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A 150 000 t·a^{-1} Post-Combustion Carbon Capture and Storage Demonstration Project for Coal-Fired Power Plants

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1. Introduction

Climate change is one of the most severe challenges facing the world today. At present, China produces total annual carbon dioxide (CO_2) emissions of over 10 billion tonnes, topping the world in this regard. Although coal empowers China's economic development, its use presents a great challenge to the nation's desired goals of peaking carbon emissions and achieving carbon neutrality. In this context, the low-carbon utilization of coal is an inevitable trend for future development. Exploring new ways to reduce CO_2 emissions on a large scale in the utilization of coal—especially during coal-fired power generation—is essential in order for China to achieve carbon neutrality.

Carbon capture, utilization, and storage (CCUS) is a technical process in which CO_2 is separated from the emission source and then utilized or stored directly to reduce CO_2 emissions [1,2]. Thus far, CCUS is the only emission–reduction technology that makes the large-scale low-carbon utilization of fossil energy a reality, so it is an important component of China's technology portfolio for carbon neutrality by 2060. The main carbon-capture techniques can be divided into three categories: pre-combustion capture, in-combustion capture (i.e., oxygen-enriched combustion), and post-combustion capture. Compared with the first two categories, post-combustion capture is an important approach for large-scale CO_2 capture at present, due to its high capture efficiency, good adaptability, wide application, and mature technology.

A post-combustion CO_2 capture technology known as the chemical absorption method involves absorbing and separating the CO_2 from flue gas using an alkaline amine-based absorbent. This method has the advantages of good flue gas adaptability, high capture efficiency, and relatively mature technology, all of which make it a potential technical route for large-scale CO_2 capture [3]. The Boundary Dam Project in Canada is one million tonnes per annual Carbon Capture and Storage (CCS) Demonstration Project (put into operation in 2014) for coal-fired power plants, which applies a SO_2–CO_2 joint capture process. The high-concentration CO_2 obtained from this process is used for oil displacement in an oilfield located 70 km away. Its capture cost is about 105 USD per tonne CO_2 (tCO_2^{-1}). The Petra Nova Project in the United States (put into operation in 2017) features a designed carbon-capture capacity of 1.4 million tonnes per annual and applies the chemical absorption method. The resulting high-concentration CO_2 is used for oil displacement, and its capture cost is about 55–60 USD·tCO_2^{-1}. The latter project was shut down during the coronavirus disease 2019 (COVID-19) pandemic; moreover, it is difficult to promote such a project on a large scale due to its high overall operating cost.

For China's 150 000 t·a^{-1} Post-Combustion Carbon Capture and Storage Demonstration (PCCSD) Project for Coal-Fired Power Plants, efforts were made to carry out research on absorbent selection, process optimization, and equipment enhancement; to innovatively integrate low-energy, high-efficiency, and energy-saving techniques; and to develop a complete low-energy CCS system for coal-fired power plants, with the aim of putting it into industrial operation.

2. Overview

The key to accelerating the commercial promotion and application of CCUS technology is to continually reduce the energy consumption of CO_2 capture. How to control and reduce carbon emissions has become one of the bottlenecks restricting coal-fired power generation and holding back the sustainable development of the power industry [4]. Considering the large flow and complicated composition of flue gas, the low partial pressure of CO_2, and the presence of SO_2, nitrogen oxides (NO_x), and other acid gases in flue gas, innovative research on the optimization of post-combustion CCS techniques were performed for coal-fired power plants, following the concept of a high-efficient, low-energy, and cost-effective carbon-capture design. As a result, the 150 000 t·a^{-1} PCCSD Project for Coal-Fired Power Plants was built (as shown in Fig. 1), which is the largest post-combustion CO_2 capture, enhanced oil recovery (EOR), and sequestration whole-process demonstration project for coal-fired power plants in China to date.

