Research progress in CO_2 capture technology

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Abstract. The creation of effective CO_2 capture systems is a critical undertaking since carbon dioxide (CO_2) emissions have a significant impact on global climate change. Carbon dioxide capture technology is an important environmental protection technology that can effectively reduce greenhouse gas emissions. In this article, the technical principles of carbon capture are introduced, along with a thorough explanation of the benefits and drawbacks of each carbon capture technology. The article also discusses the potential future directions for development of technologies. The use of activated carbon, organic amine water, amino acid and other technologies to capture carbon dioxide has been put into application. To achieve higher treatment efficiency and efficiency, new materials such as metal-organic frameworks (MOFs), biological methods, and membrane separation method are also being further explored. Overall, carbon capture technology is a technology with broad development prospects and application prospects. Although most of these technologies are still in the laboratory stage and only a small portion are in operation, they will shine brightly in the future and become a top priority in affecting climate change of Earth.

Keywords: Carbon dioxide, carbon capture, adsorption, membrane, algae.

1. Introduction

Currently, the greenhouse effect and global warming are attributed primarily to human-caused excessive emissions of greenhouse emissions like CO_2 [1-3]. Global warming has had a profound impact on human society and natural ecosystems, including an increase in extreme climate events, rising sea levels, and ecosystem damage [1, 2]. In response, Rockström et al. proposed a planetary boundary framework, attempting to determine the processes and related thresholds of the Earth system. If these thresholds are exceeded, the Earth may experience unacceptable environmental changes [1]. A common goal was established to control global temperature rise within 2 ^oC in this century and strive to limit it to 1.5 ^oC as early as the Paris Agreement, which was passed in 2015. It is evident that cutting greenhouse gas emissions, particularly carbon dioxide emissions, has become a top priority for the entire world. According to Wilberforce et al., trapping carbon dioxide from industrial industries is essential for lowering atmospheric carbon emissions [4]. The total emissions from the industrial sector will be reduced by around one-fifth by using carbon capture and storage technology [4]. Therefore, carbon capture, as an important technology that can reduce carbon dioxide emissions, is believed to be effective in addressing climate change.

The idea behind carbon capture is to physically or chemically capture and utilise atmospheric carbon dioxide to lessen greenhouse gas emissions. There are currently three main research directions for carbon capture technologies. The first type is CO_2 absorption technology, which uses solutions or adsorbents to absorb carbon dioxide. Commonly used solutions and adsorbents include alkaline oxides, amino acids, activated carbon, metal-organic framework materials, etc. The second type is biological capture technology, which utilizes organisms such as algae for photosynthesis and converts carbon dioxide into organic matter. The third type is membrane separation technology, which uses special membrane materials to separate carbon dioxide through permeation and selective adsorption. Commonly used membrane materials include polymer membranes.

This article mainly introduces several mainstream carbon dioxide capture technologies, elaborates on the current status of their progress aims to collect information on the development and challenges of CO_2 capture technology, to explore its importance and potential opportunities.

2. Carbon Dioxide Capture Technology

Carbon capture, utilization, and storage (CCUS) is one of the important means to address climate change, with adsorption technology being a crucial link. Adsorption technology can be divided into physical adsorption and chemical adsorption based on its different properties.

2.1. Physical adsorption

The principle of physical adsorption of carbon dioxide is mainly achieved through intermolecular van der Waals forces. The porosity structure and surface characteristics of an adsorbent have an impact on its ability to absorb carbon dioxide during the physical adhesion process. In general, adsorbents with better porosity and larger specific surface area have stronger adsorption capacity [5]. In addition, the chemical properties of the adsorbent surface can also affect the adsorption effect of carbon dioxide such as charge, and functional groups. By optimizing the structure and properties of the adsorbent, the efficiency of physical adsorption of carbon dioxide can be improved, thereby achieving more effective carbon capture. Typical physical adsorption methods often use activated carbon or metal-organic frameworks (MOFs) to adsorb CO_2.

