

Research and Development on the Technology of Oxy-Fuel Combustion

Faran Zhang *

School of Energy Science and Engineering, Central South University, Changsha, Hunan

* Corresponding Author Email: 2784143137@qq.com

Abstract. Oxy-fuel combustion technology is one of the most promising technologies for large-scale carbon capture in coal-fired power plants. Based on a brief introduction of the R&D progress of Oxy-fuel combustion technology at home and abroad, this study summarizes the development process of Oxy-fuel combustion technology at this stage, and specifies the next development direction of Oxy-fuel combustion technology. It should further improve the economy of Oxy-fuel combustion technology and promote the large-scale demonstration and application of Oxy-fuel combustion technology through the development of low-energy and low-cost oxygen generation technology, further implementation of Oxy-fuel burner amplification, and exploration of new low-NO_x Oxy-fuel combustion systems such as hierarchical Oxy-fuel and flameless Oxy-fuel. Further research and development of acid gas co-compressing process and the optimization of the whole-plant system coupling should be carried out to support the research and development of a new generation of Oxy-fuel combustion technology.

Keywords: Oxy-fuel combustion; process; technology.

1. Introduction

With the growing threat of global warming, limiting carbon emissions has become a top priority for all countries. As a novel high-efficiency energy-saving combustion technology and carbon dioxide emission reduction technique, Oxy-fuel combustion has piqued the interest of governments all over the world. In general, when Oxy-fuel combustion occurs, the CO₂ concentration in the flue gas increases dramatically, typically exceeding 20%. Compared to conventional combustion, this high CO₂ output feature allows for the subsequent use of carbon capture and storage technology, reducing greenhouse gas emissions and having a positive impact on climate change mitigation. By using oxygen instead of air as the combustion agent, Oxy-fuel combustion technology dramatically raises the CO₂ content in the flue gas, frequently by more than 20%, making it an ideal pre-condition for carbon capture and storage (CCS) technology. Compared to normal burning, this high CO₂ concentration substantially simplifies the subsequent CO₂ separation and storage process, lowering greenhouse gas emissions. As a result, Oxy-fuel combustion technology has significant application value in reducing climate change and is a critical technical direction in worldwide emission reduction efforts. China, the US, Spain, Canada, Australia, Japan, and other countries has been independently developed Oxy-fuel combustion technology and equipment.[1] Leading Oxy-fuel combustion companies worldwide include Alstom, Proterial, Ltd, Babcock & Wilcox and others. At present, the research and development of Oxy-fuel combustion technology has entered the pilot demonstration stage, and four sets of 30 ~ 35 MW demonstration power plants have been put into operation worldwide.[2] The world's first full-process 30 MW Oxy-fuel combustion experimental unit was constructed by Schwartz Pump Company in Germany. The system comprises an air separation system, an Oxy-fuel combustion boiler unit, a flue gas recirculation system, a flue gas dust removal device, a desulfurization and denitrification system, a steam water separation and flue gas compression unit, a CO₂ liquefaction rectification unit, and a CO₂ transport and storage system.[3] The performance tests of the CO₂ compression purification system conducted on this experimental device show that the final CO₂ purity after passing through the CO₂ treatment unit is more than 90%. The performance assessments of the CO₂ compression purification system on the experimental equipment indicate that the final CO₂ purity exceeds 90% after passing through the CO₂ treatment unit.[4]

To enhance the utilization of Oxy-fuel combustion technology throughout industrial sectors, it is essential to innovate diverse Oxy-fuel combustion devices tailored to certain industrial settings. Simultaneously, research is being conducted on fractional combustion and low NO_x Oxy-fuel combustion technology. Furthermore, to achieve energy-efficient and cost-effective oxygen production technology, there is a focus on advancing membrane separation technology for widespread industrial use. It is essential to optimize the connection of the thermal system minimizes energy consumption and maximizes the utilization of waste heat from smoke exhaust and oxygen production. It is also necessary to enhance the carbon trading system by converting the carbon reduction benefits of Oxy-fuel combustion, such as energy efficiency, carbon emission reduction, and carbon capture, into tradable commodities to encourage the adoption of Oxy-fuel combustion technology in industries.[5] Actually, utilizing Oxy-fuel combustion technology to its full potential is crucial for advancing the low-carbon transformation of energy structure. Thus, it is essential to categorize and consolidate the current Oxy-fuel combustion technology to serve as a guide for future research and development in this field.