Located in the grounds of CHN Energy Jinjie Energy Co., Ltd. (Jinjie Energy), the PCCSD Project runs smoothly at 50%–110% capacity and can capture 18.75 t of CO_2 per hour from the desulfurized flue gas after ultra-low emission transformation resorting to

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Fig. 1. Panorama of 150 000 t·a^{-1} PCCSD Project.

the 600 MW subcritical unit No. 1. It is a major project-based carbon emission–reduction demonstration project built by CHN Energy Investment Group Co., Ltd., in cooperation with relevant enterprises, universities, scientific research institutes, and so forth in China, under the model of industry–university–institute cooperation through collaborative innovation. Commenced in 2016, PCCSD Project has now been configured from 95% self-developed devices after proposal research, the preparation of technical conditions, bench-scale test validation, new equipment research and development, technology package development, and demonstration project construction. A complete low-energy CCS system that is adaptable to the characteristics of the flue gas from coal-fired power plants has been developed. Moreover, a comprehensive overall analysis has been done of the entire industrial chain, from CO_2 capture, transportation, sales, and utilization to sequestration/EOR, while considering the local actualities in order to work out a comprehensive carbon-reduction solution for large thermal power plants.

3. Engineering technologies

3.1. Integrated high-efficiency and energy-saving techniques

To address the low CO_2 concentration, large total quantity, high humidity, and complicated composition of the flue gas, a high-efficiency and energy-saving technique featuring inter-cooling, staged desorption, and mechanical vapor recompression (MVR) flash evaporation was innovatively developed for PCCSD Project (as shown in Fig. 2). The aim was to simultaneously improve the technical and economic efficiency of the overall system in the three dimensions of absorption, regeneration, and energy conservation, to obtain a low-energy and cost-effective system. The inter-cooling process inside the absorber fully takes into account the optimal absorption temperature of the absorbent. It controls the temperature distribution in the absorber to improve the absorption efficiency. The shunt desorption process inside the stripper helps to determine an appropriate shunting proportion via energy matching and gradient utilization, thereby reducing the energy consumption for regeneration. Hot lean amine steam is recovered by MVR vacuum flash evaporation. The application scenarios in coal-fired power plants are further coupled by the integrated technology, thus achieving intensive energy conservation. The waste heat from the regeneration gas in the complete CCS system and from the power plant is fully utilized in order to effectively reduce the regeneration energy consumption of the system. With the joint effect of this new low-energy absorbent and energy-saving technique, the energy consumption can be reduced by 40% compared with the monoethanolamine (MEA) absorption system, forming a new technological system for high-efficiency and low-energy CO_2 capture suitable for coal-fired power plants in China.

The flue gas is desulfurized by the unit No. 1 of Jinjie Energy and extracted from the outlet flue; it then enters the scrubber for washing, cooling, and deep desulfurization. Next, it flows to the absorber where the inter-cooling technique is applied. After absorbing the CO_2 in the flue gas, the new absorbent becomes amine rich and flows out from the bottom of the absorber in two streams. One stream first enters the exchanger for heat recovery and then flows into the desorption column; the other stream goes directly into the desorption column, where CO_2 is desorbed under the heating action of the reboiler. The second stream then becomes the lean amine stream, flowing out from the bottom of the desorption column and entering the flash tank for flash evaporation. The desorbed CO_2 passes through the gas–liquid separator, resulting in gaseous CO_2 with a purity of more than 99.5% (dry gas), which

