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Carbon capture technology in industrial flue gas treatment

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Abstract:
With the acceleration of industrialization, the emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2) has increased significantly, and the problem of climate change has become increasingly serious. Carbon capture technology is regarded as an important means to reduce CO_2 emissions from industrial flue gas, mainly including membrane separation, physical adsorption, chemical chain combustion, low-temperature condensation, and amine absorption. Membrane separation is suitable for high-temperature and high-pressure environments, but material stability and cost are challenges; physical adsorption is excellent on high specific surface area adsorbents but is susceptible to high temperatures and high humidity; chemical chain combustion has high-efficiency capture potential but materials are easily depleted; low-temperature condensation is suitable for high humidity flue gas treatment but consumes high amounts of energy; and amine uptake is widely used, but is faced with the problems of absorber degradation and high regeneration energy consumption. In the future, these technologies need to be optimized for efficiency, cost, and compatibility with existing industrial systems to help achieve global carbon neutrality.

Keywords: carbon; dioxide; carbon capture

1. Introduction:

In recent years, with the rapid advancement of industrialization and urbanization worldwide, the emission of greenhouse gases such as carbon dioxide (CO_2) has surged, exacerbating global climate change. As a major source of CO_2 emissions, thermal power generation plays a significant role in contributing to global warming. In response to the climate crisis, many countries have set ambitious targets for reducing greenhouse gas emissions. China, in particular, has committed to achieving a carbon peak by 2030 and carbon neutrality by 2060, aiming to reduce carbon intensity through a series of measures and a transition to a more sustainable energy structure.

Despite these efforts, global CO2 concentrations continue to rise. By 2022, the atmospheric CO_2 concentration had reached approximately 0.042%, significantly exceeding the goal of keeping it below 0.035%, as outlined in the Paris Climate Agreement. At present, due to the insufficient storage and

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peak-shaving capacity of renewable energy, fossil fuel-based power generation remains dominant, accounting for roughly 47% of global CO_2 emissions. Additionally, sectors such as transportation and industrial production are also significant sources of emissions. This persistent high level of CO_2 emissions poses severe threats to global ecosystems and biodiversity, underscoring the urgent need for effective mitigation strategies.

Carbon capture technology, identified in the Paris Agreement as a critical tool for CO_2 emission reduction, has gained widespread recognition. By capturing and storing CO_2 from industrial emissions, this technology offers a viable solution to achieving carbon neutrality. Future research is expected to focus on enhancing absorption and desorption efficiency, developing advanced CO_2separation membranes with high permeability and selectivity, and integrating condensation-coupling technologies. These advancements will play a pivotal role in scaling up carbon capture technologies for industrial applications and accelerating progress toward global carbon reduction goals.

2. Carbon capture and storage technology

Carbon capture technology is the core technology to reduce CO2 emissions from industrial flue gas. According to different working principles and capture paths, carbon capture technology is mainly categorized into chemical absorption, physical adsorption, membrane separation, low-temperature condensation, and chemical chain combustion technology. Each technology has its unique advantages and shortcomings in industrial applications. These technologies and their progress will be discussed in detail below.

2.1 Membrane Separation

Membrane separation is a separation technology based on the selective permeability of membrane materials to gases. It relies on the difference of diffusion coefficient and solubility of different gases in the membrane to realize the purification and recovery of gases through physical separation and separate the target gases from the mixture of gases, and this technology is especially suitable for processing gases such as CO_2 and H_2S. Membrane selectivity is determined by differences in molecular size, solubility, and diffusion rate. Common membrane materials include inorganic membranes, polymer membranes, and composite membranes, which are suitable for capturing greenhouse gases such as carbon dioxide.

In recent years, the membrane separation method has made significant progress in materials science, and researchers have developed a composite membrane based on graphene oxide, which is a membrane material that exhibits excellent CO_2 capture performance with high flux and high selectivity. In addition, the modification of polymer membranes has also attracted much attention, and composite membranes using novel copolymers and nanoparticles can significantly improve their contamination resistance and stability.

2.2 Physical adsorption

The physical adsorption method separates CO_2, NO_x, SO_x, and other gases in the flue gas through the physical adsorption of gas molecules on the surface of the adsorbent. Commonly used adsorbents include activated carbon, zeolite, metal-organic framework (MOF), etc., which are widely used in the field of flue gas treatment because of their high specific surface area and strong adsorption capacity.

The research hotspot of physical adsorption is the development of new adsorbents, especially MOF materials, which are considered to be candidates for the next generation of highly efficient adsorbents due to their structural tunability and ultra-high specific surface area. Wang et al. investigated a new copper-based MOF material, which showed excellent adsorption performance in CO_2 and NO_x traps, and at the same time, the material had good regeneration and stability. Has good regenerability and stability. In addition, significant progress has been made in optimizing the adsorption performance of modified activated carbon and porous carbon materials.

