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Application and Trends of Carbon Capture Technology

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Abstract. Increased fossil fuel burning leads to the continuous accumulation of carbon dioxide (CO_2) in the atmosphere, ultimately causing global warming. To mitigate this problem, humans have proposed carbon capture as the primary solution to deal with CO_2 in the atmosphere. In this review, the first part introduces the background and challenges of carbon capture technology. It also points out the specific uses of CO_2, aiming to emphasize the importance of carbon capture. Part Two introduces three major technologies: pre-combustion capture, post-combustion capture, and oxygen-fuel combustion. The principles behind the three technologies are explained, and the advantages and disadvantages of each technology are analyzed. Part Three mentions five capture methods: absorption, adsorption, chemical looping combustion, membrane separation, and direct capture, and analyzes the advantages, disadvantages, and trends of each method. Finally, this review, through analysis and summarization, predicts that green development will become a trend in carbon capture, providing a new perspective for future researchers.

Keywords: Carbon dioxide (CO_2), Carbon Capture, Greenhouse Effect.

1. Introduction

Carbon dioxide is a hydrocarbon with the chemical formula carbon dioxide (CO_2). It is a component of air and is a gas produced by living organisms during respiration. CO_2, a major greenhouse gas, is the main culprit behind global warming. Industrialization, the burning of fossil fuels, and explosive population growth have led to increased CO_2 emissions. The book "Taking Our Breath Away," which discusses the health effects of air pollution and climate change, mentions that in the past 100 years, due to the significant increase in the use of fossil fuels, The concentration of CO_2 in the atmosphere increased from 280 parts per million (ppmv) to 360 ppmv, an increase of nearly 30%.Stern found that global annual CO_2 emissions increased by about 80% between 1970 and 2004 [1]. The Intergovernmental Panel on Climate Change (IPCC) concluded that atmospheric concentrations have continued to rise since 2011, with the annual average CO_2 concentration reaching 410 ppm (parts per million) in 2019 [2]. Global warming has led to severe climate change. To address this situation, international organizations have proposed capturing and storing CO_2 as a core strategy, because it not only provides a possibility for meeting the growing demand for fossil fuel energy in the short to medium term, but also is an effective means to significantly reduce the CO_2 concentration.. Lu et al. summarized the four major carbon capture technologies after 2014: carbon dioxide capture before combustion, carbon dioxide capture after combustion, oxygen fuel

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combustion, and chemical looping combustion [3]. With in-depth research into carbon capture technology, various techniques, including absorption and adsorption, membrane separation, and chemical looping, have been developed. This review mainly analyzes the application and development of carbon capture technology.

2. Carbon capture environment background

2.1. Greenhouse effect and global warming

The greenhouse effect is a natural physical phenomenon of the Earth's atmospheric system. Most greenhouse gases in the atmosphere absorb some of the radiation that reaches the ground, while the other part of the radiation reflected into space is selectively absorbed by the greenhouse gases in the form of heat and transmitted back to the Earth, thus maintaining the Earth's surface heat and the temperature for life [4]. However, the accumulation of the greenhouse gas CO_2 in the atmosphere traps more heat and exacerbates Global Warming Potential (GWP). Of course, naturally occurring gases such as methane (CH_4) and nitrous oxide (N_2O), which are present in very small amounts in the atmosphere, as well as certain man-made compounds, also contribute to the greenhouse effect.

Global warming is a long-term climate change phenomenon, mainly caused by increased emissions of greenhouse gases such as carbon dioxide and methane, which leads to an enhanced greenhouse effect and a continuous rise in the Earth's atmospheric and ocean temperatures. The IPCC noted that the Paris Agreement, in order to strengthen action against the threat of global warming, set a target of limiting the increase in global average temperature to well below 2°C below pre-industrial levels and, where possible, to keep the increase to within 1.5°C below pre-industrial levels, with the goal of significantly reducing greenhouse gas emissions by 2030. However, recent emissions trends have deviated from the path of keeping global warming well below 2°C. If emissions reductions are not increased in the coming years, global warming will exceed 1.5°C in the coming decades, leading to irreversible damage to the most vulnerable ecosystems and posing a major crisis for humanity.