2. Pulverized coal boiler Oxy-fuel combustion technology

Pulverized coal boilers use Oxy-fuel combustion technology, which is an advanced combustion technology. Pulverized coal is fully combined with oxygen at a high temperature by infusing high concentrations of oxygen, which improves combustion efficiency and reduces dangerous gas emissions. In this technique, burning under oxygen-rich conditions increases the concentration of CO₂ in the flue gas, while the concentration of oxygen is higher than that of air combustion, thus modifying the physical and chemical properties of the combustion process.[6]

The oxygen concentration in Oxy-fuel combustion technology and the CO₂ content in the final flue gas are critical criteria. A coal power business saw a significant benefit improvement after transforming its pulverized coal boiler to Oxy-fuel combustion technology. Prior to the change, the boiler's combustion efficiency was around 85%, and the CO₂ percentage of the flue gas was roughly 12%. After transforming to Oxy-fuel combustion technology, the combustion efficiency is enhanced to 90%, and the CO₂ content in the flue gas is more than 20%.[7]

Oxy-fuel combustion technology provides benefits in enhancing energy utilization efficiency and decreasing emissions. However, its practical implementation requires careful consideration of equipment cost, energy consumption, and other relevant aspects. Oxy-fuel combustion technique necessitates additional equipment such a pulverized coal preparation system and powder feeding system. The overall investment and operational costs of these equipment should be thoroughly evaluated. Oxy-fuel combustion can lead to corrosion of the boiler's metal wall, necessitating frequent inspection and maintenance, hence raising operational and maintenance expenses.[8] As a result, while transforming Oxy-fuel combustion technology, it is critical to carefully analyze investment and revenue and select the most appropriate technological scheme to ensure economic viability.

Utilizing micro-Oxy-fuel combustion technology involves pre-mixing oxygen and air to manage the oxygen concentration in the mixed gas between 21% and 23%, which can enhance boiler efficiency and save operating costs to a degree. The current pulverized coal boiler at the chemical plant operates with an average efficiency of 88% and incurs considerable operational costs. The boiler's efficiency climbed to 89% and operating costs decreased by 5% following the implementation of micro-Oxy-fuel combustion technology. Preliminary estimations suggest that approximately 100,000 yuan can be saved in annual running costs.[9]

Utilizing micro-Oxy-fuel combustion technology can enhance the combustion efficiency of the boiler, decrease coal consumption, thus lowering the operational expenses of the boiler and enhancing its economic viability. The Oxy-fuel combustion technology of pulverized coal boiler and its enhanced micro-Oxy-fuel combustion technology are highly important for enhancing energy utilization efficiency, decreasing emissions, and cutting operational costs. When using this concept in practice, it is important to take into account elements such as technical proficiency, cost-

effectiveness, and other relevant considerations in order to select the most suitable technical approach.[10] The application of Oxy-fuel combustion technique was initially implemented in a pulverized coal boiler. Excessive gas recirculation, high power consumption and poor efficiency are drawbacks of using Oxy-fuel combustion in pulverized coal boilers. The present research on Oxy-fuel combustion in boilers is primarily centered on circulating fluidized bed boilers.