2.3 Chemical chain combustion adsorption

Chemical Looping Combustion (CLC) is a novel combustion technology that reacts carbon in fuel with oxygen to form CO_2 and H_2O by using metal oxides as oxygen carriers. Since CO_2 is generated directly from the combustion process and does not require an additional separation step, CLC is considered a highly efficient CO_2 and H_2 method. $_2$capture technology.

In recent years, research on chemical chain combustion adsorption has focused on the development and optimization of oxygen carrier materials. Zhou et al. investigated a nickel-based oxygen carrier and found that it maintained good redox properties after several cycles of use, indicating its good durability. In addition, iron-based and calcium-based oxygen carrier materials have also received extensive attention, and studies have shown that these materials not only have better reactivity but also reduce the material cost to a certain extent.

2.4 Low-temperature condensation method

Low-temperature condensation method is by cooling the flue gas to a very low temperature, so that the water vapor and other condensable gases (such as CO_2) condensation precipitation, to realize the separation and purification of gas. This method performs particularly well in the treatment of high-humidity flue gases.

Xu et al. showed experimentally that the low-temperature condensation method can effectively capture CO_2 in the flue gas, and the selective condensation efficiency of the gas can be significantly improved under the control of the cooling temperature. In addition, optimizing the condenser design and improving the energy efficiency of the condensation process have become the focus of research. New heat exchange materials and condenser structure design have significantly reduced the energy consumption of the condensation system.

2.5 Amine Absorption

The amine absorption method is one of the most widely used CO_2 capture technologies. This method utilizes amine compounds to react with CO_2 to form reversible bicarbonate or carbonate, thus realizing the capture and separation of CO_2. Commonly used amine absorbents include monoethanolamine (MEA), diethanolamine (DEA), and triethanolamine (TEA). In recent years, the amine absorption method has made important progress in the development of absorbents and process optimization. Garcia et al. proposed an amine absorber based on a deep eutectic solvent, which has higher CO_2 capture capacity and regeneration performance at lower energy consumption. In addition, the improvement of the absorber tower design to increase the gas-liquid contact efficiency has also become an important direction of technological progress.

3. Post-combustion capture technology

3.1 Flue gas cooling

Before the flue gas enters the absorption tower, it must be cooled first. The flue gas temperature from combustion is usually high, and the cooled gas temperature can improve the efficiency of the subsequent chemical absorption stage. Cooling is usually provided by air or water coolers. Post-combustion capture can be applied to existing coal-fired power plants and other industrial facilities and is particularly suitable for retrofitting and upgrading existing facilities. Since it treats the emission gases after the fuel has been combusted, it does not require major modifications to the existing combustion process. This characteristic makes PCC technology one of the easiest of today's emission reduction technologies to implement.

3.2 Chemical absorption

The cooled flue gas is introduced into an absorption tower where it reacts with an absorbent. Currently, **amine solvents** (e.g., monoethanolamine, MEA) are the most commonly used chemical absorbers. These solvents can react efficiently with CO_2 to produce soluble bicarbonates or other compounds. The use of MEA has been extensively studied, but it also faces problems such as high energy consumption and solvent degradation. Improved amine solvents and novel adsorption materials, such as metal-organic frameworks (MOFs), are being investigated to improve capture efficiency and reduce costs.PCC can treat flue gases from a wide range of fuels, such as coal and gas, and can be combined with other carbon capture technologies, such as Bioenergy with Carbon Capture and Sequestration (BECCS), to achieve negative emissions. In addition, through chemical absorption, CO_2 can be efficiently removed from low-pressure, low-concentration flue gases, which is critical for many industrial facilities.

3.3 Absorbent Regeneration

The solution that has captured CO_2 in the absorber tower is then sent to the regeneration tower where it is heated to release high purity CO_2 gas and the absorbent is regenerated and recycled. This process is one of the most energy-intensive aspects of post-combustion capture, as the regeneration of the solvent consumes a large amount of thermal energy. Studies have shown that energy consumption can be significantly reduced by improving the regeneration process and selecting more efficient solvents.

3.4 Carbon dioxide storage and compression

Captured high-purity CO_2 is subsequently compressed and stored, typically for geological sequestration or other industrial applications. Compressing CO_2 is a critical step in its transportation to a storage site or other use. Further improvements in energy efficiency in this process can be achieved by optimizing the compression equipment.

3.5 Carbon capture and absorption solvent types

The most commonly used solvents in Post-Combustion Capture (PCC) technology are amine solvents, the most widely used of which include monoethanolamine (MEA), diethanolamine (DEA), and methyl diethanolamine (MDEA). These solvents are more frequently used in industrial capture due to their high CO_2 absorption efficiency and ease of handling.PCC technology is based on proven chemical absorption processes, especially us-

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ing amine solvents (e.g., MEA), which have high CO_2 capture efficiency. A large number of experimental and industrial projects have been carried out showing that PCC technology can capture more than 90% of CO_2.

