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The application of green hydrogen in iron ore smelting under the target of carbon neutralization

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Abstract. Currently, green development and sustainable development have become a global consensus. In March 2023, the Intergovernmental Panel on Climate Change (IPCC) released the sixth comprehensive assessment report Climate Change 2023, which pointed out that greenhouse gas emissions are currently at the highest level in human history, and the global temperatures has been about 1.1 ℃ higher than that before industrialization. In July, 2023, the government of China also emphasized that the construction of ecological civilization in China has entered a critical period with carbon emission reduction as the focus. According to the survey, the steel industry in China has the highest carbon emission in manufacturing industry, and it is also one of the most important areas for China to deal with climate change. Based on the basic principle of blast furnace iron making, this paper first analyzes the causes of high emissions in the steel industry, and draws the conclusion that hydrogen metallurgy technology must be developed to achieve low-carbon development; Then, depending on different energy endowments, the differences in metallurgical technology between China and other countries are analyzed, and brief conclusions and suggestions are given on the basis of analyzing the challenges faced by low-carbon development of China’s steel industry. This study provides insights into the importance of hydrogen metallurgy technology and enhance our understanding of how to achieve low-carbon development in China’s iron and steel industry.

Keywords: Steel industry, Hydrogen metallurgy, Green hydrogen, Low carbon

1. Introduction

1.1. Background

At present, global warming has become one of the main challenges of the global environmental situation. In March 2023, the Intergovernmental Panel on Climate Change (IPCC) released its sixth comprehensive assessment report, Climate Change 2023 [1], pointing out that greenhouse gas emissions are at the highest level in human history, and the global temperature is about 1.1℃ higher than before industrialization. Global warming has already had a great impact on the global environment. Rising sea level, melting glaciers, increasing extreme weather events, decreasing biodiversity and intensifying soil desertification are threatening the survival and development of global ecosystems and human beings.

To meet this challenge, countries all over the world have reached a consensus on green development and sustainable development. From the adoption of the United Nations Framework

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Convention on Climate Change (1992) to the signing of the Kyoto Protocol (1997) and the Paris Agreement (2015) [2], low-carbon development has become a consistent goal of all countries in the world. More than 65% of countries have formulated the goal of "carbon neutrality" in order to slow down the pace of global climate change. Carbon neutrality has become the mainstream and direction of global development.

Carbon neutrality means that in a certain period of time, the total amount of carbon dioxide or greenhouse gases emitted by a certain area is offset by afforestation, energy conservation and emission reduction, thus achieving relative "zero emission".

During the process of carbon neutrality, the low-carbon development of steel industry has become an important step. According to the data of CHINA IRON & STEEL ASSOCIATION (CISA) [3], the global crude steel output in 2022 is 1.89 billion tons, and the total output of crude steel in China accounts for 55.3%, which is about 1.04 billion tons. In 2022, China's steel industry will emit about 2.2 billion tons of carbon dioxide, accounting for 15% of the country's total carbon dioxide emissions and more than 60% of the global steel industry's total carbon dioxide emissions. Furthermore, as the most critical basic industry, the green development of the steel industry itself can promote the low-carbon technological progress of the whole industry and contribute to the construction of a low-carbon society. Steel can be used in various fields of human life, including buildings, automobiles, cargo ships, washing machines, refrigerators and scalpels. Hence, the steel industry is closely related to infrastructure, agriculture, industrial manufacturing, transportation and energy supply. To reach the China's carbon neutrality goal in the future, the steel industry must take the road of "green steel" with zero carbonation.

