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A Review of Carbon Capture Technologies: Current Capture Technologies, Challenges, and Future Development

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Abstract:

Nowadays, global warming has become one of the significant issues that humans are facing. Carbon capture technologies, as essential tools to mitigate carbon dioxide (CO_2) emissions, have been applied in power plants and industrial processes globally. This paper examines prevalent carbon capture technologies by reviewing the relevant principles and research progress in the field of carbon capture. Three combustion configurations: pre-combustion, post-combustion, and oxy-fuel combustion are elaborated in this review concerning carbon capture. Pre-combustion carbon capture extracts CO_2 before the combustion process, transforming the hydrocarbon fuels into syngas which are composed of CO_2 and hydrogen for later combustion. Post-combustion carbon capture aims to capture CO_2 after the combustions. Various techniques can be applied for carbon capture after the combustion, with chemical absorption and membrane separation widely used. Oxy-fuel combustion uses pure oxygen to accomplish the combustion so that the exhausted gases can mainly composed of CO_2 and water vapor, which is easy for CO_2 capture. This paper also highlights the critical role that carbon capture technologies will play in Carbon Capture and Storage (CCS) and emphasizes the current technology drawbacks. It provides a reference for future carbon capture studies and developments, which will be crucial for achieving international climate goals.

Keywords: Carbon dioxide; Carbon capture and storage; Carbon capture technology; Carbon treatment.

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1. Introduction

The rapid development in advanced technology and growth in world population have significantly increased the demands in fossil fuel combustion. According to the World Meteorological Organization, the concentration levels of greenhouse gases in the atmosphere reached a record high, with carbon dioxide (CO_2) reaching the average concentration of 417.9 ± 0.2 ppm, which is 150% of the pre-industrial level [1]. The European Union also has committed to a national economic target of reducing greenhouse gas emissions by at least 55% from the emission level in 1990 by 2030 and accomplishing carbon neutrality by 2050 [2]. Although the global community has already made great endeavors with respect to reducing CO_2 emissions, CO_2 emissions are still a central focus of environmental policy and technological innovation. A study tracing emission to major fossil fuel producers found that 90 entities were responsible for 63% of cumulative worldwide emissions of industrial CO_2 and methane between 1751 and 2010, with half of these emissions occurring since 1986 [3]. In 2020, fossil fuels, including coal which identified as the backbone of electricity generation worldwide historically, supporting over 80% of world energy use. In response, various green technologies related to the generation of other renewable energies such as solar power, wind power, and hydropower were then developed to mitigate the pressing situation. In the same year, renewable energy sources contribute approximately 12.6% of world energy use, including 6.86% of hydropower, 2.90% of wind power, 1.54% of solar power, and the rest of other renewable energy sources [4]. However, the huge gap between the two types of energy sources is still considerable nowadays. Coal remains a major contributor to CO_2 emissions, particularly in developing economic sectors where it continues playing a crucial role in energy security. To address this issue, research is being conducted on high-efficiency power generation technologies and methods to capture and store CO_2 from power plants.

This review paper seeks to provide a comprehensive overview of modern carbon capture technologies, aiming to explore the mechanisms of three prevalent capture configurations: post-combustion, pre-combustion, and oxy-fuel combustion, analyzing their current applications, and future expectations to the global community.

