

# Technology and advancement in carbon capture based on post-combustion

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**Abstract.** Carbon capture technologies are urgently required to reduce carbon emissions and reach the target of net-zero emissions for all countries because the significant amount of CO<sub>2</sub> emissions brought on by human activities has contributed to many environmental problems, including global warming and extreme climate. In this paper, the fundamentals of the three primary post-combustion CO<sub>2</sub> capture methods—absorption separation, adsorption separation, and membrane separation—are discussed. Additionally, the most recent advancements in these technologies are discussed. The paper also compares the benefits and drawbacks of each of the three technologies, emphasizing a number of difficulties and challenges currently faced by each of the three carbon capture technologies, including high cost, high energy consumption, low stability and low selectivity. Finally, the development prospects and research priorities of the three carbon capture methods are analyzed, and it is indicated that the primary paths for the advancement of carbon capture technologies in the future will be cost reduction and rapid commercialization and industrialization.

## 1 Introduction

With the unprecedented increase in the scale of global industrial and human activities, carbon dioxide emissions are also rising rapidly, and the resulting ecological damage is a serious problem. According to statistics, global CO<sub>2</sub> emissions reach 34.9 Gt in 2021, rebounding after a decline in 2020 [1]. China, as a rapidly developing country, emitted  $108.67 \times 10^8$  t of CO<sub>2</sub> in 2021, accounting for approximately 31.10% of global carbon emissions according to the BP World Energy Statistics Yearbook 2022 [2]. The main source of atmospheric CO<sub>2</sub> is human activity, where the burning of fossil fuels for power generation, industrial production and transport has caused a sharp rise in atmospheric CO<sub>2</sub> concentrations, while agricultural activities and deforestation have also contributed to the rise in CO<sub>2</sub> concentrations. According to the latest statistics given in the 6th Intergovernmental Climate Assessment Report (IPCC-AR6), if CO<sub>2</sub> emissions are not controlled by countries around the world, by the end of the 21st century, the radiative flux from the atmosphere to the surface will increase by about  $8.5 \text{ W} \cdot \text{m}^{-2}$ , corresponding to a global temperature rise of almost 4.7 °C. If governments take appropriate measures to control CO<sub>2</sub> emissions, global temperatures will rise by around 2.7 °C. If CO<sub>2</sub> emissions are strictly controlled, temperatures will rise by about 1.5 °C [3]. In 2016, the Paris Agreement, signed by governments in Paris, agreed to limit global warming to 1.5 to 2 °C by the end of the century. As a result, governments need to implement stringent carbon reduction measures to ensure they meet their targets. Most countries have set net-zero emission

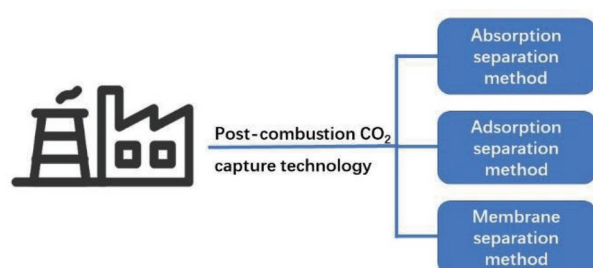
targets, with China proposing in September 2020 to work towards achieving carbon neutrality by 2060. Carbon Capture and Storage (CCS) technology will provide a huge incentive for China and other countries and regions around the world to meet their carbon targets.

CCS technology is critical for mitigating climate change, reaching net-zero goals, and safeguarding the human living environment. CCS technology not only achieves net-zero emissions from and promotes deep emission reduction in difficult industries such as cement and steel, but the flexibility of the power system will also be greatly enhanced under the carbon constraint. In addition, CCS technology is important for ensuring a secure and stable supply of electricity and offsetting emissions of CO<sub>2</sub>, which is difficult to reduce. The Intergovernmental Panel on Climate Change (IPCC) has analyzed the worldwide potential of CCS to cut emissions, and if global warming is to be contained to 1.5 °C by 2100, CCS will need to reduce carbon emissions by a total of  $5.5 \times 10^{11}$  to  $1.017 \times 10^{12}$  t CO<sub>2</sub> [4]. Under the carbon neutrality target, China will use CCS to capture  $21.6 \times 10^9$  t CO<sub>2</sub> [5]. CCS technology will be a critical element in China's measures in order to meet carbon peaking and carbon neutrality ambitions.