2.1.1. Activated carbon

In the early stages, people used zeolite to adsorb CO_2, but due to its sensitivity to H_2O adsorption, the adsorption efficiency of zeolite for carbon dioxide decreased and the adsorption efficiency was not ideal [3]. Later, people began to study activated carbon. Li et al. created porous carbon spheres (PCSs) that have elevated CO_2 absorption capability using basic materials generated from starch without the use of a template [6]. A PCS with a regular spherical form, an enormous area (3350 m^2/g), and a high pore capacity (1.75 mL/g) is rather remarkable for physiologically activated carbon [6]. Due to its structural characteristics, activated carbon's intake of CO_2 (21.2 mmol/g, 298 K) at 19.74 atm is one of the highest documented values yet [6]. The fact that the adsorption of the above gases on the material is reversible further shows that PCS may be readily replenished utilizing pressure swing adsorption. As a result, the produced PCS is a solid option for storing a variety of gases connected to energy [6]. In recent years, Chiang et al. reported a new technology for carbon dioxide adsorption using activated carbon fibers (ACFs) [5]. This technology activates activated carbon fibers through KOH to generate and increase pore volume on their surface [5]. The outcomes revealed that activated carbon fibers treated with KOH have a large pore volume, a big specific circumference of 1565 m^2/g, and a CO_2 absorption rate of 2.74 mmol/g at 1 atm and 298K [5]. KOH activation, however, makes it simpler for nitrogen atoms to flee from the surface of ACFs, which eventually affects the capacity of carbon dioxide to be captured [5]. Therefore, this technology continues to explore the optimal ACFs activated by KOH [5]. However, this report undoubtedly provides new ideas for carbon capture adsorption technology [5].

2.1.2. Metal-organic frameworks

An example of a porous substance is a metal-organic framework (MOF), which is created by coordination bonds between metal ions and organic ligands. They are thought to offer significant promise for gas adsorption because of their large specific surface area, adaptable structure, and chemical properties. Compared to zeolite and activated carbon, MOFs always exhibit higher pore volume and surface area, with some having an internal surface area larger than7000 m^2/g, which is by far the largest [7]. Therefore, Trickett et al. believe that MOFs have the potential to meet the needs of various aspects of the CO_2 cycle and provide a cylinder filled with MOF-177 as evidence [8]. This cylinder has a Brunauer Emmett Teller (BET) area of the surface of 4500 m2/g and can absorb 9 times more carbon dioxide than a cylinder without MOF [8]. In terms of maximum working capacity, MOFs with linkage unaltered metal sites, such as CuBTTri and Mg-MOF-74, perform better than zeolites and carbon electrodes [8]. Li et al. discussed the feasibility of MOF materials adsorbing CO_2 based on the background of adsorbent separation, and studied the CO_2 absorption efficiency of Mg-MOF-74 under low-pressure drying conditions (5.28mmol/g at 313K and 0.15atm) [9]. It was found

that its effective absorption rate mainly comes from high-density open metal sites (OMS) [9]. Yu et al. conducted in-depth research and reported that the properties and positions of functional groups in MOFs can affect CO_2 adsorption capacity [7]. A typical example is the zeolite imidazole ester backbone (ZIFs). When there are asymmetrically substituted imidazole ester (Im) ligands, such as NO_2/OH and Cl/OH combinations, ZIFs are considered the most suitable for CO_2 adsorption [7]. However, the research on MOF materials is still in its preliminary stage and requires continuous optimization and research to achieve further applications.

2.2. Chemical adsorption

The principle of chemical adsorption of carbon dioxide is different from physical adsorption, as it is achieved through a chemical reaction between the adsorbent and carbon dioxide molecules. In this process, the chemical groups on the surface of the adsorbent react with carbon dioxide molecules to form chemical bonds, which fix the carbon dioxide molecules on the adsorbent. Common chemical adsorbents include amine compounds, amino acids, and so on [10-12]. Compared with physical adsorption, chemical adsorption has higher selectivity and stability but usually requires certain reaction conditions and energy input. Therefore, chemical adsorption also has certain application prospects in the field of carbon capture.