Therefore, the energy transformation of the steel industry is very important. Globally, hydrogen energy is regarded as the most potential clean energy in the 21st century [4]. Its advantages include zero carbon emissions, diverse sources, high flexibility and rich application scenarios. Many countries have incorporated it into their national energy strategic deployment. In this regard, China should assess the situation and take the "hydrogen economy" industrial revolution to replace fossil energy as an important strategic goal to realize China's new industrialization and low-carbon development. For iron and steel enterprises, the hydrogen metallurgical process using hydrogen to make steel is a revolutionary technology and one of the effective ways to optimize the energy structure, process flow and industrial structure of iron and steel enterprises. The low-carbon transformation of iron and steel industry is considered as an important means to promote the high-quality development of the industry, and it is also an inherent requirement to cope with global climate change and meet the high-quality development. This will open up broader development space for steel enterprises.

1.2. Research objective

This paper mainly studies how to apply hydrogen metallurgy technology to iron and steel industry in order to achieve the goal of low carbon emission. This new process will have a great impact on carbon emissions in the steel production process, which will help to promoting green and sustainable economic development.

Under the background of global warming, the common pursuit of carbon neutrality at home and abroad makes it urgent for the steel industry with high carbon emissions to change the traditional smelting process and achieve green development. Based on the basic chemical principles of iron and steel smelting, this paper summarizes the traditional smelting process at home and abroad, and emphasizes that China must find a large number of hydrogen sources to solve the decarburization problem in the steel industry. In addition, this paper also mentions the metallurgical technology of replacing coke with green hydrogen at home and abroad and its differences. Although this technology has made some progress in the world, it still faces many challenges in China. Finally, this paper draws a conclusion and puts forward some suggestions for the green development of iron and steel industry in the future.

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2. Current sustainable development and low-carbon development of iron and steel industry

At present, the global environmental situation is facing many challenges such as climate warming, biodiversity loss, water shortage and pollution. In this regard, all countries are actively promoting sustainable development in order to achieve coordinated development of economy, environment and society. In the process of coping with the challenge of global warming, the low-carbon development of the steel industry is of great significance. The steel industry accounts for 3%–4% of the global greenhouse gas emissions [5], and it is one of the largest carbon emission sources in the manufacturing industry. To cope with the challenge of global climate change, the steel industry must take more active measures and take the road of “green steel” to cope with global climate change.

2.1. International sustainable development situation

In order to achieve sustainable development, the international community has taken a series of actions. Countries have promulgated laws, made plans and taken measures. For example, the United States has implemented a renewable energy plan, the European Union has formulated an energy efficiency action plan, Japan has launched a low-carbon society action plan, and Australia has set a 2030 carbon emission reduction target. These policies aim to reduce carbon emissions, protecting natural resources and improving energy efficiency. Measures such as carbon trading market, renewable energy, and energy efficiency standards provide impetus for green transformation.

In addition, international organizations and international agreements have also played an important role. The United Nations Sustainable Development Goals (SDGs) and the Paris Agreement provide a global cooperation platform for sustainable development. In order to promote sustainable development, countries have adopted various methods, including formulating policies and regulations, innovating technologies, and strengthening publicity and education. For example, the carbon trading market, the popularization of renewable energy like wind energy and solar energy, and the promotion of the United Nations sustainable development goals have all promoted the attention and participation of all sectors of society in the process of environmental protection and sustainable development.

2.2. Low-carbon Development in China

In response to global climate change, China has also adopted a series of low-carbon development policies, including reducing the use of fossil energy, improving energy efficiency, promoting the adjustment of industrial structure, implementing carbon trading market, and strengthening the construction of forest carbon sinks. China municipal government plans to reduce the coal consumption ratio to less than 55% by 2030, promote the use of clean energy and renewable energy, and at the same time, strive to improving energy efficiency and reach the advanced level in the world.

After China president was announced in the general debate of the 75th UN General Assembly on September 22nd, 2020, the China Municipal Government has formulated the plan of “National Independent Contribution” [6]. The goal of the Plan is that by 2030, China’s carbon emissions will peak, and the carbon dioxide emissions per unit of GDP will be reduced by about 20% compared with 2005; By 2050, China’s carbon emissions will be significantly reduced, and the carbon dioxide emissions per unit of GDP will be reduced by more than 80% compared with 2030; By 2060, China will achieve carbon neutrality, that is, through afforestation, carbon capture and storage, the total amount of carbon dioxide absorbed will be equal to the total amount of carbon dioxide discharged.