Currently, carbon capture technologies can be classified into pre-combustion capture, post-combustion capture, oxygen-fuel combustion and air capture according to the sequence of carbon source capture and combustion processes. On an industrial scale, post-combustion CO<sub>2</sub> capture is the most widely used carbon capture technology. There are a large number of carbon dioxide emissions in industry, and most of the gases

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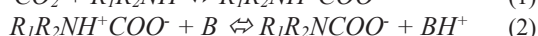
emitted are combinations of gases containing carbon dioxide, and the concentrations of carbon dioxide in the resulting emissions vary. It is difficult to capture all the carbon dioxide in industry by a single carbon capture method, and it is often necessary to use different carbon capture technologies for different combinations of gases, or to couple multiple carbon capture technologies to achieve a technically reliable and economically viable goal. As shown in Fig. 1, the main carbon dioxide capture technologies are absorption separation, adsorption separation and membrane separation. Based on this, this paper mainly compares and summarizes the research progress of the above three carbon capture technologies, analyses the advantages and shortcomings of the three technologies, and proposes possible future research priorities and application prospects.



**Fig.1.** Three main carbon capture technologies (Picture credit: Original)

## 2 Absorption separation method

The absorption separation method of separating CO<sub>2</sub> by liquid absorbent to separate the gas mixture is widely used in the chemical industry such as petroleum and power plants. The principle of absorption separation method is to use liquid phase solution as the absorbent, using alkaline absorbent and CO<sub>2</sub> acid-base neutralization reaction to form unstable salts, and through the reverse decomposition of salts to achieve solution regeneration, so as to achieve the purpose of separating the CO<sub>2</sub> in the gas mixture. From the perspective of the principle, absorption separation method can be divided into physical and chemical method. The most commonly used method of post-combustion carbon capture technology is the liquid ammonia absorption separation method of the chemical absorption separation method. Liquid ammonia absorption and separation is the most mature and the only carbon capture technology that can be used on a large commercial scale currently. In general, the absorption mechanism of carbon dioxide varies depending on the type of liquid ammonia, and the absorption mechanism is mainly divided into amphoteric and alkali-catalyzed mechanisms. The chemical reaction equations are as follows



The overall reaction equation is as follows



Monoethanolamine (MEA), one of the most common liquid ammonia absorbents, is currently applied as a standard chemical absorbent in order to evaluate and compare the performance of various carbon capture technologies. However, the MEA absorption and separation method has drawbacks, such as high upfront investment costs and operational energy consumption due to the high mixed flue gas flow rate and low partial pressure of carbon dioxide. Several scientists have developed new methods for capturing carbon dioxide via absorption separation in recent years, resulting in much higher carbon dioxide absorption efficiency.

### 2.1 Two-phase amine absorbers

After CO<sub>2</sub> absorption, two-phase amine absorbers form two phases, CO<sub>2</sub>-rich and CO<sub>2</sub>-poor phases. The latter is typically found in the upper layer, where the main component is a few unreacted active amines, whereas the rich phase is typically found in the lower layer, which is the CO<sub>2</sub>-enriched zone. In comparison to the traditional chemical absorption and separation process for CO<sub>2</sub> absorption, the two-phase amine CO<sub>2</sub> absorption process consumes less heat during regeneration, lowering energy consumption costs. ZHOU et al. developed a novel biphasic solvent consisted of a polyamine (diethylenetriamine, DETA) and a tertiary amine (pentamethyldiethylenetriamine, PMDETA) and investigated the two-phase PMDETA/DETA absorber with different molar concentration ratios. He found that the solution was divided into two phases, aqueous and organic, after absorbing CO<sub>2</sub>, and the addition of 2-amino-2methyl-1-propanol (AMP) to the system could effectively improve the absorption performance of PMDETA/DETA. The amount of energy that must be used in order for this absorber to undergo regeneration was estimated to be around 1.83 GJ·t<sup>-1</sup>CO<sub>2</sub> [6]. GAO et al. developed a new two-phase amine absorber consisting of triethylenetetramine (TETA), AMP and N-methylformamide (NMF). During the process of absorption, CO<sub>2</sub> is combined with TETA to form TETAH<sup>+</sup>CO<sub>2</sub><sup>-</sup>/TETACO<sub>2</sub><sup>-</sup> for the first time, and then with AMP to form AMPCO<sub>2</sub><sup>-</sup>. TETA-carbamate significantly reduced the potency of H bonds and Van der Waals interaction between AMPH<sup>+</sup> and AMPCO<sub>2</sub><sup>-</sup>, enhancing the solubility of the intermediates and fulfilling the goal of reducing the reaction's inherent phase separation. It also solves the unchanged liquid-liquid two-phase separation and the plugging problems associated with solid-liquid mixtures [7].