2.2.1. Organic amine

The common chemical adsorption on the current market is amine washing, which is mainly achieved through an organic amine aqueous solution, with monoethylamine (MEA) as the main solvent. However, the use of diethanolamine, methyl diethanolamine, steric hindrance amine, and olefin amine can also be used to enrich carbon dioxide [10]. It is mainly used in flue gas, but it has the disadvantage of high corrosiveness [3]. The reason for choosing MEA for carbon dioxide adsorption is because it has a fast reaction speed with CO_2, reasonable absorption capacity, and relatively low cost. In recent years, Yin et al. have studied and tested the characteristics of MEA-based organic solvents in absorbing carbon dioxide, and it is proposed that adding organic solvents can reform the temperature and consumption, which is beneficial for improving adsorption efficiency, especially by adding ethanol [10]. The adsorption temperature at which MEA/ethanol is 20 ^oC lower than that of MEA/water, whereas the average desorption rate is greater in the initial 20 minutes and the regeneration rate is higher by 5.52% [10]. When the CO_2 concentration of the absorbent is 0.07 and 0.23mol CO_2/mol MEA, the renewable energy requirements for MEA/ethanol absorbers are 80% and 48.8% lower than those for MEA/water, respectively (Fig.1) [10]. Yin et al. also proposed that the future development direction is to study faster desorption methods, as desorption can be completed faster after reducing energy consumption and equipment size [10].

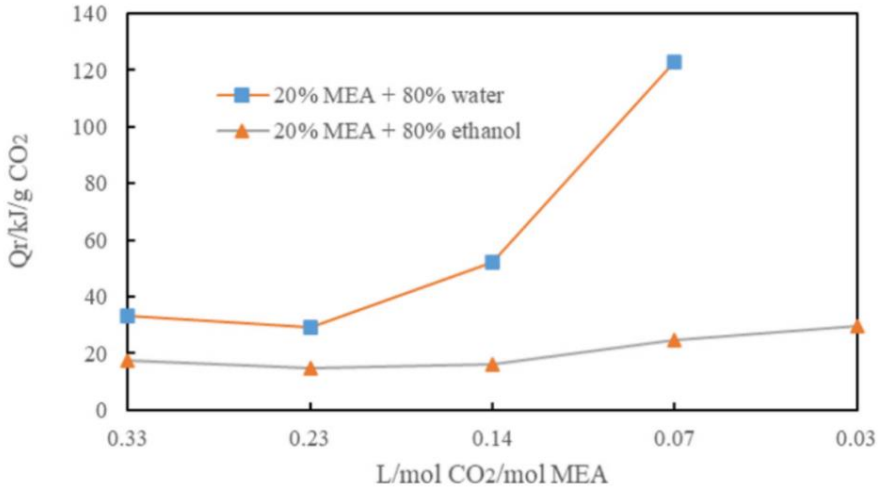


Figure 1. CO_2 loading capacity of different MEA/water and MEA/ethanol absorbents [10].

2.2.2. Amino acid

An adsorbent using 2,6-Pyridine bis (iminoguanidine) (PyBIG) has been previously developed by Seipp et al. It can absorb CO_2 from the surrounding air and attach it to solid carbonates through guanidine hydrogen bonds [11]. Based on this, Custelbean et al. reported a technique of using amino acid aqueous solutions (such as glycine potassium and sarcosine potassium) to absorb CO_2, and then regenerating amino acids using solid m-phenylenediamine guanidine (m-BBIG) reaction [12]. The main form of CO_2 in the two adsorbents (glycine potassium and sarcosine potassium) is bicarbonate, accounting for 69% and 82% of the total absorption of glycine and sarcosine, respectively. After 24 hours, the highest CO_2 loadings for glycine potassium and sarcosine potassium were 0.80 and 0.73 mol CO_2/mol amino acids, respectively. The two adsorbents were then regenerated by adding solid m-BBIG, and the regeneration reaction was quite quick, reaching equilibrium in just over an hour and finishing 90% of the process in just over 20 minutes [12]. In comparison to PyBIG, the anticipated cost of m-BBIG is $2/kg, which is a 1000-fold savings [12]. However, the adsorption of carbon dioxide by amino acids only exists on a laboratory scale and further detailed testing is needed.

