedures, improves energy efficiency, and paves the way for a more direct approach to subsequent product preparation. However, the challenges faced lie in whether the structure of this bifunctional material can withstand hundreds or thousands of cycles, and how long its catalytic activity can be maintained. Unless these technical bottlenecks can be overcome, large-scale application will be difficult to achieve.

4.2. Coupled CO_2 capture and conversion technologies versus series-coupled CO_2 capture and conversion technologies

Carbon dioxide is captured and converted using displacement coupling technology, which works like the old chemical absorption technique except that it doesn't require a desorption tower to let go of carbon dioxide. Displacement-coupling swaps out the desorption tower entirely for a converter instead; this means any carbon dioxide managed to be captured gets transformed into different things on site.

Question's second method is series connection, which uses physical equipment to make the connection between capture and conversion. but it's just an experiment and very far from being able to go into commercial production Advantage is flexible, the modules for capturing and converting can be combined as needed: However,this difficulty is also due to this kind of connecting device which has complicated designs and constructions making them hard to promote.

5. Conclusion

This paper provides a systematic review and comparison of the current mainstream CO_2 capture and conversion technologies. Each capture technology has its own advantages and disadvantages; in

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practical application, this depends on the specific context—for example, direct air capture can achieve negative emissions but is costly. As for conversion technologies, thermocatalysis has already been industrialised, whilst areas such as electrocatalysis and photocatalysis are still working to overcome key bottlenecks. As for integrated capture-conversion systems, whilst they hold significant potential for energy conservation and carbon reduction, they still face considerable challenges in areas such as materials and industrialisation. The findings of this study can provide technical guidance for relevant research institutions, enterprises, and policymakers. Against the backdrop of the 'dual carbon' goals, accelerating innovation in CO_2 capture and conversion technologies is of great significance for driving the transformation of the energy structure and achieving low-carbon development.

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