3. Circulating Fluidized Bed(CFB) Oxy-fuel Combustion Technology

More than 3,000 circulating fluidized bed (CFB) boilers have been erected in China, bringing the total installed capacity to close to 100 million kilowatts. By replacing existing boilers with Oxy-fuel combustion technology, it will be possible to preserve the low pollutant emission characteristics while simultaneously increasing heat transfer efficiency and lowering flue gas emissions.[11] This technology's application indicates that it will evolve into a more beneficial combustion technology and signifies the advancement path of clean coal power technology. The researchers discovered that increasing the oxygen content in the furnace improved the burnout of the fuel through numerical simulations. A study on a 200 MW Oxy-fuel combustion boiler revealed that radiation heat transfer intensity rose in the high temperature zone, whereas convective heat transfer intensity fell in the low temperature zone due to reduced smoke volume.[12] The Oxy-fuel combustion method of CFB boiler enhances heat transfer intensity in the furnace by reducing gas volume, boosting temperature, and improving radiation heat transfer. Research indicates that there exists an ideal level of oxygen that enhances thermal efficiency and ensures proper burn down time. The method prolongs the fuel's stay in the furnace, enhances the combustion rate, decreases solid loss from incomplete combustion, reduces smoke loss, and ultimately enhances the boiler's efficiency.[13] A study on oxygen enrichment transformation of a 210 MW CFB boiler revealed that gas recirculation technology can lower the oxygen levels in the primary air without impacting the boiler's fluidization efficiency. This creates a reducing atmosphere in the dense phase area and decreases the production of nitrogen oxides.[14]

Circulating fluidized bed and Oxy-fuel combustion technologies have garnered significant interest for their high efficiency, environmental sustainability and cost-effectiveness. This technology involves injecting oxygen-rich air into the furnace to enhance fuel combustion, utilizing circulating fluidized bed technology to recover and reuse heat and exhaust gas, thereby greatly enhancing combustion efficiency. This method involves burning fuel at high temperatures, then efficiently recycling the generated heat and exhaust gases to heat the fuel and air in a closed-loop cycle. This technique improves combustion efficiency, decreases exhaust emissions, and minimizes environmental harm.[15]

4. Catalytic Cracking Oxy-fuel Combustion and Carbon Capture and Storage Technology

The catalytic cracking Oxy-fuel combustion carbon capture technology integrates catalytic cracking with Oxy-fuel combustion to enhance combustion efficiency and carbon dioxide (CO₂) capture efficiency, thereby reducing greenhouse gas emissions. Figure 1 illustrates the process flow of Oxy-fuel combustion carbon capture in catalytic cracking. This method enhances fuel combustion and elevates CO₂ levels in the flue gas by utilizing high-purity oxygen instead of regular air as an oxidizer in the catalytic cracking process. This adjustment decreases the formation of nitrogen oxides (NO_x) and makes it easier to capture and use CO₂ because nitrogen is reduced during burning.[16]

During catalytic cracking, heavy hydrocarbons are transformed into lighter hydrocarbons and CO₂. Oxy-fuel combustion also increases the amount of CO₂ in the flue gas. The final outcome of this sequence of reactions is carbon dioxide (CO₂), which can be collected, pressurized, and utilized in several industrial processes.[17] In this way, The catalytic cracking Oxy-fuel combustion method enhances energy conversion efficiency and minimizes greenhouse gas emissions. The application

examples demonstrate that implementing Oxy-fuel combustion carbon capture technology may greatly enhance combustion efficiency and CO₂ capture rate. An instance is a coal-fired power station that enhanced its coal efficiency from 85% to 90% via technological upgrades and simultaneously achieved a CO₂ capture rate above 90%. This enhancement substantially decreases real CO₂ emissions, successfully aiding in environmental protection and climate change mitigation objectives.[18]

