# Progress in Post-Combustion Technology for Carbon Dioxide Capture

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**Abstract.** In the face of climate change and global warming caused by the increase in atmospheric carbon dioxide released by the combustion of fossil fuels, carbon capture technologies become pivotal for mitigating greenhouse gas emissions, particularly carbon dioxide. Among these carbon capture technologies, post-combustion capture has gained widespread application. In this article, the absorption and adsorption methods in post-combustion carbon capture technology, including the mechanism of the chemical and physical aspects of both methods as well as the absorbents and adsorbent materials used in them, will be specifically introduced. Moreover, the current and potential applications in the field of emissions reduction are also elaborated. These post-combustion carbon capture methods are expected to reduce environmental harm while maintaining energy efficiency, providing an effective solution to the problem of global warming.

**Keywords:** Post-combustion capture, absorption, adsorption, absorbents and materials, application progress.

## 1. Introduction

Climate change is a significant challenge facing humanity today and addressing it has become a global consensus. According to the report of the Intergovernmental Panel on Climate Change (IPCC), the combustion of fossil fuels has led to a 40% increase in atmospheric carbon dioxide concentration since industrialization, contributing to approximately 70% of surface warming. In December 2015, a total of 178 nations officially ratified the Paris Agreement. This accord established a paramount objective: to cap the increase in global temperatures at a maximum of 2°C above pre-industrial benchmarks by the close of the 21st century, with a long-term target of 1.5°C to combat climate change. As a result, carbon capture technologies have gained increasing attention due to their potential to positively mitigate climate change [1-2].

Compared to the development and utilization of alternative energy sources, carbon capture technologies maintain energy efficiency while reducing environmental harm in the current energy-intensive landscape and provide an effective method to control climate change without the technical challenges associated with developing new energy sources. Besides, there is currently ample storage space for captured carbon dioxide on Earth once the capture process is complete. The development of carbon capture technologies has been rapid, primarily based on the principle of separating, collecting, purifying, and compressing $CO_2$ from emissions at combustion sources to reduce $CO_2$ levels in the atmosphere. Available technologies include pre-combustion capture, oxy-fuel combustion capture, and post-combustion capture [1-2]. Pre-combustion capture is the process of separating $CO_2$ before fossil fuel combustion by converting fossil fuels into $H_2O$ and $CO_2$, allowing for effective $CO_2$ separation and capture. Rich oxygen combustion is the separation of $CO_2$ and water vapor produced during fossil fuel combustion in oxygen or oxygen-enriched conditions, followed by condensation to separate $CO_2$. post-combustion capture is the process of capturing $CO_2$ from flue gas produced during fossil fuel combustion in the air. Among these, post-combustion capture technology is relatively mature and offers advantages in terms of widespread applicability and simplicity in system principles. Post-combustion technology now mainly includes absorption, adsorption, and membrane separation methods. Both absorption and adsorption methods encompass chemical and physical approaches, with the primary distinction lying in the chemical reactions or physical forces between the absorbents or adsorbent materials and carbon dioxide. In absorption methods, chemical

absorption employs absorbents such as liquid amine and mixed amine absorbents, while physical absorption relies on physical forces like van der Waals forces to achieve gas absorption. In adsorption methods, chemical adsorption mainly utilizes materials like metal-organic frameworks, while physical adsorption employs adsorbent materials such as activated carbon and zeolite molecules.

In addition to specifically focusing on the widely employed absorption and adsorption methods in post-combustion carbon capture technology, this article will further elucidate the chemicals, physical reagents, and materials used in these methods, as well as present the current progress and viable application scenarios of both chemical and physical approaches.

## 2. Absorption

Post-combustion capture has received extensive research attention due to its technological maturity and the advantage of not requiring significant modifications to existing equipment [1]. As one of the most mature post-combustion capture processes, absorption has achieved significant success and widespread application in CCUS demonstration projects and commercialization after years of research. The following sections will provide a detailed exposition of the specific mechanisms underlying the chemical absorption method and physical absorption methods.

### 2.1. Chemical Absorption

The chemical absorption method utilizes alkaline chemical absorbents or their aqueous solutions to react with acidic carbon dioxide gas under specific conditions, separating $CO_2$ from the gas source. Subsequently, the solution produced from the reaction can be regenerated through methods like heating, allowing for the release of $CO_2$ and enabling the reuse of the absorbent cyclically. Chemical absorption methods have a strong affinity for binding with $CO_2$, allowing them to capture carbon dioxide more efficiently and effectively [2]. Various chemical substances are utilized as absorbents in chemical absorption methods. Currently, rapidly developing and widely used absorbents in commercial applications include liquid amine, mixed amine, and potassium carbonate.