2.3. Low-carbon Development of China Iron and Steel Industry

During the process of carbon neutrality, the low-carbon development of steel industry has become an important step. According to the data of CISA, the global crude steel output in 2022 is 1.89 billion tons, and the total output of crude steel in China accounts for 55.3%, which is about 1.04 billion tons. In 2022, China’s steel industry will emit about 2.2 billion tons of carbon dioxide, accounting for 15% of the country’s total carbon dioxide emissions and more than 60% of the global steel industry’s total carbon dioxide emissions. Furthermore, as the most critical basic industry, the green and low-carbon development of the steel industry itself can promote the low-carbon technological progress of the

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whole industry and contribute to the construction of a low-carbon society. Steel can be used in various fields of human life, including buildings, automobiles, cargo ships, washing machines, refrigerators and scalpels. Hence, the steel industry is closely related to transportation, infrastructure, agriculture, industrial manufacturing and energy supply. The low-carbon transformation of the steel industry will lead the whole industry chain to green development. In order to achieve the goal of carbon neutrality in China in the future, the steel industry is facing severe challenges and must take the road of "green steel" with zero carbonation.

3. Basic principle of smelting and its development status at home and abroad

3.1. Basic principle of smelting

Steel-making is a part of metallurgy, which refers to reducing iron ore or scrap steel to remove impurities, improve purity and produce high-quality steel products. In order to simplify the description, this paper refers specifically to the pig iron smelting process. This process is mainly to extract iron from iron ore through heating, reduction and refining. The main raw materials are iron ore and coke. Iron ore provides iron, while coke provides carbon and heat source. Its principle is based on chemical principle, which uses carbon as reducing agent to reduce iron oxide to metallic iron. Of course, there are some impurities, such as Mn, Si, P, S, etc. In the process of low-temperature smelting, Si, P and S will be oxidized, and the impurities in the simple state will become the impurities in the combined state, which will be further removed. In order to facilitate the explanation, this paper will simplify these processes.

The two chemical equations of pig iron smelting are:

$$Fe_2O_3+3CO \rightarrow 2Fe+3CO_2 \quad (1)$$

$$FeO+C \rightarrow Fe+CO \quad (2)$$

These two equations describe two main reaction processes in pig iron smelting. In the first equation, iron oxide (Fe_2O_3) in iron ore reacts with carbon monoxide (CO) in coal to produce pure iron (Fe) and carbon dioxide (CO_2). This process is a reduction reaction, because it reduces iron oxide to pure iron. In the second equation, iron oxide (FeO) in iron ore reacts with carbon (C) in coal to generate pure iron (Fe) and carbon monoxide (CO). This process is a carbonization reaction, because it reduces iron oxide to pure iron, and carbon is added in the process.

Both of these reactions require high temperature and pressure, and are usually carried out in a blast furnace. Blast furnace is a large-scale industrial equipment that heats iron ore and coal to high temperature for reduction and carbonization. In the blast furnace, iron ore and coal are put into the top of the furnace, and then air and fuel are injected through the nozzle at the bottom of the furnace to maintain high temperature and high pressure.

Smelting pig iron is a very important process because iron is the basic material of many industrial products, including steel, automobiles, building materials, etc. Although the traditional pig iron smelting process is mature and effective, it is characterized by high energy consumption, heavy pollution and low environmental protection. A large amount of waste water, waste gas and solid waste produced in the production process have seriously polluted the environment. At the same time, the traditional technology consumes a lot of energy and resources, and the chemicals and additives used will also have a negative impact on the environment.