2.2. Carbon Capture and Storage (CCS)

CCS scheme, proposed to address the increasing CO_2 content, is based on the core logic of capturing CO_2 generated during industrial production and energy consumption through technological means, preventing CO_2 from being directly released into the atmosphere, and then achieving zero or negative carbon emissions through storage or conversion, thereby mitigating the greenhouse effect. Of course, capturing and storing CO_2 is not only for alleviating environmental problems, but also has many practical uses. It is mainly applied in four different fields: conventional use, biological use, chemical production, and fuel production, such as beverage making and food preservation, cryotherapy, metal processing and enhanced oil recovery [3]. However, this technology is a double-edged sword. Critics argue that carbon capture and storage projects could lead to catastrophic events such as large-scale CO_2 leaks from storage sites. Therefore, carbon capture and storage technologies have different debates on site feasibility, high operating costs, future security and legal liability, which makes carbon capture and storage projects face challenges in startup, implementation and operation [5].

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3. Carbon capture technology

CO_2 is produced during combustion. Different CO_2 capture processes are selected for different combustion processes. Therefore, there are three main types of carbon capture systems related to different combustion processes: pre-combustion capture, post-combustion capture, and oxygen fuel combustion [6].

3.1. Pre-combustion capture technology

It refers to the reaction of fuel with gas to produce a "synthesis gas" or "fuel gas" consisting of carbon monoxide (CO) and hydrogen (H_2). Then, carbon monoxide continues to react with steam in the catalytic reactor to produce carbon dioxide and more hydrogen. At this point, CO_2 is separated into a hydrogen-rich fuel through physical or chemical absorption processes. One added value of pre-combustion capture is the flexibility of power plant output, namely the joint production of hydrogen and electricity, and the ability to switch between power generation and hydrogen production according to power generation needs. However, due to the relatively high investment cost, the syngas portion is more suitable for operation at base load. Finally, due to the maturity and similarity of the technologies, pre-combustion carbon dioxide capture technology can be applied to industries with high carbon dioxide emissions, such as coal, chemical and natural gas processing industries. Nevertheless, human development and investment in pre-combustion capture technology have always been limited, as the field has focused on post-combustion capture technology using improved and novel chemical solvents [7].

3.2. Post-combustion capture technology

This method is the most popular so far. It refers to the removal of CO_2 and other gases from burning fossil fuel resources based on physical or chemical adsorption or absorption mechanisms after combustion. Carbon dioxide-containing flue gas is typically collected from the flue gas emissions of conventional oil, coal, and natural gas power plants. Based on the principle of the capture process, this This technology includes adsorption, absorption, membrane separation, chemical reaction, and other approaches. Simultaneously, according to the different regeneration principles, post-combustion capture technology can also be divided into variable temperature, variable pressure, variable vacuum, variable electricity, and hybrid processes [8]. Compared with other capture technologies, it has the advantages of being easy to retrofit existing power plants, handling large amounts of gas, and having a good CO_2 separation rate [3]. However, it also has many drawbacks, including the need for a large amount of energy for solvent regeneration, the susceptibility of flue gas to corrosion and oxidative degradation, and the fact that solvents can reduce efficiency and increase electricity production costs for other byproducts in flue gas (such as sulfur oxides and nitrogen oxides).

3.3. Oxygen fuel combustion technology

It is essentially an improvement on post-combustion capture technology, achieving this by burning fuel with oxygen (O_2) to obtain a directly sequesterable gas stream, and then recovering or separating the water vapor after condensation, which can almost eliminate CO_2 in the exhaust gas. The combustion chamber (boiler) is a key device in this process. When the fuel is burned in pure oxygen, a portion of the CO_2-rich flue gas usually needs to be circulated back into the combustion chamber to reduce the combustion temperature and improve the fuel combustibility [2]. This

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technology is less efficient per unit energy output, but it is more efficient than conventional power plants with storage technology [9]. Therefore, it is mainly used in large power plants, which will reduce CO_2 emissions at the expense of thermal efficiency [10].