#### 2.1.1. Liquid Amine

As the most mature technology to date, liquid amine absorption is fundamentally based on the reversible chemical reaction between acidic gases and alkaline absorbents [3], forming salts that can be decomposed to release $CO_2$. This method exhibits a high absorption capacity but relatively slow absorption rates [2]. Within organic amine absorbents, primary amines and secondary amines demonstrate faster reaction rates and are therefore commonly used absorbents. Here are the equations of the reaction: [3] ($R_1$ and $R_2$ represent alkyl groups).

$$R_1R_2NH + CO_2 \rightarrow R_1R_2NH{+}COO^- \quad (1)$$

$$R_1R_2NH{+}COO^- + R_1R_2NH \rightarrow R_1R_2NH_2{+} + R_1R_2NCOO^- \quad (2)$$

$$\text{Overall Reaction: } 2\ R_1R_2NH + CO2 \rightarrow R_1R_2NH_2{+} + R_1R_2NCOO^- \quad (3)$$

The amine type and its solution concentration can affect the efficacy of the liquid amine absorption technique [4]. Common liquid amine absorbents include monoethanolamide (MEA), diethanolamine (DEA), and N-methyl diethanolamine (MDEA). Among these, primary amines and secondary amines exhibit relatively fast reaction rates. Hu et al. reported that the absorption capacity of primary amines and secondary amines for $CO_2$ is approximately 0.5 mol $CO_2$/mol amine. Their reaction mechanism involves primary amines and secondary amines initially reacting with $CO_2$ to form zwitterions, followed by further reactions to form azidoformate and protonated alkali. On the other hand, tertiary amines lack hydrogen atoms in the amino group and react with $CO_2$ to generate bicarbonate. They have slower reaction rates but higher absorption capacities, approximately 1 mol CO2/mol amine. Tertiary amines exhibit strong absorption capabilities, low heat absorption, and lower energy-

consuming carbonate formation during $CO_2$ reactions. However, their reaction kinetics are slower, often requiring mixing with other amines as absorbents to enhance absorption performance [2].

### 2.1.2. Mixed Amine

Challenges may arise when endeavoring to find a single-component absorbent that can effectively fulfill the concurrent requisites of rapid minimal heat reaction and absorption rate and absorption capacity. As a result, combining absorbents that function differently, such as tertiary amines, with those that perform differently, such as primary amines, can improve the overall absorption performance [5].

In 2021, a group of researchers, among them Wang et al., collaboratively employed a blend of N, N-dimethyl cyclohexylamine (DMCA) and N-methyl cyclohexylamine (MCA) as absorbents based on amines. This particular absorbent demonstrated remarkable efficacy in the absorption of $CO_2$, attaining an absorption capacity spanning from 0.875 to 0.985 mol $CO_2$/mol amine. Notably, the energy consumption for the regeneration process was only approximately 2.20 GJ/t $CO_2$. This absorbent demonstrated exceptional absorption rates and highly efficient capture and regeneration capabilities [6].

### 2.1.3. Hot Potassium Carbonate

This approach enables the liberation of $CO_2$ from potassium bicarbonate, transforming it into potassium carbonate for subsequent reuse. To enhance the absorption rate, it is essential to incorporate a heat-enriched solution and activators like diethanolamine (DEA), piperazine (PZ), and other alcohol amine organic compounds, considering that potassium carbonate exhibits limited solubility at lower temperatures. Therefore, the addition of activators is the primary factor influencing the hot potassium carbonate method since activators are indispensable accelerators for enhancing the absorption rate of this method. According to data from Hu et al., the Enid Fertilizer plant in the United States utilizes piperazine as an activator in the Benfield process for $CO_2$ capture, with an annual capture capacity of approximately 700,000 tons [2].

## 2.2. Physical Absorption

The physical absorption method leverages the disparity in solubility between $CO_2$ and other components present in the gas source to achieve the separation and removal of $CO_2$. Among the various physical absorbents, some that have seen significant development and widespread application include methanol utilized in the Restisol method and polyethylene glycol dimethyl ether utilized in the Seloxol method [7].