3.2. Smelting process of international steel industry

At present, the global steel industry is mainly divided into long process and short process. Long process refers to the process of blast furnace iron-making and converter steel-making with coal char as the main component, and its reaction principle is shown in 2.1; The short process is electric furnace steel and direct reduced iron treatment, which mainly uses natural gas as raw material to produce hydrogen-based reducing gas, and then uses gas-based shaft furnace to reduce pellets.

The main reaction equation of direct reduction of iron in short process is as follows:

Production with reducing gas:

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$$CH_4+CO_2 \rightarrow 2CO+2H_2 \quad (3)$$

$$CH_4+H_2O \rightarrow CO+3H_2 \quad (4)$$

Iron ore reduction:

$$Fe_2O_3+3H_2 \rightarrow 2Fe+3H_2O \quad (5)$$

$$Fe_2O_3+3CO \rightarrow 2Fe+3CO_2 \quad (6)$$ [7]

The data show that the carbon emission of traditional long-process steel-making is about 1 t of steel and 2 t of CO_2, and the reduction of steel by short-process natural gas smelting can achieve 0.76 t of CO_2 [8]. In 2020, the output of China steel was 1.06 billion tons [9] (including 954 million tons of long-process steel, accounting for 89.6%; The output of short-process electrical steel was 110 million tons, accounting for 10.4%), accounting for over 50% of the world's total steel output. The output of short-process steel in the United States has reached more than 75% in the United States and 55% in Europe [10]. China's steel industry is under enormous pressure to reduce carbon and emissions.

3.3 Main smelting processes in China

At present, the smelting process in China is mainly a long process with coke as reducing agent. China has relatively abundant coal resources, but relatively few natural gas resources. Using coke as metallurgical energy in China is more in line with the present situation of resource supply, and it is also relatively more economical and reasonable. Some countries are rich in natural gas resources, which is more convenient for metallurgical production. From an economic point of view, using coke for metallurgy may require more technical and economic input. For example, the production of coke requires more equipment and technology, as well as more energy and labor. At the same time, some countries in the world have higher environmental regulations and requirements, so it may be more appropriate to use natural gas for metallurgical production. The combustion of coke may produce more pollutants, but it is more common to use coke for metallurgical production in China due to technical and equipment reasons.

The long process reaction equation using coke as reducing agent is as follows:

$$Fe_2O_3+3CO = 2Fe+3CO_2\uparrow \quad (7)$$

$$2Fe_2O_3+3C=4Fe+3CO_2\uparrow \quad (8)$$

Both of the above reactions are completed at high temperature.

As can be seen from the above chemical reaction equation, during the process of pig iron smelting, a large amount of carbon dioxide will be generated. These emissions of carbon dioxide will have a great impact on the environment. Therefore, China lacks the hydrogen source needed to produce direct reduced iron, and needs to find a low-carbon, cheap, large-scale and easily available hydrogen source to solve the decarbonization problem of China's steel industry.

4. New metallurgical technology-development and challenge of replacing coke with green hydrogen

4.1. Current development of green hydrogen metallurgical process

At present, hydrogen metallurgical steel-making has been applied to mature industrial production. Hydrogen metallurgy uses hydrogen instead of carbon to reduce iron ore to generate water, which not only has no carbon dioxide emission, but also has a very fast reaction speed. There are two main design schemes for hydrogen metallurgy: partial utilization of hydrogen and full utilization of hydrogen. In the scheme of completely using hydrogen, all iron elements are reduced by hydrogen, but there is no carbon, but there are still many challenges in completely using hydrogen. Up to now, although there have been some industrialization projects of hydrogen energy iron-making, it is still far from large-scale application. At present, the main methods of hydrogen production on the market are electrolytic water, water gas, synthetic gas and petroleum pyrolysis natural gas. In addition, with the popularization of the fourth generation nuclear power plants in the world, the use of nuclear energy to produce hydrogen has gradually attracted wide attention. However, the cost of preparation, storage and transportation of hydrogen is very high, the density of hydrogen is less than 1/15 of that of air, and it is flammable and explosive, which requires extremely special storage and transportation conditions, greatly limits the industrial development of hydrogen metallurgy [11].