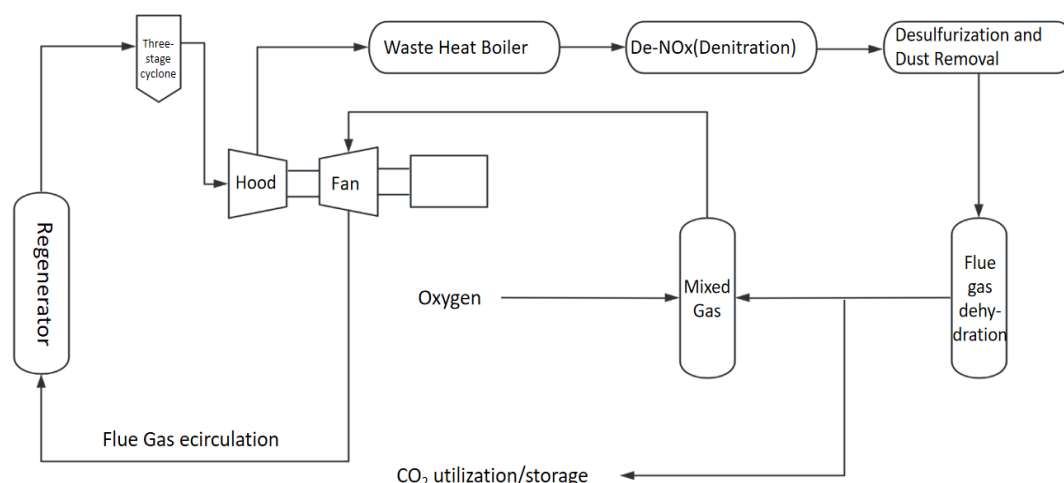


Figure 1. Flowchart of Oxy-fuel combustion carbon capture in catalytic cracking.

Catalytic cracking is an essential process in the secondary refining of crude oil, leading to the significant production of CO₂ greenhouse gas. This technique utilizes Oxy-fuel combustion technology, substituting oxygen (O₂) for air as the regeneration gas in the regenerator to enable catalyst regeneration by combustion. This technique efficiently captures high concentrations of CO₂ by recycling it from the flue gas, preventing dilution by nitrogen during air regeneration. This results in lower energy consumption and reduces the challenges and expenses associated with CO₂ capture. This method can be integrated by partially upgrading current catalytic cracking equipment, offering benefits including cost-effectiveness, flexibility, and high capture efficiency. Although the technology offers substantial environmental advantages and economic possibilities, its adoption is hindered by various obstacles. The requirement for high oxygen concentrations necessitates the availability of oxygen production facilities and technical assistance, leading to increased operational costs and technological complexity. The treatment and purification of high-concentration CO₂ flue gas necessitates the utilization of advanced technologies and equipment, leading to heightened technical complexity and increased expenses. Furthermore, the extensive use of technology necessitates corresponding policy backing and accompanying infrastructure.

In the future, advancements in technology and increasing global demands for environmental protection and carbon reduction are expected to lead to wider adoption of catalytic cracking Oxy-fuel combustion carbon capture technology. Research interests involve investigating reaction mechanisms in CO₂/O₂ environments, enhancing regeneration processes, optimizing flue gas circulation systems, creating cost-effective oxygen generation technologies, and decreasing energy consumption and costs by optimizing systems. These endeavors will significantly aid in reaching the objective of carbon neutrality.

5. Flue Gas Purification Technology of Oxy-fuel Combustion

Oxy-fuel combustion technology produces flue gas with SO_x, NO_x, Hg, and inert gases, which hinder the efficiency of carbon capture and storage (CCS). The presence of SO_x (primarily SO₂) in coal combustion flue gas has significant environmental consequences, such as causing acid rain, and poses technological and economic challenges in carbon capture processes. Research is focused on

finding a cost-effective and efficient way to filter contaminants and impurities in Oxy-fuel combustion flue gas to achieve the CO₂ purity requirement. SO_x purification commonly utilizes flue gas desulfurization (Flue Gas Desulfurization) technologies such as dry, semi-dry, and wet FGD. Dry desulfurization utilizes a liquid-free medium for processing. While equipment corrosion and maintenance costs are minimal, its desulfurization efficiency is relatively low. For instance, in some coal-fired power plants employing this technology, the desulfurization efficiency is only 60%. Wet desulphurization processes flue gas in a wet state, achieving up to 90% desulphurization efficiency. However, it is expensive to operate and maintain, and it also generates challenging wastewater issues.