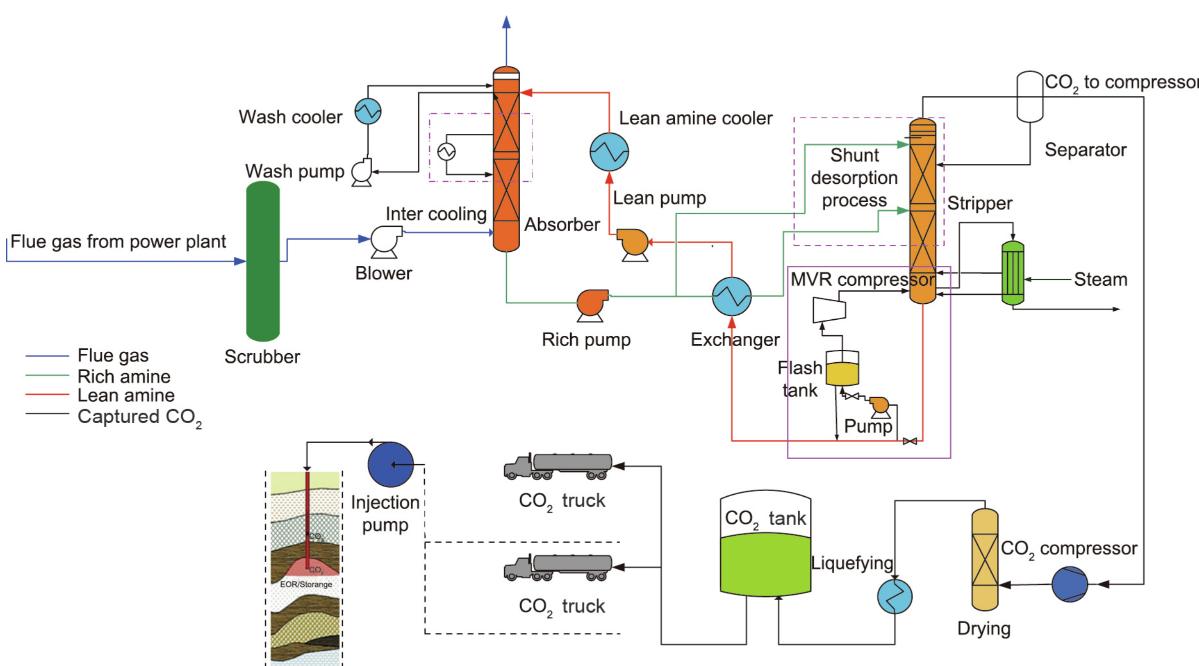

Fig. 2. The high-efficiency and energy-saving technique applied by the capture device.

then enters subsequent sections such as compression for further processing. The pressure of the CO_2 at the outlet of the compressor is 2.5 MPa (gauge) and the temperature is 40 °C. The compressed CO_2 enters the purifying column for dehydration and drying. The dried CO_2 then enters the CO_2 condenser and sub-cooler for liquefying and cooling to below −20 °C. After being completely liquefied, the CO_2 is sent to the CO_2 tank for storage.

3.2. New absorbent and recovery

A new organic composite amine-based absorbent has been applied in PCCSD Project. Compared with conventional MEA-based absorbents, this novel absorbent combines a polyamine–amine with a sterically hindered amine to form a composite amine with a large absorption capacity (as shown in Fig. 3). The absorption capacity, desorption effect, and operational stability of the composite amine has been ensured through molecular design and functional group matching, while absorbent recovery and regeneration technology was applied in a targeted manner. The volatilization characteristics of the absorbent directly affect the operating cost, and low-loss operation of the absorbent can be realized through compounding and fined regulation of the absorbent. A small number of foreign gases (e.g., NO_x, SO_x, and O_2) in the coal-fired flue gas will react with the organic amine; thus, long-term operation will lead to the formation and enrichment of heat-stable salt (HSS) in the amine solution, which will further result in a decrease in the absorption capacity of the solution. Therefore, the HSS level in the amine solution is controlled at below 3% of the amine concentration for efficient operation of the system.

3.3. Research and development of a complete CCS system

A complete CCS system comprising columns, heat exchangers, power equipment, compression and liquefying devices, and drying and purifying devices was developed and successfully applied to PCCSD Project for Coal-Fired Power Plants, which is the largest project of its kind in China to date, achieving the high-efficiency capture of low-concentration CO_2 and obtaining liquid CO_2 with a purity of up to 99.97%. The performance of the complete carbon capture system was optimized to align with the characteristics of coal-fired power plants, as well as the situation of the upstream and downstream links.

3.3.1. High-efficiency columns

Given the low concentration and partial pressure of CO_2 in coal-fired flue gas in a real-life scenario, special types of separating elements and internals were used. Finally, a three-column device comprising a new high-efficiency scrubber, an absorber, and a stripper suitable for the capture of carbon in coal-fired flue gas was successfully developed. The columns provide structured packing, support plates, support beams, initial liquid distributors, liquid collectors, two-stage liquid redistributors, and gas distributors. High-efficiency internals for the separating column are used to build a uniform distribution system in the column to increase the gas–liquid contact area and residence time, thereby reducing the pressure drop, improving the absorption efficiency, and reducing the energy consumption. A modified polypropylene plastic packing was used in the column for the first time (as shown in Fig. 4), and the absorption capacity and hydrophilicity of the plastic packing were improved through chemical modification. The total weight of the column bodies and the total investment were reduced while ensuring that the requirements for the columns were satisfied. The absorption efficiency of the chemical absorption solvent and the operation stability of the large-scale device were improved through a recollection and redistribution design in order to reduce energy consumption and solvent loss.