2.2.3. Mixed system adsorption

When physical adsorption is combined with chemical adsorption, it can also improve the capture of carbon dioxide. For example, Boruban et al. reported a technology that uses activated carbon loaded CuO nanoparticles to adsorb carbon dioxide [13]. This technique, which combines both chemical and physical adsorption to form a combined mixture of activated charcoal and CuO, evenly distributes CuO nanoparticles over the surface of activation carbon [13]. The physical, chemical, and biological adsorption of the carbon dioxide by CuO and activated carbon increases the capacity for adsorption of carbon dioxide [13]. The capacity of activated carbon to adsorb CO_2 increases by around 70% when CuO nanoparticles are added to it under the recommended conditions of 1 atm and 298 K [13]. If only the amount of CO_2 physically adsorbed is considered, TGA can be significantly increased by 68%. When only the amount of CO2 chemically adsorbed is considered, the improvement can even be more significant by 76% [13].

2.3. Biological capture

Biocapture technology is the technique of turning atmospheric carbon dioxide into organic matter by using the metabolic processes of living things like bacteria and algae. Algae have been reported by Tsai et al. to have the highest rate of CO_2 absorption and utilization of CO_2 efficiency, which other plants cannot match. Non-woody plants have almost no help in CO_2 capture, while the CO_2 absorption capacity of woody crops is estimated to be 18.1% of that of algae [14]. This demonstrates how crucial role algae play in absorbing and consuming CO_2 is, demonstrating the enormous potential of algae for carbon capture [14]. Under optimal conditions, using algae to capture CO_2 can achieve efficiencies of up to 80% to 99% [15].

Microalgae have been used to trap carbon, according to Alami et al [15]. Microalgae can accumulate high-fat content, with an oil content of up to 80% depending on the species, making it a good raw material for creating biodiesel in contrast to giant algae that have low fat content [15]. Due to their great photosynthetic efficiency, microalgae consume a lot of CO_{2s} and grow quickly. They are able to survive a variety of environmental conditions and can quadruple their biomass every 4-6 hours [15]. Studies have shown that freshwater algae species seem to have higher CO2 absorption rates than marine species [14, 15]. Chlorella can achieve a maximum biomass concentration of 2.05g/L at a CO_2 concentration of 10% [15]. When compared to normal settings (atmospheric CO_2 concentration), Scenedesmus can even survive at 100% CO_2 concentration, and its plant biomass content can increase to 3.65g/L within a month [15].

2.4. Membrane separation

Carbon capture, utilization, and storage (CCUS) technology utilizes membrane separation as a key technique. This technology utilizes the selective separation characteristics of membrane materials to

capture and separate carbon dioxide from the gas flow. The primary advantages of membrane separation are its compactness, modularity, ease of construction by prying, use in remote areas (such as offshore), versatility in upkeep and operation, and, in the majority of instances, reduced capital costs and less energy consumption [16]. Materials such as polymers, graphene, and MOFs are always used for membrane fabrication.

A water membrane for separating carbon dioxide has been proposed by Jung et al (Fig. 2). By injecting pressurized air or a mixture of gases into the area above the water barrier in the separation tank, gas is separated off the bottom section of the water barrier in contact with the rigid support membrane [17]. Because temperature, pH, and water salinity hardly affect the separation of CO_2, plain water can be effectively used for water membranes at room temperature [17]. As membrane thickness is reduced, the water membrane's permeability and selectivity will rise [17]. The water membrane is successful at separating or purifying these gases because it has a CO_2 selectivity of about 86, 67, and 74, respectively, compared to N_2, CH_4, and H_2 [17].