Many scholars have different researches.[19] ALLAM and other scholars from Air Products in the United States introduced a novel technique for the concurrent elimination of NO_x and SO_x during the flue gas compression process. They developed the lead chamber method (LCP method) to efficiently eliminate SO₂ and NO_x by transforming them into sulfuric acid and nitric acid in a low-temperature, high-pressure, aqueous setting. Experiments conducted on Doosan Babcock's 160 KW experimental unit confirmed the efficacy of this approach. Additional research has demonstrated that raising pressure can facilitate the transformation of NO to NO₂, hence aiding in improving the water solubility of NO_x and enhancing the efficiency of its removal. When liquid water is present, the transformation of NO into NO₂ is more pronounced. Experimental findings indicate that at high pressure, the conversion efficiency of NO to NO₂ can achieve 90%. The primary conversion path is as follows.[20]



Many scholars continue to study this theory.[21] They specifically conducted an in-depth study on NO_x removal in the compression process, discussed the conversion of NO to NO₂ and NO_x removal under dry and wet conditions in the presence of oxygen, and clarified the law of NO conversion to NO₂ under different pressure conditions. The study found that increasing pressure helps convert NO, which is insoluble in water, into NO₂, which is easily soluble in water, which is a key factor in achieving NO_x removal. The effects of residence time and liquid water addition on NO conversion behavior were also studied. The results revealed that increasing the residence time was helpful to the conversion of NO to NO₂. In the presence of liquid water, the fraction of NO transformed to NO₂ rises, and the resultant NO₂ rapidly dissolves in water. Studies have shown that under high pressure conditions, the ratio of NO to NO₂ can reach 90%, while under lower pressure, this ratio is only 60%. These findings are a useful reference for further optimizing NO_x removal technology. In addition to the treatment of the aforementioned contaminants, inert gas purification plays an essential role in industrial production. Adsorption, condensation, membrane separation, and chemical absorption are examples of modern purification technologies, each with its own set of advantages and limitations.[22] For instance, the adsorption method is appropriate for situations where the operation is straightforward and high purification efficiency is required, but the adsorbent must be replaced on a regular basis; the membrane separation method is preferred for its low energy consumption and equipment simplicity, despite the limitations of membrane material selection and service life. With the acceleration of industrialization, the importance of Oxy-fuel combustion gas purification technology has grown. Whether in the sphere of energy, chemical industry, medical treatment, or environmental protection, effective and low-cost purification technology is critical to achieving environmental protection and sustainable growth. In the future, via extensive research and technological innovation, enhancing purifying efficiency, lowering operating costs, and optimizing system design will give significant technical support for more environmentally friendly and economically efficient industrial production.

6. Industrial Demonstration Progress of Oxy-fuel Combustion

Oxy-fuel combustion technology, as an innovative technique to enhance combustion efficiency and minimize greenhouse gas emissions, has been implemented and proved in numerous industries.[23] The industrial demonstration progress of Oxy-fuel combustion technology is shown in Figure 2. Here are some key points about the progress of Oxy-fuel combustion technology in industrial demonstration.