### 2.2.1. Seloxol Method

The Seloxol method is the method of using polyethylene glycol dimethyl ether (a light yellow transparent organic liquid, which is also called NHD liquid) as an absorbent for carbon dioxide absorption. It is characterized by being non-toxic and chemically stable. However, the drawback of this method is the relatively high investment and operational costs [8]. According to Lin et al.'s paper, the Pikes Peak facility in the United States uses the Selexol process to process a gas stream containing 43% CO, resulting in a purified gas with only 3% $CO_2$ content [9]. However, based on data from Wang et al., the absorption efficiency of NHD solution for carbon dioxide is relatively low, with a rate of only 40-55 $m^3$ at a pressure of 3.1 MPa [10].

### 2.2.2. Restisol Method

The Restisol method is the use of methanol as an absorbent for carbon dioxide removal. It is characterized by low regeneration energy requirements and resistance to degradation. However, this method necessitates strict temperature control and can only be operated under low-temperature conditions (-55~35°C) [8]. Data from Liu et al. indicate that methanol can recover absorbed impurities during the regeneration process, resulting in high gas purity, capable of purifying $CO_2$ to below $10\times10^{-6}$ $m^3$ [11]. However, according to data from Wang et al., at the same pressure of 3.1 MPa, 1 $m^3$ of methanol solution can absorb $CO_2$ at a rate of 160-180 $m^3$. Its $CO_2$ absorption capacity

is approximately four times that of NHD solution in Selexol. Low-temperature methanol washing with methanol solution has a smaller circulation volume, fewer device installations, and lower overall energy consumption when absorbing an equivalent number of acidic gases [10].

### 2.3. Application

Within the realm of chemical absorption methods, the liquid amine absorption technique, known for its maturity in carbon capture technology, has successfully transitioned into commercial applications. Prominent in the realm of commercially established amine absorption processes stand the Kerr-McGee/ABB Lummus Crest (KMALC) method, jointly presented by Kerr-McGee and ABB-Lummus Crest in the United States. The Econamine FG Plus (EFG+) technique, pioneered by Fluor in the United States; the Kansai Mitsubishi Carbon Dioxide Recovery (KM-CDR) approach, established by Mitsubishi Heavy Industries in Japan; and the utilization of the Cansolv system, developed by the Royal Dutch Shell Group in the Netherlands [3]. On the other hand, physical absorption methods are generally limited by the operating conditions of low temperature and high pressure, making it challenging to meet high purification requirements. Some of the applied projects in this area include the Shute Creek 7 million t/a natural gas processing carbon capture project, the Great Plains synthetic fuel plant 3 million t/a carbon capture project, and the Century Plant 8.4 million t/a carbon capture project [2].

## 3. Adsorption

Adsorption, facilitated by traditional materials like activated carbon, silica gel, zeolite, and emerging porous materials such as metal-organic frameworks, is an effective process for separating $CO_2$ from gas mixtures due to their substantial surface area and porous structures [12]. Adsorption methods mainly comprise two approaches: chemical adsorption and physical adsorption.

### 3.1. Chemical Adsorption

In the process of chemical adsorption, chemical reactions occur between carbon dioxide and the adsorbent. For instance, certain chemicals can be loaded onto the surface of solid adsorbents, where they chemically react with $CO_2$, causing them to be adsorbed onto the material's surface [13]. Adsorbing materials falling under the category of chemical adsorption include Metal-organic framework materials.

#### 3.1.1. Metal-organic framework materials (MOFs)

MOFs are a highly promising class of adsorbent materials formed through self-assembly via coordination between metal ions or clusters and organic ligands. They offer advantages such as large surface area, high porosity, and strong controllability of structural design [14]. Under test conditions of 10 kPa and 293-298 K, Yazaydin et al. conducted a comparative analysis of the $CO_2$ adsorption performance of 14 different MOF materials. The research results revealed that materials formed using 2,5-dioxo-1,4-benzenedicarboxylic acid (DOBDC) as a ligand, such as M\DOBDC (where M stands for Zn, Mg, Ni, Co), exhibited higher $CO_2$-selective adsorption capacity. Furthermore, among the M\DOBDC materials, Mg\DOBDC exhibited the highest $CO_2$ adsorption capacity, reaching 5.95 $mmol \cdot g^{-1}$. The selective adsorption capacity for $CO_2$ followed the order of central metal Mg > Ni > Co > Zn, and the reason for this difference was attributed to the longer M-O bond lengths, which exhibited ion-like characteristics, between the metal center and the oxygen atoms in the ligand. [15]

### 3.2. Physical Adsorption

Physical adsorption refers to the phenomenon in which gases are adsorbed onto the surface of an adsorbent through van der Waals forces. This method includes a simpler process that is non-corrosive, non-volatile, cost-effective, and environmentally friendly [16]. However, it is currently challenging to apply to large-scale carbon capture projects [17].