3.4. Specific technologies

A comparison of advantages, disadvantages, and trends is shown in Table 1 [11-13].

3.4.1. Absorption and adsorption methods

Chemical absorption and physical absorption are the two main components of absorption methods. Lu et al. mentioned that chemical absorption is often used as the main method for post-combustion capture technology, while amine absorption is the most mature and commercialized technology at present, and has a mature application background in natural gas desulfurization and the petrochemical industry [14]. The "wet-scrubbing" CO_2 capture technology after combustion is mainly based on primary alkanolamine Multilateral Environmental Agreement (MEA). CO_2 reacts with ammonia solution through a zwitterionic mechanism to form carbamate, and then releases CO_2 by heating. Subsequently, the ammonia solution enters the reaction tower for circulation to further absorb CO_2 [15]. Physical absorption uses organic solvents to physically dissolve acidic gases. Its solubility serves as the driving force for CO_2 absorption. The main research objective is to reduce energy demand and decrease equipment size [3].

Adsorption is the process of capturing CO_2 from a gas mixture and fixing it onto the surface of an adsorbent. It has two main categories: physical adsorption and chemical adsorption. The core of adsorption is the adsorbent. Zeng et al. summarized that CO_2 adsorbents can be classified into physical adsorbents and chemical adsorbents. The structural characteristics of physical adsorbents are the key factors affecting adsorption performance. The entire adsorption process is a surface process, mainly based on the intermolecular attraction between the guest molecules and the active sites on the surface of the adsorbent [16]. Chemisorbents are materials that enable the selective capture of target substances (adsorbates). The core principle is based on the formation of stable chemical bonds between the active sites on the surface of the adsorbent and the adsorbate molecules. These bonds are usually metal elements, which are used in the form of salts or oxides. A variety of adsorbent materials have been studied for use in pressure swing adsorption technology to adsorb CO_2 and improve biogas quality. For example, various solid adsorbents such as activated carbon, zeolite and metal-organic framework (MOF) can capture carbon dioxide through pressure swing adsorption (PSA) [12]. There are also some unconventional adsorbents, such as covalent organic frameworks, activated carbon fibers and ordered porous carbon [12], but they are not within the scope of this article. Das et al. concluded that adsorption technology should focus on the application materials, such as nanomaterials, and then select gas-solid contact reactors based on the type of material and system type to ensure their effectiveness and safety [17].

3.4.2. Chemical Loop Combustion Method (CLC)

CLC is an unconventional combustion method. It was originally designed for fluidized bed systems and has inherent CO_2 capture and separation capabilities. It uses metal oxides as oxygen carriers to transfer O_2 from combustion air to fuel, avoiding direct contact between the two. Subsequently, the combustion products will be separated from the remaining flue gas [11]. In other words, the essential difference between CLC and other conventional carbon capture technologies is that by changing the

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combustion process itself, a high-concentration, nitrogen-free CO_2 stream is generated at the source. The chemical looping combustion system has two reactors, one for air and one for fuel. The oxygen carrier circulates between two reaction vessels, one of which undergoes oxidation and the other undergoes reduction.

3.4.3. Membrane separation method

Membrane separation is a separation method that selectively allows one component of a mixture to pass through while retaining the others. There are four main separation mechanisms: Knudsen diffusion, surface diffusion, molecular sieving, and configurational diffusion. There are many types of membranes, such as Carbon Membranes, Inorganic Membranes, Mixed Matrix Membranes, etc. Different types of membranes have different effects, but in reality, no membrane system can completely achieve this effect [13]. For example, reverse osmosis membranes can be used to prepare medical pure water, water for injection, and concentrate low molecular weight substances such as alkaloids; ultrafiltration membranes can be used to separate proteins, enzymes, etc. Carbon capture uses carbon capture membranes, which are devices that only allow carbon dioxide to pass through while blocking other components in the flue gas. However, the performance of membrane systems is greatly affected by flue gas conditions (such as low carbon dioxide concentration and low pressure), which are the main obstacles to the application of this technology [6].