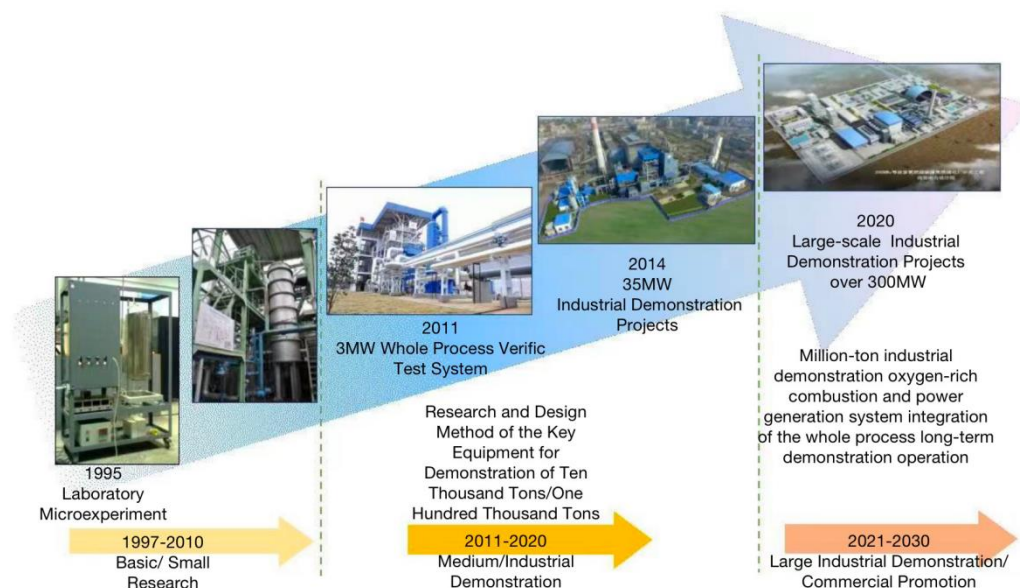


Figure 2. Industrial demonstration progress diagram of Oxy-fuel combustion.

6.1. Electric Power Industry

The electric power industry is one of the most widely used fields of Oxy-fuel combustion technology.[24] Several countries have established demonstration projects for coal-fired power plants that use Oxy-fuel combustion technology to improve combustion efficiency, reduce pollution emissions, and promote carbon dioxide capture and storage. The Callide Oxyfuel project in the United States is a successful example, showcasing the potential of Oxy-fuel combustion paired with CCS technology for practical power production.[25]

6.2. Steelmaking Industry

Because of its high energy consumption and carbon emission features, Oxy-fuel combustion technology is viewed as a viable technique of reducing energy consumption and carbon emissions. Using Oxy-fuel combustion in blast furnaces and furnaces may considerably enhance thermal efficiency and production efficiency while lowering polluting emissions like as nitrogen oxides. Steel industries have already begun to adopt Oxy-fuel combustion technology in demonstration projects to boost capacity and improve the environment.[26]

6.3. Cement manufacturing Industry

The cement industry is a major source of CO₂ emissions globally. Oxy-fuel combustion technology can increase combustion temperature and energy efficiency while lowering nitrogen oxide creation in cement clinker manufacture. Some cement manufacturing businesses have begun using test Oxy-fuel combustion technology to meet the goal of reducing emissions and conserving energy.[27]

The Oxy-fuel combustion technology demonstration project in the cement sector has yielded impressive results. For example, a 35 MW Oxy-fuel combustion carbon capture demonstration facility in China represents a significant step forward in the field of Oxy-fuel combustion plants, with

an annual processing capacity of 100,000 tons. The facility combines systems for oxygen separation, boiler and combustion, flue gas purification, and circulation to form a comprehensive production chain.[28] The demonstration project operates at moderate temperatures and pressures (superheated steam conditions of 3.82 MPa, 450°C). The boiler is intended for natural circulation, with a single drum π -type construction and an evaporation capacity of 38 tons per hour. Combustion uses a single furnace design with micro-positive pressure operation, a dual-channel smoke exhaust system, primary and secondary air independent settings, and a tubular air preheater.[29]

The various advantages of Oxy-fuel combustion technology are illustrated by this demonstration project, which also lowers theoretical combustion temperatures and increases fuel reactivity, full burnout rates and combustion rates. Significant improvements are made to the combustion efficiency, particularly during real operation. This allows the pulverised coal to reach the ignition temperature faster, releasing energy more concentratedly and using less energy overall. This method increases the rate at which heat is utilised while improving the concentration of combustion and flame intensity. Research indicates that raising the flame temperature lowers heat loss and raises the temperature of combustion. Concurrently, when flame blackness increases, radiation heat transfer is strengthened, resulting in a greater conversion of combustion energy into material heating and a decrease in energy lost through exhaust gas.[30]