The adsorption mechanism employed by porous materials such as activated carbon and Zeolite molecular sieves falls into the category of physical adsorption [3].

### 3.2.1. Activated Carbon

Activated carbon is typically prepared through carbonization and activation of carbonaceous materials such as wood, nutshells, coconut shells, coal, organic waste, and polymer materials. It has a wide range of inexpensive raw material sources and was one of the earliest adsorbents applied to $CO_2$ capture, achieving commercialization. Extensive research has been conducted both theoretically and practically in the field of $CO_2$ capture using activated carbon [10]. When employed in adsorption processes, activated carbon primarily utilizes van der Waals forces for adsorption within its micropores [18]. One of its major advantages in carbon capture is its hydrophobic nature, as industrial flue gases often contain water vapor that can weaken the adsorption capacity of adsorbents. Activated carbon, however, remains unaffected by water vapor, ensuring efficient $CO_2$ adsorption [17]. Sevilla et al. demonstrated the preparation of activated carbon materials using starch, cellulose, and sawdust as precursors through hydrothermal carbonization and KOH activation. The resulting activated carbon materials exhibited excellent $CO_2$ separation and storage capabilities, achieving the highest adsorption capacity of 4.8 $mmol \cdot g^{-1}$ at room temperature. Further characterization tests revealed that the physical properties of the formed activated carbon were independent of the precursor choice, indicating high adsorption performance in $CO_2$ separation [19].

### 3.2.2. Zeolite molecular sieves

Zeolite molecular sieves typically refer to crystalline aluminosilicate materials, either naturally occurring or synthetically produced. They are composed of interconnected silicon-oxygen tetrahedra and aluminum-oxygen tetrahedra linked together by oxygen bridge bonds, forming a system of pores and cavities with dimensions ranging from approximately 0.3 to 2.0 nm. These materials possess the ability to selectively adsorb molecules [20]. The ability of zeolite molecular sieves to adsorb and separate $CO_2$ from mixed gases arises from the relatively large quadrupole moment of $CO_2$ molecules, enabling strong electrostatic interactions with the cations within the zeolite pore space [10]. Merel et al. conducted a study using the TSA (Temperature Swing Adsorption) process, simulating $CO_2$ adsorption from flue gas using 5A zeolite. The optimal performance achieved a $CO_2$ capture rate of 18% and a volumetric production rate of 23% [21].

### 3.3. Application

Given the principles and characteristics of adsorption, it is suitable for industrial applications with high pressure, high $CO_2$ concentration, and low impurities. Therefore, it has found extensive application across industries including fertilizer production, ammonia synthesis, and hydrogen manufacture. In the hydrogen manufacturing sector, for instance, projects like the Port Arthur project in the United States and the Air Products Steam Methane Reformer project have employed adsorption technology to capture $CO_2$ from the syngas during hydrogen production. In the ammonia synthesis field, companies like KTI in the Netherlands and ICI in the United Kingdom utilize pressure swing adsorption for carbon capture [2].

## 4. Summary

The massive emissions of $CO_2$ resulting from fossil fuel combustion have had a significant impact and pose a great threat to global warming and the greenhouse effect, affecting human survival and various forms of life worldwide. Therefore, governments around the world attach great importance to measures aimed at mitigating global warming and reducing $CO_2$ emissions, which has led to the rapid development of carbon capture technologies. Among these technologies, post-combustion carbon capture, as one of the widely applied methods, has received unprecedented attention.

In this article, a systematic review and discussion of the current research status of absorption and adsorption methods in post-combustion carbon capture technology in recent years are provided.

Moreover, it covers the mechanisms, materials used and the application progress of the absorption and adsorption methods. Chemical absorption methods have already achieved commercial industrial applications, while adsorption separation methods show significant energy-saving potential and application prospects. Despite significant progress in research on absorption and adsorption processes and materials, there is currently no carbon capture method that can be carried out independently, efficiently, and economically on a large scale. Challenges such as the potential environmental impacts during the absorption process, the selection of absorbents, energy consumption during adsorption, and the high investment required for high-performance adsorbent material synthesis still need to be addressed shortly.

Therefore, the advancement of carbon capture technologies that are both economically viable and highly efficient in the future will require addressing the current issues and challenges in various technologies and harnessing the advantages of different approaches to create more effective carbon capture techniques.

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