3.4.4. Direct capture method

Table 1. Comparison of five types of methods

	Advantages	disadvantages	trends
Absorption	Environmental protection, energy conservation, and simplified recycling processes	Complex process, narrow application range, rapid solvent degradation and solvent evaporation	Environmental friendliness and energy reuse align with current sustainable development principles.
Adsorption	Low energy consumption, fast reaction rate, and easy to operate	Low adsorbent yield, poor adsorbent durability and stability, and long gas flow path switching time.	Develop efficient and economical adsorbents with high carbon dioxide adsorption capacity, selectivity, and stability.
Chemical looping combustion	Low cost, recyclable metal oxides, 100% carbon removal efficiency	Lack of experience makes large-scale application difficult.	It can be extended to the combustion of solid fuels and the production of carbon dioxide-free hydrogen.
Membrane separation	High energy efficiency	Membranes are easily degraded	This research aims to improve mechanical strength, chemical and thermal resistance, and reduce the effects of aging without compromising performance.
Direct capture	Reduce energy demand	High cost and large water consumption	Advanced and most promising

Direct air capture (DAC) refers to the process of directly extracting carbon dioxide from the atmosphere to generate a high-concentration airflow, thereby enabling large-scale storage of carbon dioxide and climate intervention. It can be deployed in any region (such as deserts or near the ocean) without relying on centralized emission sources such as factories or power plants, and can directly

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reduce atmospheric CO_2 concentration. However, the costs of adsorption materials, desorption energy consumption and equipment maintenance are high, and the desorption process requires a large amount of energy. Despite current challenges such as high costs and insufficient scalability, this technology has the potential to become an important component of the global carbon removal system in the future, thanks to material innovation, clean energy integration, and policy support.

4. Conclusion

Global warming is a major challenge facing the world in the 21st century, and humanity has introduced the concept of carbon capture to reduce carbon emissions. Currently, there is no single solution to the carbon capture problem; rather, a comprehensive approach is needed that considers capture materials, capture costs, and capture applications. This review aims to highlight the feasibility of existing methods in addressing challenging problems by listing their definitions and characteristics.

Pre-combustion capture allows the product (hydrogen) to be used for power generation after CO_2 is separated. Although pre-combustion capture has the advantages of being environmentally friendly and energy-saving compared to other capture methods, its process is more complex and costly, making it less suitable for commercial applications. Post-combustion capture holds the most promise in the short term. Compared to pre-combustion and oxygen-fuel capture technologies, it can be applied to existing emission technologies without requiring major modifications, making it a feasible carbon capture technology. While the specific methods involved in post-combustion capture are practical in application, they suffer from drawbacks such as high energy and material consumption and environmental unfriendliness. Oxygen-fuel combustion technology, through its innovative design of "oxygen substitution + flue gas recirculation," combines "clean combustion" with "efficient carbon capture," making it one of the core technologies for the low-carbon transformation of the fossil energy industry. In the future, with reduced air separation costs, optimized system integration, and policy support, it is expected to become the mainstream technological path for high-emission industries under the "carbon neutrality" framework.

Currently, adsorption-based CO_2 capture technology and direct capture technology show promising prospects, but several challenges remain to be addressed before large-scale successful application. It is worth noting that with the advancement of sustainable development strategies, the requirements for capture technology are increasingly demanding. Cost-effectiveness and large CO_2 capture capacity are not the only requirements; their environmental friendliness (e.g., using clean energy systems for combustion, and combining with clean energy sources such as photovoltaics, wind power, or geothermal energy) may also be a focus of future development.

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