2. Carbon Capture in Carbon Capture and Storage (CCS) Technology

2.1 Carbon Capture and Storage

In IPCC's Sixth Assessment Report, addressed that carbon dioxide removal is necessary to neutralize the numerous CO_2 emissions and achieve the Paris Agreement climate goals. The combustion of fossil fuels in power plants produces vast amounts of CO_2, which is a leading driver of anthropogenic climate change. The combustion of fossil fuels accounts for around 80% percent of the world's CO_2 emissions [5]. To further mitigate the current issue to a greater extent, more and more approaches are receiving abundant attention from not only scientists but also governments and global institutions, especially the carbon capture and storage (CCS) technology approach. CCS is a critical technology in the global effort to mitigate climate change by reducing CO_2 emissions from industrial processes and power generation, which are responsible for 45% of both direct and indirect global CO_2 emissions [6]. Significant advancements have been made in CCS, to meet the urgent need to reduce atmospheric CO_2 levels. The concept of CCS originated in 1977, aiming to reduce CO_2 emissions through three stages: capturing CO_2 at the source, transporting it to a storage site, and injecting it into underground geological formations for long-term storage. The CCS is a comprehensive set of technologies that involve the process of capturing CO_2, transporting it to selected locations, and storing/utilizing it at the locations. CCS can play a crucial role in achieving the goals that are set out in international agreements, such as the Paris Agreement. Since the application of CCS technology in the fields of power generation and industrial processes, 14% of global CO_2 emissions have been reduced [7].

In CCS technology, the CO_2 capture process plays a vital role. It not only determines the quality of CO_2 that is captured during the process but also this CO_2 capture process accounts for approximately 70%-80% of the CCS total cost [8]. The CO_2 capture process can be divided into three main categories: post-combustion, pre-combustion, and oxy-fuel combustion.

2.2 Carbon Capture Development

2.2.1 Early Development Stage

During the 1903s, the concept of capturing CO_2 emerged, primarily driven by the oil and gas industry's demand to separate CO_2 from natural gas during production. Amine-based solvents, particularly monoethanolamine (MEA) and diethanolamine were put into use during the time period. Amine solvents have been used by hundreds of plants to in the function of removing CO_2 from natural gas, and other fuels [9]. Later, this technology was discovered effective for the mitigation of greenhouse gas emissions and gradually gained attention from scientists. The amine-based solvent displayed its outstanding capability in the field of CCS by dealing with carbon emissions for large-scale industries. This approach established the foundation for future developments in carbon capture. However, these early technologies were usually accompanied by high financial and energy costs, which limited them from widespread usage scenarios.

2.2.2 Mature Stage

As global warming and related issues are getting severe, the need for rapid development in carbon capture technologies becomes urgent and inevitable, which is driven by current emerging policies and agreements with respect to carbon emissions. In recent years, carbon capture technologies have matured significantly, mainly reflected in the improved efficiency of capture methods such as the advanced amine-based solvents that cut down the operational cost and energy consumption. Additionally, the enormous progress in the field of pre-combustion and oxy-fuel combustion technologies also opened new pathways for capturing CO_2. For instance, the membrane technology aims to filter CO_2 through specific membranes to separate CO_2 from other components. This approach compared to other carbon capture technologies, has made significant progress economically and energetically. Although the current development in carbon capture has gained huge achievements, particularly in terms of efficiency and cost, the applications of these technologies on a broader scale to meet the global climate goals still require further cost reductions, policy support, and infrastructure development.

3. Current Carbon Capture Technology

3.1 Pre-Combustion Carbon Capture

Pre-combustion carbon capture is one of the main technologies for mitigating climate change by removing CO_2 before fuel combustion. The capture focuses on extracting CO_2 from fossil fuels or biomass before the combustion process. This technique is firstly utilized in the gasification of coal, natural gas, and biomass to produce syngas, which are mainly composed of hydrogen (H_2), and carbon monoxide (CO) through water-gas shift reaction. The syngas produced are widely used in the power generation plant and hydrogen production industry, which utilize coal, natural gas, and petroleum as raw materials [10]. Pre-combustion carbon capture typically involves three main steps: hydrocarbon conversion, water-gas shift reaction, and CO_2 removal.

3.1.1 Early Development Stage

As the initial step of pre-combustion carbon capture, it aims at transforming hydrocarbon fuels into a mixture of H_2, CO, and CO_2. Depending on the type of feedstock used, the conversion process differentiates. Steam methane reforming (SMR), partial oxidation (POX), and autothermal reforming (ATR) are normally applied to accomplish the conversion. The chemical reaction equations and other features for those three technologies are shown in Table 1.