In recent years, with the gradual popularity of graphene, people have conducted research on it in many fields, and graphene films have also emerged. Singh et al. introduced the performance of numerous graphene membranes in their report, all of which have a common feature of high CO_2 selectivity and permeability [16]. Among them, the highest nanoporous graphene has CO_2 selectivity for CH_4 and N_2 up to 100 and 300 at 300K, and permeability up to 106 GPU and 105 GPU, which are much higher than membranes made of other materials [16]. However, currently, due to the lack of mechanical stability, nanoporous graphene can damage the functionality of membranes in practice [16]. In addition, controlling the size and distribution of pore formation is a challenge. Therefore, the main research directions for graphene films in the future will focus on solving these problems.

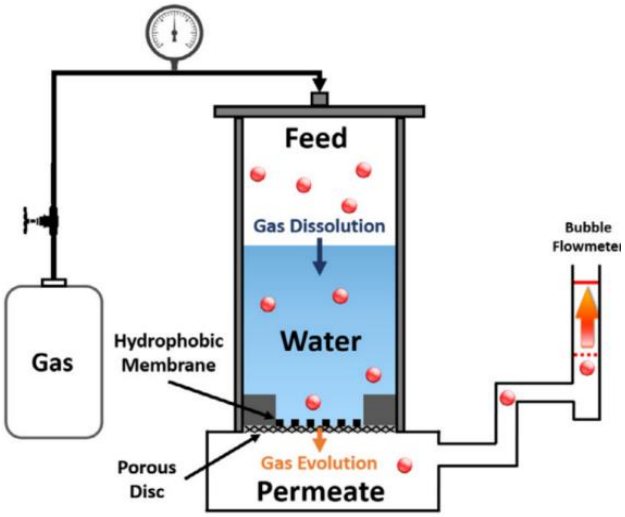


Figure 2. Flow Chart of Water Membrane Gas Separation [17].

3. Summary

Carbon capture technology is a key technology for reducing carbon emission which will greatly improve industrial and energy efficiency, reduce dependence on natural resources, weaken the greenhouse effect, and alleviate global climate change, which has made important contributions to environmental protection and sustainable development. This paper offers a review of current developments in CO_2 capture technology research. By understanding the advantages, disadvantages, and applicability of various carbon dioxide capture technologies, it can be seen that these technologies have high efficiency and sustainability in capturing carbon dioxide. The adsorption method has high efficiency, safety, and high applicability, but it has a high cost in the production of current new adsorbents. Microalgae in biological treatment methods have multifunctional properties and can be used to produce biomass fuels, but their growth stability and lifespan are limited, and their efficiency is low. The membrane separation method has high selectivity and simple operation, so its treatment

efficiency is high. However, it requires high energy consumption and is difficult to put into large-scale production. In addition, this article also demonstrates the future development direction of carbon dioxide capture technology. Adsorption methods need to continue to explore how to increase the specific surface area or the renewable performance of adsorbents. Membrane treatment methods need to improve membrane selectivity while continuing to reduce energy consumption. Biological treatment methods need to explore and maintain the stability of organisms. In the future, with the continuous progress of technology and the reduction of costs, carbon dioxide capture technology will be widely applied in various fields. With industrial production applications, carbon capture technology can reduce industrial emissions from power plants, steel plants, and cement plants, which will help mitigate climate change. With energy production, carbon capture technology can improve oil collection efficiency, produce synthetic fuels, and improve energy utilization efficiency ultimately. With biological production, carbon capture technology can generate biomass energy, which helps achieve sustainable development. The goals of the Paris Agreement will undoubtedly be met thanks to the widespread use of carbon capture technologies in the future.

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