4.2. International development of green hydrogen metallurgy technology

Compared with China, some countries in the world are rich in natural gas resources, so the cost of hydrogen production is relatively low, and the economic problems in the metallurgy of green hydrogen production are not so prominent. In addition, these countries have higher environmental laws and regulations, so the use of green hydrogen metallurgy has a long history and deeper technical exploration.

The following are some examples of the green hydrogen metallurgical technology explored abroad. Many iron and steel enterprises in the world tend to inject hydrogen-rich gas into blast furnaces as a technical route for carbon reduction. COURSE 50 project in Japan aims to realize low-carbon smelting of blast furnace by using hydrogen-rich blast furnace reduction technology and CO_2 capture and recovery technology, and finally realize 30% CO_2 emission reduction in 2030. South Korea's Pohang nuclear energy hydrogen production project will also develop the hydrogen reduction iron-making process. It is planned to start work on the test furnace in 2025 and put 12 blast furnaces into operation in 2040, thus completing the hydrogen reduction iron-making process. The ThyssenKrupp hydrogen based iron-making project in Germany was tested in Duisburg No.9 blast furnace (the daily output of hot metal is about 4600 t), and the carbon dioxide emission per ton of iron can be reduced by 19%[12].

In addition, many foreign steel companies are exploring hydrogen-based direct reduction process. At the beginning of 2017, Aogang launched the H_2 Future project, which aims to reduce CO_2 emissions in the steel production by developing a breakthrough H_2 instead of coke smelting technology. The project plans to directly reduce iron by hydrogen, and finally achieve the objective of reducing CO_2 emissions by 80% by 2050. Swedish Iron and Steel Company, Swedish State-owned Iron Ore Company (LKAB) and Swedish Great Falls Power Company jointly set up HYBRID Company to jointly develop hydrogen-based direct reduction iron-making technology which replaces coke with hydrogen generated by electrolytic water with renewable power, and plan to directly reduce pellets with hydrogen to produce reduced iron.

4.3. Development of Green Hydrogen Metallurgical Technology in China

4.3.1. Exploration. More than 80% of pig iron in China is produced by blast furnace process, and the crude steel output produced by long-term process accounts for about 90% of the national crude steel output in 2022. Domestic iron and steel enterprises are also actively exploring the hydrogen metallurgical process with carbon reduction or even zero carbon. Replacing carbon with hydrogen around the blast furnace to improve the reduction ratio of hydrogen is the first choices for technical improvement at present. In 2019, China Baowu, Hegang and Rizhao Iron and Steel respectively proposed hydrogen metallurgy schemes; China Baowu has signed agreements with China National Nuclear Corporation and Tsinghua University to produce hydrogen from nuclear energy, and then use it in iron ore metallurgy [13].

In addition, He Gang Group used the world's most advanced direct reduction technology of hydrogen energy to build the world's first 1.2 million tons of hydrogen energy reduction demonstration project to prepare high-quality metallized burden, aiming to build a hydrogen reduction factory with the most advanced equipment and technology through innovative research and development. The hydrogen-based direct reduction project (CSDRS) of Shanxi Company with an annual output of 300,000 tons of direct reduced iron officially entered the trial production stage in June 2021. It uses modified coke oven gas as iron ore reductant to produce high-quality sponge iron with a metallization rate over 90%. Jianlong Group has built a project (CISP) of smelting high-purity cast iron with an annual output of 300,000 tons by hydrogen-based smelting reduction in Wuhai, Inner Mongolia [14]. Compared with the traditional blast furnace, this process saves the sintering and coking processes with serious pollutant discharge, and greatly reduces pollutant discharge.

The research of hydrogen-rich smelting of blast furnace in China is mainly to inject hydrogen-rich gas into the blast furnace. Only from the perspective of renewable energy, large-scale hydrogen energy preparation and cost advantage can hydrogen energy iron-making be widely promoted.