Table 1. Features of commercially available reforming technologies [11]

	Steam reforming	Partial oxidation	Autothermal reforming
Abbreviation	SMR	POX	ATR, CPO
Catalyst	Ni	-	Partial oxidation: - Steam reforming: Ni
Pressure	15-40 bar	> 150 bar	20-40 bar
Temperature	750-900 °C	1200-1600 °C	850-1100 °C
Reaction	$CH_4 + H_2O <-> CO + 3H_2$	$CH_4 + 1/2\ O_2 <-> CO + 2\ H_2$	$CH_4 + 1/2\ O_2 <-> CO + 2\ H_2$ $CH_4 + H_2O <-> CO + 3H_2$
Enthalpy	+ 206.2 MHJ/kmol CH4	– 35.7 MHJ/kmol CH4	Exothermic
H_2/CO ratio	3-6	1.8	1.8-3.7

3.1.2 Water-Gas Shift Reaction

The water-gas shift reaction is a reversible, exothermic process that converts carbon monoxide and water into CO_2 and hydrogen. Water molecules are composed of hydrogen and oxygen atoms. During the reaction, certain conditions are applied to enable the combination of the oxygen atom and carbon atom, which eventually forms a mixture of carbon monoxide and hydrogen gas. The purpose of the reaction is to convert the CO that is generated from the hydrocarbon conversion process into CO_2. During the water-gas reaction equation, CO reacts with H_2O to produce CO_2 and H_2. The reaction is exothermic, with a change in enthalpy (ΔH) of -40.6 kJ per mole. The reaction typically occurs in two stages: high temperature (320-450°C) called high-temperature shift, and low temperature (150-250°C) called low-temperature shift, with the iron-based catalysts and copper-based catalysts respectively [12].

3.1.3 CO_2 Removal:

The removal of carbon dioxide in this process is treated to enrich the combustion material, hydrogen. The current technologies that are able to remove CO_2 from the mixture of hydrogen and CO_2 are physical absorption, cryogenic separation, and membrane separation.

- Physical absorption: Physical solvents like Selexol, Purisol, and Morphysorb are used in the absorption of CO_2. These absorption processes can remove CO_2 from syngas efficiently. It is also has been proved that physical solvents have a higher CO_2 absorption capacity under high pressure, compared to chemical solvents [13].
- Cryogenic separation: To separate CO_2 and hydrogen, by cooling the syngas to carbon dioxide's frost point (-100 to -135°C), under the pressure of 100-200atm, CO_2 will transfer its physical state from gas to solid [14]. Collect the hydrogen that remains in the gas state.
- Membrane Separation: Separating CO_2 and hydrogen by filtering the syngas through certain membranes. The material of the membrane is the core of this approach, including polymeric, inorganic, and mixed matrix membranes. Compared with the traditional absorption methods, low consumption, less pollution, and simple operation are the advantages of membrane separation technology.

3.2 Post-Combustion Carbon Capture

Post-combustion carbon capture is a prevalent technology for the capture of CO_2 from industrial combustions. This capture approach refers to the separation of the carbon dioxide from the waste gas or the flue gas after the combustion is completed. Post-combustion carbon capture is a carbon capture technology that is more suitable for existing coal-fired power plants, with the advantages of minimal modifications on plant transformations, as well as operational flexibility [15]. Figure 1 shows the basic workflow of post-combustion carbon capture. Chemical absorption and membrane separation are two mainstream carbon capture technologies at present.