3.3.2. Energy-saving heat exchanger

As it is difficult to make use of the low-grade heat from the chemical absorption system, a fully welded plate heat exchanger, which has high efficiency and a low terminal difference, was independently developed. The heat exchanger is composed of heat exchange plates, an upper cover plate, a lower cover plate, a baffle board, a sealing gasket, and support, forming a cross-flow passage (as shown in Fig. 5); the exchanger features a compact structure, quick disassembly, a small installation space, and a flexible installation method. With their large heat-transfer area and good heat-transfer effect, plate-type heat exchangers are widely used in the chemical industry. Compared with a traditional tube-type heat exchanger, a plate-type heat exchanger can effectively reduce the terminal temperature difference of the heat exchange by 10 °C on average, increase the overall heat-recovery efficiency by 0.5%, and reduce the material consumption of the heat exchanger by about 50%.

The application of a new falling film reboiler (as shown in Fig. 6) assists in alleviating the thermal degradation of the absorbent due

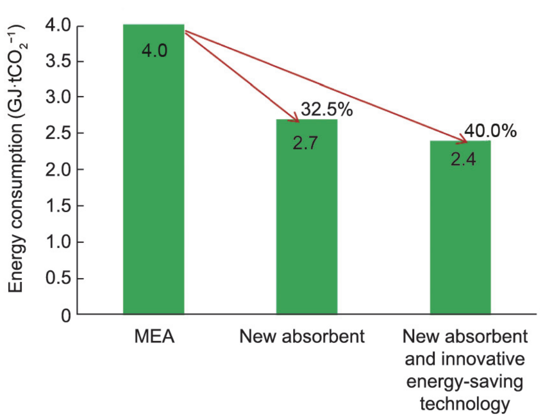

Fig. 3. Changes in the energy consumption of the capture device for 150 000 $t\cdot a^{-1}$ PCCSD Project.

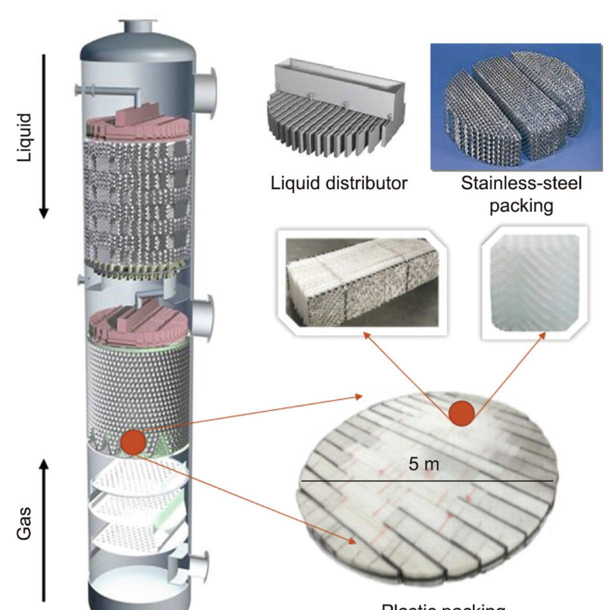

Fig. 4. Internal structure of the column and main internals.

to a short residence time and completes the evaporation process inside due to a large heat-transfer coefficient, with no space required for gas–liquid separation. With great operation flexibility and single-pass evaporation intensity, the reboiler can maintain a relatively high heat-transfer coefficient when running at a load of 50% flow. Featuring a compact structure and a one-time evaporation capacity of up to 30%, it is more efficient than conventional horizontal reboilers.