3.5.1 Monoethanolamine (MEA)

MEA is the most commonly used solvent for CO_2 absorption at this stage, with the advantage of high absorption efficiency and the ability to effectively capture CO_2 at lower CO_2 partial pressures. Its fast absorption kinetics gives it a high capture efficiency in the early stages of capture, making it suitable for most combustion flue gas treatments. Higher energy consumption: The regeneration process of MEA requires a high level of heat, which can lead to a reduction in the energy efficiency of the whole system. Highly corrosive: MEA is highly corrosive and requires additional protection of the equipment. Solvent degradation issues: MEA is prone to degradation at high temperatures or when in contact with other impurities, which can affect its service life and cost.

3.5.2 Diethanolamine (DEA)

DEA has a relatively low absorption efficiency compared to MEA, but is less corrosive,which makes it safer and more economical for certain industrial applications. Solvent regeneration is more efficient and requires less regeneration energy compared to MEA.Lower absorption efficiency than MEA: DEA has a slower absorption rate and is therefore inferior to MEA in application scenarios where efficient capture is required.

3.5.3 Methyl Diethanolamine (MDEA)

MDEA has high selectivity and can effectively capture CO_2 while absorbing less of the other gases in the flue gas (e.g., H_2S), which is more favorable for the treatment of mixed gases.The regeneration process of MDEA requires less thermal energy, which helps to reduce system operating costs.Slower absorption: The absorption kinetics of MDEA is slower than both MEA and DEA, which may result in lower capture efficiency, especially at lower CO_2 concentrations.

4. Carbon dioxide storage applications and challenges:

Despite the advantages of simple structure, low energy consumption, and non-pollution, membrane separation methods still face challenges in large-scale industrial applications such as stability of membrane materials, performance degradation under high temperature and high-pressure conditions, and high cost of development of efficient membrane materials. In addition, the membrane has a limited lifetime and is easily affected by impurities in the flue gas, such as particulate matter and water vapor, which reduces the separation efficiency under complex industrial conditions. The limitations of physical adsorption methods mainly lie in the selectivity and regeneration performance of adsorbents. Conventional adsorbents are prone to degradation under high temperature and high humidity conditions, which affects the stability of long-term operation, and how to improve their selectivity and adsorption capacity under mixed-gas environments still needs to be addressed.

Although chemical chain combustion adsorption has significant advantages in CO_2 capture, the cost and recycling performance of oxygen carrier materials are the main bottlenecks for its industrial application, and oxygen carriers are susceptible to structural damage under high-temperature conditions, leading to a decrease in activity. In addition, seamless integration with existing industrial combustion equipment is an urgent issue. The biggest challenge of low-temperature condensation is the high energy consumption, the cooling process requires a lot of energy when treating large amounts of flue gas, and the system is expensive to operate. The main challenges of amine absorption are absorber degradation and high energy consumption, and the regeneration process of the absorber usually requires high-temperature heating, limiting its industrial application. Future research directions include the development of new solvents, improvement of process efficiency, reduction of energy consumption, and construction of stable CO_2 storage networks.

5. Conclusion

Carbon capture technologies are critical in reducing CO_2 emissions from industrial flue gases. Current technologies include membrane separation, physical adsorption, chemical chain combustion, low-temperature condensation, and amine absorption, as well as post-combustion capture technologies. Each technology has its advantages and disadvantages in industrial applications. Membrane separation is based on selective permeability and is suitable for high-temperature and high-pressure environments, but material stability and development costs are bottlenecks. Physical adsorption, on the other hand, relies on high specific surface area adsorbents, which, although more selective, are susceptible to degradation at high temperatures and high humidity. Chemical chain combustion utilizes metal oxides as oxygen carriers for efficient CO_2 capture, but the materials are costly and easily damaged when recycled. Low-temperature condensation is suitable for high-humidity flue gas, but high energy consumption limits its large-scale application. Amine absorption is widely used for CO_2 capture, but degradation of the absorbent and high energy consumption during regeneration are major challenges. The development and optimization of these technologies play an important role in driving the industrial application of carbon capture.

6. expectation

The future development of carbon capture technology will be devoted to improving the efficiency and economy of various technologies. First, the membrane separation field will focus on the development of highly efficient, pollution-resistant composite membrane materials to cope with the problem of performance degradation under high-temperature and high-pressure environments. Meanwhile, the research of physical adsorption technology will focus on the development of new adsorbents, especially the application of highly selective adsorbent materials such as metal-organic framework materials (MOF). Chemical chain combustion technology, on the other hand, needs to make breakthroughs in the cost and stability of oxygen carrier materials to achieve long-term stable capture performance. For low-temperature condensation technology, reducing energy consumption and optimizing heat exchange design will be the core tasks. In addition, amine absorption will improve the capture efficiency by developing new low-energy absorbers and optimizing the absorption tower design. In the future, the wide application of carbon capture technology will need to be combined with the construction of supporting facilities such as CO_2 compression, transportation, and geological storage, to realize the carbon emission reduction target and promote the global progress towards carbon neutrality.

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