4.3.2. Challenge. In 2020, the output of natural gas in China will reach 192.5 billion cubic meters, and the imports will reach 101.926 million tons, equivalent to 142.7 billion cubic meters of natural gas. In 2020, the apparent consumption of natural gas in China will reach 328.9 billion cubic meters, accounting for more than 40% of the total imports [15]. The high price of imported natural gas is a great challenge to the production of direct reduced iron from natural gas in China.

First, the economic challenge of smelting green hydrogen in iron ore is a big problem. Replacing traditional fossil fuels with green hydrogen needs a lot of capital investment, including the production of green hydrogen and the cost of iron ore purification. At present, the production cost of green hydrogen is much higher than traditional energy. The production of green hydrogen requires a lot of electricity, so the equipment cost and electricity cost are the key factors affecting the production cost of green hydrogen. Alkaline electrolytic water technology can produce 1000m^3 hydrogen per hour, but each equipment needs 8-10 million yuan [16]. In addition, waste treatment also increases the cost of green hydrogen production. It is more expensive to purify hydrogen. In the process of iron ore purification, other chemical reactions may occur, consuming green hydrogen and increasing purification cost.

Second, traditional fossil fuels like coal and natural gas have been used in the steel industry over a long period, and the related technologies and equipment are also very mature. The new green hydrogen smelting technology is bound to have an impact on the original production technology and operation mode of the factory. In addition, the introduction of new technologies will also affect employees' employment. New employees need to learn new and unfamiliar skills, while old employees may face the risk of large-scale unemployment. Meanwhile, the transformation of the steel industry may also affect the local ecological environment. For instance, the change of factory address will occupy new land, so we should consider environmental sustainability. Therefore, the transformation of the steel industry will be a slow and difficult process.

Third, the production, transportation and storage of green hydrogen have safety factors and need highly specialized technical support. Hydrogen energy is usually processed and used in the form of liquid hydrogen. However, liquid hydrogen is an energy intensive medium. Because the temperature of liquid hydrogen is extremely low, if it is not handled carelessly, low-temperature burns will occur. In the process of transportation, storage and use of hydrogen, hydrogen atoms will diffuse into the container material, weakening the mechanical integrity of the material, thus causing foaming inside the container, further embrittle the container, reducing the strength of the metal container and producing cracks or gaps. In severe cases, it will lead to hydrogen leakage, leading to risks such as fire and explosion.

5. Conclusion and outlook

The iron and steel industry is the foundation of modern industry, and it is also one of the important sources of carbon emissions. In order to reach the objective of peak carbon dioxide emissions and carbon neutrality, the steel industry needs to carry out innovative energy structure adjustment and process structure optimization. Hydrogen energy, as the most potential clean energy, has become the best energy choice for the steel industry to achieve zero carbon emissions. Nowadays, most of the experimental processes are to produce hydrogen from fossil energy. However, with the continuous improvement of technology and in-depth research, we will gradually turn to the technical road of producing hydrogen from clean and renewable energy.

The popularization and application of green hydrogen metallurgy technology will help the iron and steel industry get rid of its dependence on fossil energy, thus completely solving the problem of carbon emission. However, there is still a long way to go for the development and application of hydrogen metallurgical technology, and policy guidance and technical support are two crucial factors. In the

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future, it is necessary to establish a complete innovation-driven policy framework for hydrogen energy industry to guide the rapid development and breakthrough of hydrogen metallurgical technology and processes.

In promoting the development and application of hydrogen metallurgy technology, we need to strengthen basic research and cooperation with Industry-University-Research, so as to improve efficiency of hydrogen metallurgy technology and reduce the cost. The government can take measures of encouragement and financial support, enterprises should actively explore and innovate, and academic circles should provide theoretical support and technical guidance. Only through joint efforts can we promote the development and application of hydrogen metallurgical technology and make an important contribution to the realization of peak carbon dioxide emissions and carbon neutrality.

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