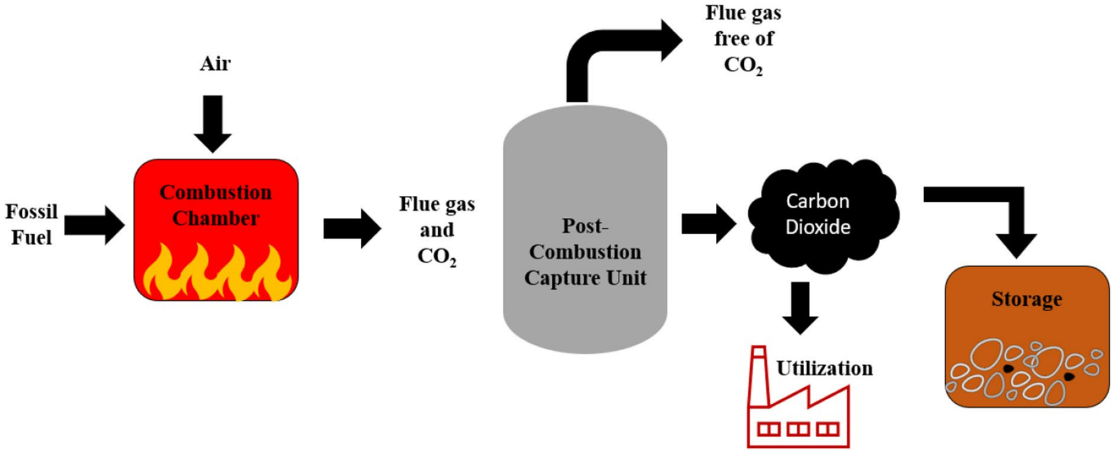

Fig. 1 Work flow of post-combustion carbon capture [16]

3.2.1 Chemical Absorption Methods

Chemical absorption is a mature and widely applied technology for post-combustion carbon capture. It is a prevalent technology for mitigating CO_2 emissions from power plants and industrial sources. CO_2 is typically captured by chemical absorptions after combustion by amine solvents. This method is considered the most mature and widely applicable, which accounts for 57% of post-combustion CCS research [17]. Amine-based chemicals have been practiced in the absorption of CO_2 for a long period. This method involves the use of amine solvents, such as MEA to react with CO_2, forming a stable carbamate. This reaction captures CO_2 from the gas phase into the liquid phase effectively. After the CO_2 absorption process, collected CO_2 needs to be transferred into the gas phase which is called the regeneration process. By heating the amine solution that absorbed CO_2, it causes the carbamate to decompose through the reverse reaction that occurred in the absorption process, and release CO_2 back into the gas phase. In addition to organic solvents, inorganic solvents also display prominent performance in CO_2 capture. Potassium carbonate, sodium hydroxide, and ammonia are often applied in the absorption process. The reactions between inorganic solvents and CO_2 commonly result in the formation of carbonate or bicarbonate ions. While both amine-based and inorganic solvents are used for CO_2 capture, they differ significantly in their absorption mechanisms, efficiency, energy conditions, etc. For instance, inorganic solvents are often less expensive than amine-based solvents. However, inorganic solvents have less absorption capacity, compared to the one for amine-based solvents.

3.2.2 Membrane Separation

Compared to the traditional chemical absorption approach,

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the membrane separation technology offers new perspectives and potential advantages in energy efficiency and environmental impact. During the membrane separation, gases that are collected after combustion flow through a membrane that allows CO_2 to pass through selectively. Other gases, such as nitrogen and oxygen are intercepted by the membrane. Therefore, the materials that make up the membrane are crucial in this approach. Various membrane materials such as polymers, inorganics, and hybrid matrices, have been investigated for their CO_2 and nitrogen selectivity and permeability. Permeability refers to the speed at which CO_2 can pass through the membrane, while selectivity refers to the ability of the membrane to differentiate CO_2 from other gases [18]. Polymeric and inorganic membranes are currently prevalent in the market because of their certain advantages such as processability, stability, and mechanical strength. Nevertheless, each of these two materials has its disadvantages, challenging the market from using them. Fortunately, the presence of a mixed matrix membrane combines the properties of both polymeric and inorganic materials by dispersing inorganic materials within a polymer matrix. The integration combined the advantages of both materials: the processability and mechanical strength of polymers and the superior separation performance and stability of inorganic materials.

Not only have the membrane materials gained progress, but the membrane systems are also optimized. Single membrane system that has been underestimated historically in the field of CO_2 capture. In a single membrane system, the gas-only needs to be filtered through one membrane unit. Although the process is simple and easy to operate, it is difficult to collect CO_2 with high purity. In recent years, a multi-stage membrane system presented, which allows the collection of high CO_2 purity after filtration. For example, two-stage membrane systems have demonstrated the ability to achieve CO_2 removal efficiencies of over 90%, with purity levels exceeding 95% [19].