### 2.2 Mixed amine absorbers

Conventional single-component absorbents struggle to simultaneously satisfy the requirements of rapid absorption rate, high absorption capacity, and low reaction heat. Therefore, the overall absorption efficiency can be

improved by mixing a lower-performance absorbent with a higher-performance absorbent. WANG et al. used a mixture of N,N-dimethylcyclohexylamine (DMCA) and N-methylcyclohexylamine (MCA) as an amine absorber, which had an absorption capacity of 0.875-0.985 mol CO<sub>2</sub>/mol amine and a regenerated energy consumption of about 2.20 GJ/t CO<sub>2</sub> [8]. ZHANG et al. mixed diethylenetriamine (DETA) and triethanolamine (TEA) as absorbents, and the saturated CO<sub>2</sub> absorption capacity of this absorber was 3.71 mol/L solvent, and the maximum desorption rate was 1.94 mmol/(L·min), with desorption energy consumption of 1.5 mmol/(min·min) and a desorption energy consumption of 160 kJ/mol, both of which possess a high CO<sub>2</sub> absorption capability as well as a rapid rate of absorption and an efficient capture regeneration capacity [9].

### 2.3 Ionic liquid

Ionic liquid is a type of organic salt that has excellent design features. Because of their low vapor pressure, superior thermal stability, ease of separation and recovery, as well as non-flammability, ionic liquid is a potential novel CO<sub>2</sub> absorber. A novel porous ionic liquid based on the ZIF-8 metal-organic framework (MOF) was created by AVILA et al, which absorbs 103% more CO<sub>2</sub> per unit mass of porous ionic liquid than pristine MOF at 100 kPa/303 K, greatly enhancing CO<sub>2</sub> absorption at low pressure [10].

### 3 Adsorption separation method

Carbon capture by adsorption is a technique for capturing and separating industrially generated carbon dioxide from a gas mixture based on the affinity of the adsorbent material for carbon dioxide. Depending on the principle of adsorption, adsorption separation methods can be divided into physical adsorption and chemisorption. Physical adsorption is the adsorption of gases onto the adsorbent by van der Waals forces, which has the advantages of low heat of adsorption and fast adsorption rate. The heat of adsorption is greater and the rate of adsorption is slower.

ANYANWU et al. synthesized a molecular sieve for extended SBA-15 with pore sizes of 12.3 nm (7.87 nm for normal SBA-15). By amine grafting diethylenetriaminopropyltrimethoxysilane on the enlarged and conventional SBA-15, respectively, the impact of the enlarged molecular sieve's pore structure on CO<sub>2</sub> adsorption was examined. The outcomes demonstrated that the enlarged SBA-15's larger pores enhanced CO<sub>2</sub> adsorption performance and reduced mass transfer resistance, allowing for a maximum adsorption capacity of 3.27 mmol/g [11]. The properties of the inert salt allowed oxygen to enter while simultaneously preventing nitrogen loss, which led to a high nitrogen and oxygen content in the porous carbon that was created. At low pressures, the adsorbent was capable of chemisorption of CO<sub>2</sub>, and when the pressure was increased, CO<sub>2</sub> eventually filled the pores to capacity and proved the ability to engage in multilayer adsorption. This study proposes an effective method for doping materials

with nitrogen and oxygen heteroatoms, as well as a unique concept for enhancing the surface chemical structure of carbon-based materials for optimal performance [12]. WANG et al. came up with a unique technique for post-combustion partial CO<sub>2</sub> capture that included complementing adsorption and absorption processes to reduce energy losses in the adsorption part, where the flue gas CO<sub>2</sub> concentration could be effectively increased from 5.0%, 10.0%, and 15.0% to 17.3%, 27.0%, and 33.7% respectively, by combining a rotating adsorption wheel with a conventional chemical absorption process [13].

However, in contrast to the mentioned chemical absorption separation method, adsorption for carbon dioxide separation is a low energy consumption carbon capture technology with greater potential and application prospects. Current research focuses on the creation and application of highly effective new composite adsorbents, and there are still many technical challenges on the way to large-scale industrial application of adsorption technology.

### 4. Membrane separation method

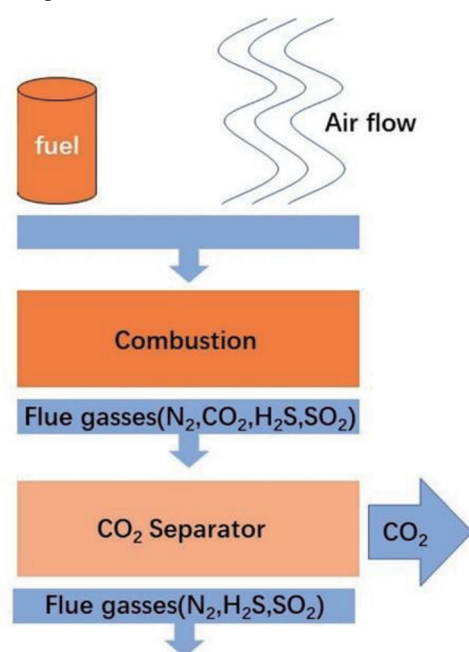
Membrane separation depends on differences in the relative permeability of membrane materials to different gas molecules due to differences in solubility and diffusion rates, and thus the separation of a particular gas. Membrane separation of carbon dioxide is based on the difference in size, condensation and reactivity of carbon dioxide and other gas components, resulting in different permeation rates of gas molecules in the membrane. It has the advantages of low energy consumption, small footprint, no solvent evaporation and high applicability, which makes it very promising for large-scale applications.