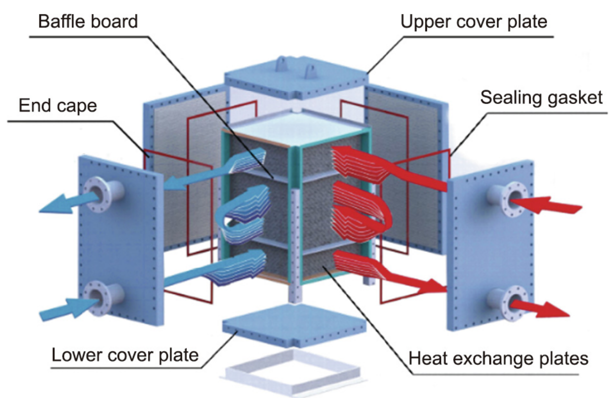

Fig. 5. Structure of the heat exchanger with high efficiency and a low terminal difference.

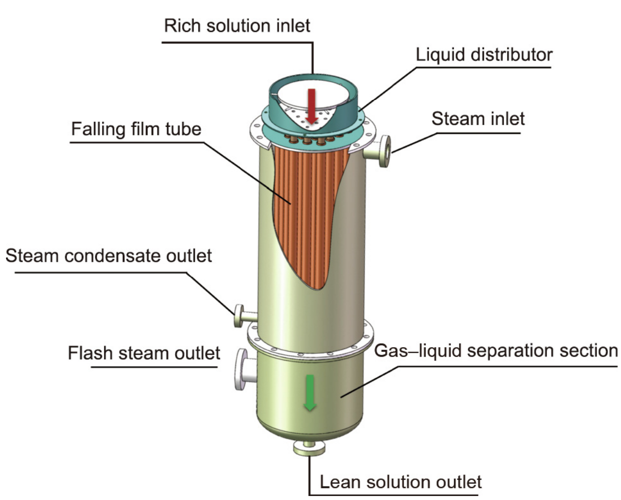

Fig. 6. Structure of the tube-type falling film reboiler.

3.3.3. Compressor

PCCSD Project uses a flexible screw-type CO_2 compressor, which has the largest single row to date. The asymmetric arc profile was developed based on full consideration of the thermal characteristics of the CO_2 working medium and the operating conditions of the carbon-capture demonstration project (as shown in Fig. 7(a)). The 5:7 gears have been adopted for the CO_2 profile. With equal diameters, the female and male rotors feature a high bearing capacity and are suitable for operating conditions with a large CO_2 pressure difference. The availability of low-pressure and high-pressure stages helps to improve the bearing capacity of the female rotor and solve the rigidity problem of the rotor under the operating conditions of the CO_2 compressor, which involve a great pressure difference. Featuring a short contact line, stable gearing, good sealing performance, and high efficiency, the compressor helps to improve the efficiency related to the natural working medium. Being regulated with a slide valve, it can be regulated within a range of 15%–100% to achieve low energy consumption. Thus, a configuration of two rows of 50% compressors (as shown in Fig. 7(b)) ensures an energy-saving, efficient, flexible, and stable system.

3.3.4. The drying system

PCCSD Project adopts a closed-cycle dehydration isobaric drying system (as shown in Fig. 8). The externally supplied regeneration gas of the drying system is repeatedly used with no steam being exhausted, which greatly reduces the steam consumption. The drying system performs drying and dehydration of gaseous CO_2, thermal regeneration of the desiccant, and cooling of the desiccant. After system optimization and programmed control, the drying unit can realize online drying and online regeneration of the desiccant, as well as continuous and stable operation through temperature swing adsorption (TSA). As it is subject to advanced intelligent control, the drying unit features a high degree of automation and can detect the flow, temperature, and pressure. The characteristics of the CO_2 were fully considered when selecting the materials, determining the structure, and designing the electrical safety of the instruments to ensure accurate monitoring and measuring.

3.4. Establishing an entire chain of CO_2 capture, transportation, and storage–EOR–utilization

The entire chain operation for coal-fired power plants, including carbon capture, transportation, and sales, carbon utilization, and EOR, has been realized for PCCSD Project. A tanker with a capacity of 20 t is used for transportation. All captured CO_2 is utilized in