3.3 Oxy-fuel Combustion Carbon Capture

Oxy-fuel combustion differentiates from conventional combustion in that oxy-fuel combustion uses pure oxygen (approximately 95 mol%) instead of air to accomplish the combustion. The purpose of this replacement is to obtain the exhaust gases that are primarily composed of CO_2 and water vapor. The choice of pure oxygen for the combustion is because the presence of nitrogen in the combustion process can lead to a significant energy penalty for carbon capture. Since nitrogen does not participate in the combustion, its presence only dilutes the concentration of CO_2 which makes the capture of high concentration CO_2 difficult. After the oxy-fuel combustion process, the separation of CO_2 and water vapor is the next step. The cooling of the exhaust gases after combustion aims to condensate water vapor from the gas phase to the liquid phase, as temperature drops below the dew point of water. The water in the liquid phase can be separated from CO_2 in the gas phase easily by using a condenser or a gas-water separator [20]. The rest of the gas, which predominantly consists of CO_2, can undergo the corresponding procedures for carbon storage.

4. Future Expectation

While there are many obstacles in the transformation from traditional energy sources to new renewable energy sources, carbon capture will be one of the important strategies to mitigate the emerging climate change issues nowadays. Although the current carbon capture technologies have made certain progress in the reduction of carbon emissions, some problems and challenges still exist. High energy consumption, high operational costs, and low effectiveness remain significant obstacles in the field, which hinder the wider applications for industrial or commercial purposes. For instance, MEA is one of the earliest amine-based solvents put into industrial use and is recognized as a benchmark solvent for CO_2 capture. MEA are widely applied due to their high CO_2 absorption capacity. However, limited overall absorption capacity still counts as a drawback of MEA since it requires two moles of amine to react with one mole of CO_2. Besides, the high maintenance costs caused by MEA corrosion, and high energy consumption for regeneration are also challenges that need to be overcome [21].

As the development of CCS technology is gaining more attention, new perspectives such as carbon utilization after carbon capture, instead of direct carbon storage, are being researched and applied in chemical and biological utilization. In the future, the developments of carbon capture technologies should focus more on the reduction of energy consumption, operational costs and increase the effectiveness to enable extensive usage. Concurrently, combining new perspectives into the technology to diversify the applications of CO_2, instead of simple sequestration.

Additionally, policy frameworks and financial incentives, both locally and globally, are crucial in favoring the development of carbon capture technology. As global climate goals are getting more detailed and pressing, carbon capture is expected to play its part as a mainstream technology in mitigating climate change, as well as achieving net-zero emissions by mid-century.

5. Conclusion

The significant advancements in carbon capture technologies have been highlighted in this review, through the analysis of mainstream operations applied in pre-combustion carbon capture, post-combustion carbon capture, and oxy-fuel combustion carbon capture. These methods, especially chemical absorption as one of the earliest methods, have evolved substantially compared to their early stages. With nowadays ongoing research focus on the improvement of efficiency, decrement of costs, and reduction in energy consumptions, new materials or approaches are put into practice, such as mixed matrix membranes, and advanced physical solvents that have been proven to have higher efficiency and lower costs than traditional chemical absorptions.

Looking forward, the current carbon technologies still face the main obstacles of high energy consumption, heavy operational costs, and low effectiveness. Therefore, the future of carbon capture is expected to optimize the present technologies, including but not limited to these obstacles. Besides, future research should also focus on the CO_2 utilization technologies to convert captured CO_2 into valuable products.

While there are still difficulties in the complete substitution of traditional resources by using renewable resources, this review elaborates on the development of carbon capture technologies and implies the importance of sustained research. Facilitating collaborations across academia, industry, and policymakers to accelerate the development and applications of carbon capture technologies.

References

[1] Ripple W J, Wolf C, Gregg J W, et al. The 2023 state of the climate report: Entering uncharted territory[J]. BioScience, 2023, 73(12): 841-850.