Membrane materials are classified into mixed matrix, inorganic and polymeric membranes depending on the material. Polymeric membranes are the fastest growing and most widely used membrane separation materials, but they also suffer from the problems of membrane permeability and selectivity. Inorganic membranes are solid membranes made from inorganic materials such as zeolites, silica and metals, which have the advantages of being suitable for high temperature and high-pressure conditions, good chemical stability and long service life, but also have the disadvantage of poor processability, and it is difficult to prepare excellent inorganic membranes in large-scale production, thus making manufacturing costs high. In view of these drawbacks, new hybrid matrix membranes (MMMs) have received extensive attention and research. Hybrid matrix membranes are inorganic fillers dispersed in a polymer matrix (continuous phase) in the form of particles or nanoparticles (discrete phase), which greatly enhance the permeability and selectivity of the hybrid matrix as the inorganic fillers are uniformly dispersed between the molecular chains of the polymer, providing channels for gas transport.

ZHANG et al. prepared a composite hybrid matrix membrane by compounding zeolite imidazolium salt skeleton (ZIF-8) with carboxylated carbon nanotubes (CNT) and embedded in a polyether block polyamide (Pebax) matrix. The studies demonstrated that the ZIF-8/CNT composite increased the hybrid matrix membrane's

free volume and enhanced CO<sub>2</sub> adsorption performance (CO<sub>2</sub> permeability of 225.5 bar and CO<sub>2</sub>/N<sub>2</sub> selectivity of 48.9). In addition, a fast CO<sub>2</sub> transport pathway was provided by the interaction between CNT and ZIF-8 and improved the mechanical properties of the hybrid matrix membrane, making this hybrid matrix membrane highly promising for application [14].

Furthermore, as illustrated in Fig. 2, membrane contactors (MC) are a post-combustion-based technology that separates gas and liquid phase material and offers a large surface area to promote improved movement between the two. For the reason that the flow rate of the gas as well as liquid (absorbent) being separated may be easily regulated, this is a particularly adaptable carbon capture technique. MC also includes a controlled interface area that may be customized. It may also be customized to meet more process needs and accommodate higher production quantities.



**Fig. 2.** CO<sub>2</sub> separation by membrane contactors (Source link: <https://www.sciencedirect.com/science/article/pii/S0045653523002631>)[15]

Polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polyethersulfone (PES), and polypropylene (PP) are excellent materials for MC applications, according to Nieminen et al. 2020 and Siagian et al. 2019. In the experiment, Nieminen used a 3M Liqui-Cel™ polypropylene hollow fiber membrane assembly and a vacuum chamber made of glass that may be used for absorbing and releasing substances, as well as an amino acid salt absorption solution with potassium glycinate. The experiments revealed a CO<sub>2</sub> flow of 0.82 mol·m<sup>-2</sup>·h<sup>-1</sup> and a CO<sub>2</sub> product purity of more than 75%. Siagian compared the carbon capture capacity of MC under high CO<sub>2</sub> concentration conditions and reviewed several materials suitable for MC [16,17].

Carbon capture technology based on membrane separation can play a significant role in major emitters including coal-fired power plants, cement and steel

facilities. However, there are still more technical challenges to overcome in membrane separation technology, such as separation performance and cost, especially in the separation of lower concentrations of carbon dioxide, not only the capture efficiency is lower, the operating energy consumption is also larger, there is still great potential for development.

## 5. Conclusion

The dramatic increase in CO<sub>2</sub> emissions caused by human activity and the resulting extreme climate problems are becoming more and more prominent. For this reason, scientists worldwide have a responsibility to research and develop CO<sub>2</sub> capture technologies. Post-combustion carbon capture is the technique used on an industrial scale more often than any of the other methods. Currently, the main post-combustion carbon capture technologies include absorption separation, adsorption separation and membrane separation. After a comparative analysis, the chemical absorption and separation method is the most mature carbon capture technology at this stage, and this technology has already achieved commercial industrial application; the adsorption and membrane separation methods have greater development potential and application prospects.

In the future, there are still many challenges to be overcome by scientists in the field of carbon capture, such as improvement of the stability and resistance to impurities of the absorbent to make it have a longer life; development of new and efficient composite adsorbent to increase its selectivity and achieve the purpose of cyclic operation, economic and efficient; research of membrane materials with a balance of permeability and selectivity, taking into account the cost and efficiency. In addition, China's carbon capture technology should also accelerate the research and development of core technologies, improve the core competitiveness of science and technology, further reduce construction and operating costs, and promote the commercialization and industrialization of carbon capture technology.

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