Oxy-fuel combustion technology also helps to minimise post-combustion exhaust volume, which reduces the quantity of smoke that takes heat away, lowering exhaust emissions and heat loss. The large reduction in exhaust gas in the demonstration project reduces the exhaust gas treatment system's processing capacity, lowering investment and operating expenses. This method also enhances the efficiency of using alternative fuels by optimising combustion conditions and ensuring that the fuel is completely consumed. In the demonstration project, the deployment of Oxy-fuel combustion technology offers the conditions for the use of additional alternative fuels, further reducing dependency on traditional fossil fuels and lowering the environmental effect.

The effective running of the 35 MW Oxy-fuel combustion industrial demonstration project illustrates the technology's enormous potential in the cement sector. It not only encourages increased fuel usage and combustion efficiency, but it also results in considerable reductions in exhaust emissions and heat loss, as well as lower capital investment and energy consumption. As a result, Oxy-fuel combustion technology has a wide range of industrial applications and is valuable in boosting the industry's environmental friendliness and energy efficiency.

6.4. Waste Incineration

In the process of waste incineration, Oxy-fuel combustion technology can improve the incineration efficiency, reduce the volume of emissions, and make the incineration process more complete and reduce the emission of harmful substances. Waste treatment plants in some countries and regions have begun to use Oxy-fuel combustion technology for industrial demonstration.

7. Conclusion

As an innovative technology to increase energy utilisation efficiency and reduce greenhouse gas emissions, Oxy-fuel combustion technology has received a lot of attention in the industrial sector in recent years. By burning fuel with pure oxygen or oxygen-rich petrol instead of air, this method may dramatically improve combustion temperature, enhancing thermal efficiency while minimising nitrogen oxide emission. Several obstacles remain in the actual use of Oxy-fuel combustion technology, including adaptation to materials and operating environments, particulate matter and ash deposition issues, and combustion performance optimisation.

The high temperature environment necessitates greater standards for equipment materials. Due to the significant increase in combustion temperature in the Oxy-fuel combustion process, high-temperature resistant materials and a specially designed operating environment are required to withstand such high temperature conditions, resulting in a limited number of relevant research,

development, and demonstration projects. The issues of particulate matter and ash deposition that may occur during the Oxy-fuel combustion process must be addressed through a investigation of their formation mechanisms as well as appropriate control and preventive strategies. To further increase CO₂ collection and utilisation efficiency, Oxy-fuel combustion technology must be optimised for combustion performance. Despite these limitations, the research and application possibilities for Oxy-fuel combustion technology remain bright. Technological advancements and breakthroughs are projected to expand the usage of this technology in the future, particularly in industries with significant energy consumption and CO₂ emissions. As technology advances and costs fall, Oxy-fuel combustion technology will become an increasingly essential option for achieving clean and efficient energy utilisation. Faced with hurdles, constant research, development, and optimisation in numerous areas are essential to encourage the widespread adoption of Oxy-fuel combustion technology. Specifically, the Oxy-fuel combustion device technology must be further scaled up and evaluated to increase its application range and enhance its efficiency. Develop low-energy and low-cost oxygen production technology to reduce overall system investment and operating costs. To improve system efficiency and economy, the acid gas co-compression process and coupling optimisation of the entire plant were investigated.

In the future, the development and implementation of a new generation of Oxy-fuel combustion technology will provide significant support for continuing technological innovation and increased market competitiveness. Oxy-fuel combustion technology is expected to play a larger role in industrial production as a result of ongoing technological innovation and optimisation, contributing significantly to the achievement of China's "carbon neutral" and "carbon peak" goals, as well as global environmental protection and sustainable development objectives. With technological advancements and cost reductions, Oxy-fuel combustion technology will open up new avenues for clean and efficient energy usage, as well as encourage the transition of conventional energy-consuming sectors to a greener and lower-carbon growth path.

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