[2] Das A, Peu S D, Hossain M S, et al. Advancements in adsorption based carbon dioxide capture technologies-A comprehensive review[J]. Heliyon, 2023, *9*(12), e22341.

[3] Heede R. Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010[J]. Climatic change, 2014, 122(1): 229-241.

[4] Holechek J L, Geli H M E, Sawalhah M N, et al. A global assessment: can renewable energy replace fossil fuels by 2050 [J]. Sustainability, 2022, 14(8): 4792.

[5] Ahmad, H. H., Saleem, F., & Arif, H. Evaluation of Catastrophic Global Warming due to Coal Combustion, Paradigm of South Asia. International Journal of Innovations in Science and Technology, 2021, 3(4), 198–207.

[6] Roussanaly S, Berghout N, Fout T, et al. Towards improved cost evaluation of Carbon Capture and Storage from industry[J]. International Journal of Greenhouse Gas Control, 2021, 106: 103263.

[7] Subraveti S G, Rodríguez Angel E, Ramírez A, et al. Is carbon capture and storage (CCS) really so expensive? An analysis of cascading costs and CO2 emissions reduction of industrial CCS implementation on the construction of a bridge[J]. Environmental Science & Technology, 2023, 57(6): 2595-2601.

[8] Dziejarski, B., Krzyżyńska, R., & Andersson, K. Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. Fuel, 2023, 342, 127776.

[9] Boot-Handford M E, Abanades J C, Anthony E J, et al. Carbon capture and storage update[J]. Energy & Environmental Science, 2014, 7(1): 130-189.

[10] Wu H, Zhang X, Wu Q. Research progress of carbon capture technology based on alcohol amine solution[J]. Separation and Purification Technology, 2023: 125715.

[11] Eide L I, Bailey D W. Precombustion Decarbonisation Processes[J/OL]. Oil & Gas Science and Technology, 2005, 60(3): 475-484.

[12] Baraj, E., Ciahotný, K., & Hlinčík, T. The water gas shift reaction: Catalysts and reaction mechanism. Fuel,2021, 288, 119817.

[13] Chen Z. A Review of Pre-combustion Carbon Capture Technology[C]//2022 7th International Conference on Social Sciences and Economic Development (ICSSED 2022). Atlantis Press, 2022: 524-528.

[14] Hoeger C, Burt S, Baxter L. Cryogenic carbon capture™ technoeconomic analysis[C]//Proceedings of the 15th Greenhouse Gas Control Technologies Conference. 2021: 15-18.

[15] Wang X, Song C. Carbon capture from flue gas and the atmosphere: A perspective[J]. Frontiers in Energy Research, 2020, 8: 560849.

[16] Alalaiwat D, Khan E. Current status and future scenarios of carbon capture from power plants emission: a review[J/OL]. Reviews in Environmental Science and Bio/Technology, 2023, 22(3): 799-822.

[17] Chao C, Deng Y, Dewil R, et al. Post-combustion carbon capture[J]. Renewable and Sustainable Energy Reviews, 2021, 138: 110490.

[18] Belaissaoui, B., & Favre, E. Membrane Separation Processes for Post-Combustion Carbon Dioxide Capture: State of the Art and Critical Overview. Oil & Gas Science and Technology – Revue d'IFP Energies Nouvelles, 2013, 69(6), 1005–1020.

[19] Fu, J., Ahmad, N. N. R., Leo, C. P., Aberilla, J. M., Dela Cruz, I. J. Techno-economic and life cycle assessment of membrane separation in post-combustion carbon capture: A review. Gas Science and Engineering, 2024, 129, 205401.

[20] Li X, Peng Z, Pei Y, et al. Oxy-fuel combustion for carbon capture and storage in internal combustion engines–A review[J].

International Journal of Energy Research, 2022, 46(2): 505-522.

[21] Asif M, Suleman M, Haq I, et al. Post-combustion CO2 capture with chemical absorption and hybrid system: current status and challenges[J]. Greenhouse Gases: Science and Technology, 2018, 8(6): 998-1031.