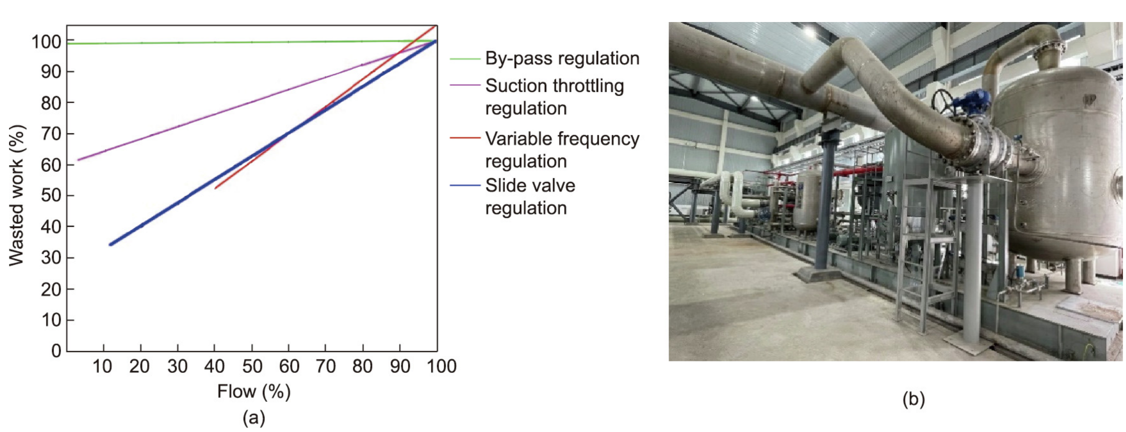

Fig. 7. Two-stage screw-type compressor and regulation capabilities. (a) Regulation capabilities; (b) the two-stage compressor.

Fig. 8. The closed-cycle drying system.

three ways, considering the actualities of the local CO_2 market. Firstly, it is used for EOR in oil fields located about 200–300 km away. Secondly, it is used to prepare baking soda (sodium bicarbonate) in the chemical industry, at a factory located about 200 km away. Thirdly, it is used to prepare high-value chemicals (e.g., dimethyl carbonate and propylene glycol) at a transportation distance of about 50 km away. As it is directly affected by the transportation distance, the cost of the produced CO_2 is roughly 0.1 $CNY{\cdot}km^{-1}{\cdot}tCO_2^{-1}$ and the capture cost is about 250–280 $CNY{\cdot}tCO_2^{-1}$. The transportation cost is about 200 $CNY{\cdot}tCO_2^{-1}$, taking full account of the distance to the utilization terminal. Thus, PCCSD Project is sustainable if the sale price is greater than 450–480 $CNY{\cdot}tCO_2^{-1}$. Accordingly, the establishment of a recycling method for the entire CO_2 chain within the range of the CCS device will promote the formation of a virtuous cycle. Further planning the industrial layout of entire-chain CO_2 cyclic utilization around the area of the CO_2 capture device is a systematic problem that will be considered in the future development of the CCUS industry.

4. Conclusions

The 150 000 $t{\cdot}a^{-1}$ PCCSD Project for Coal-Fired Power Plants applies a new-generation low-energy-consumption chemical-absorption-based CO_2 capture technique featuring high capture efficiency and reliable operation, empowering large-scale CO_2 emission reduction in coal-fired power plants. The CCS device has attracted global attention and received a strong response due to its state-of-the-art techniques, reliability, and low energy consumption, which make it a pioneer and model in the industry. Customized for carbon reduction in coal-fired power plants, the CCS device offers a systematic solution for large-scale carbon capture based on unique technical paths and a complete CCUS system.

More efforts need to be made to research and apply new technologies and equipment for CCS devices, the intelligent control of future CCS devices, the integrated design of coal-fired power plants, and overall low-energy operation for further advancement. An effective measure to reduce the operating cost of coal-fired units is to maximally reduce the absorbent loss. Establishing a large-scale carbon cycle system is an important topic for carbon neutrality in the future. As the demonstration project continues over time, the focus of carbon-emission reduction in coal-fired power plants will shift to the transportation, utilization, and storage of CO_2. Since the distance over which the CO_2 is transported is closely related to the cost, approaches involving short-distance utilization—or even local utilization—need to be explored for a more cost-effective carbon cycle.

Additional endeavors are also needed to promote the expanded utilization of CO_2 as a resource or type of energy and to collaborate with the chemical industry, building materials industry, biological carbon-sequestration industry, and other industries to seek and form multi-channel, multi-product, and multi-form utilization patterns that match the scale of CO_2 capture.

Acknowledgments

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