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DEVELOPMENT OF HYDROGEN METALLURGY IN CHINA

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Abstract

China is actively promoting its carbon peaking and carbon neutrality goals. Hydrogen metallurgy characterized by the replacement of carbon with hydrogen has attracted widespread attention as a vital component of low-carbon metallurgy. This study provides a statistical analysis of publications and patents related to hydrogen metallurgy in Chinese databases over the past five years, and summarizes the current industrial practices in hydrogen metallurgy in China. The results reveal a rapidly growing trend in theoretical research and technological development related to hydrogen metallurgy in China over recent years. Several major steel enterprises have carried out industrial practices of hydrogen-based shaft furnace and hydrogen-rich blast furnace smelting, offering initial confirmation of the feasibility of hydrogen metallurgy. Currently, the industrialization of hydrogen metallurgy in China faces a challenge of high hydrogen production costs. Therefore, this study reviews and analyzes the economics of the main hydrogen sources, including coke oven gas, natural gas, coal gasification, hydrogen from by-product during chemical processes, and hydrogen produced by water electrolysis. Although the current hydrogen sources mainly rely on gray hydrogen produced from fossil fuels, the large-scale and cost-effective production of green hydrogen from renewable energy sources in the future is expected to substantially accelerate the industrial application of hydrogen metallurgy. In summary, hydrogen metallurgy technology in China has established a solid foundation in research and accumulated certain industrial application experience. However, further research is required to improve hydrogen utilization efficiency and decrease hydrogen production costs, thereby enabling the widespread industrial application of hydrogen metallurgy.

***Keywords**: hydrogen metallurgy, low-carbon metallurgy, hydrogen sources, hydrogen production costs.*

1. INTRODUCTION

Controlling CO_2 emissions has become a global consensus and an urgent necessity in the fight against climate change and the pursuit of sustainable development. In response, China has announced its “dual carbon” goals-aiming to reach peak carbon emissions by 2030 and attain carbon neutrality by 2060. The steel industry is one of the largest sources of CO_2 emissions in China, contributes approximately 15% of the country’s total industrial emissions [1]. With the ongoing implementation of the “dual carbon” goals, the decarbonization of the steel industry has become essential. Hydrogen metallurgy, which replaces traditional carbon-based reductants with hydrogen(H_2), offers significant decarbonization potential, as its reduction byproduct is water (H_2O) rather than CO_2. Therefore, it is regarded as a promising pathway for the Chinese steel industry to achieve deep emission reductions and long-term carbon neutrality. This study provides an overview of the development of hydrogen metallurgy in China, focusing on trends in academic publications and patent authorizations over the past five years, industrial implementation of hydrogen metallurgy by Chinese steel enterprises, and the techno-economic analysis of viable hydrogen sources.

2. RESEARCH PROGRESS AND INDUSTRIAL PRACTICE OF HYDROGEN METALLURGY IN CHINA

Using the China National Knowledge Infrastructure (CNKI), a major Chinese-language academic database, paper and patent data from 2020 to 2024 were collected based on keywords including “hydrogen metallurgy,” “hydrogen-rich blast furnace (BF),” “hydrogen-based shaft furnace,” and “hydrogen reduction,” as shown in Figure 1. Statistical data show that the number of relevant papers increased significantly from 55 (2020) to 198 (2024), accompanied by a growth in patent filings from 90 to 313. This trend clearly reflects the rapid development of fundamental research and technological innovation in hydrogen metallurgy in China since the announcement of the “dual carbon” goals in September 2020.

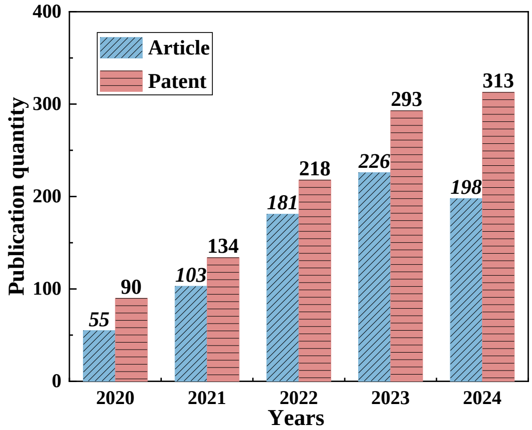

Figure 1. Number of hydrogen metallurgy-related papers and patent in the CNKI (2020-2024)

At present, industrial applications of hydrogen metallurgy in China primarily follow two technological pathways: H_2-rich BF and hydrogen-based shaft furnaces. Given that the BF-BOF (basic oxygen furnace) route accounts for approximately 90% of China’s steel production, H_2-rich BF is expected to remain the dominant decarbonization strategy for the industry over the next 10 to 20 years. This technology involves injecting H_2-rich gas either at the tuyeres or furnace shaft, reducing coke consumption while simultaneously lowering CO_2 emissions. In recent years, several major Chinese steel producers have actively implemented H_2-rich BF in industrial practice (see upper part of Figure 2). In 2010, Jinan steel injected coke oven gas (COG) into a 350 m^3 BF, reducing the fuel ratio by 45.91 kg/THM and CO_2 emissions by 75 kg/THM at an injection rate of 62.51 m^3 per ton of hot metal (m^3/THM) [2]. In 2021, Jinnan Steel injected COG into an 1860 m^3 BF, achieving a 32 kg/THM reduction in fuel ratio and about 80 kg/THM decrease in CO_2 emissions at 65 m^3/THM injection [3]. In 2022, Bayi Steel completed an industrial trial of a 400 m^3 H_2-rich carbon recycling oxygen blast furnace, integrating H_2-rich gas injection, 1200 °C top-gas recycling, and full oxygen smelting, resulting in a 21% reduction in CO_2 emissions [4]. In 2021, Xingguo Foundry successfully performed pure H_2 injection in a 40 m^3 pilot BF. Industrial practice indicates that tuyere injection of COG is currently the mainstream H_2-rich BF technology in China, with a relatively high level of process. However, due to the irreplaceable the coke as the structural support in the BF and the relatively low utilization efficiency of hydrogen, the carbon emission reduction of H_2-rich BF is generally limited to the range of 10% to 20%.

In contrast, hydrogen-based shaft furnaces use an H_2-CO mixed gas as the reductant, offering substantial carbon reduction potential (50%-95%). Although this technology started later in China, its industrialization is accelerating. Recent landmark projects include Zhongjin Taihang, Baosteel, and Hebei Iron & Steel Group (HBIS), China Iron & Steel Research Institute Group (CISRI) (see lower part of Figure 2) [5]. In June 2021, Zhongjin Taihang built the world's first COG-based hydrogen shaft furnace direct reduced iron (DRI) production line with an annual capacity of 300,000 tons, supported by a 1 million ton coke plant, proving the feasibility of hydrogen-based direct reduction in China. In December 2022, HBIS completed a 1.2 million ton-scale COG zero-reforming hydrogen shaft furnace and began continuous production in 2023, decreasing CO_2 emissions by about 70%. In December 2023, Baosteel commissioned a million-ton hydrogen shaft furnace, achieving a CO_2 emission reduction of 58%-89%. In 2024, CISRI started the world's first pure hydrogen shaft furnace in Linyi, using 100% green hydrogen and achieving an 87% reduction in CO_2 emissions. In summary, large-scale industrial practices in China have preliminarily demonstrated the engineering feasibility and CO_2 emission reduction potential of hydrogen metallurgy.

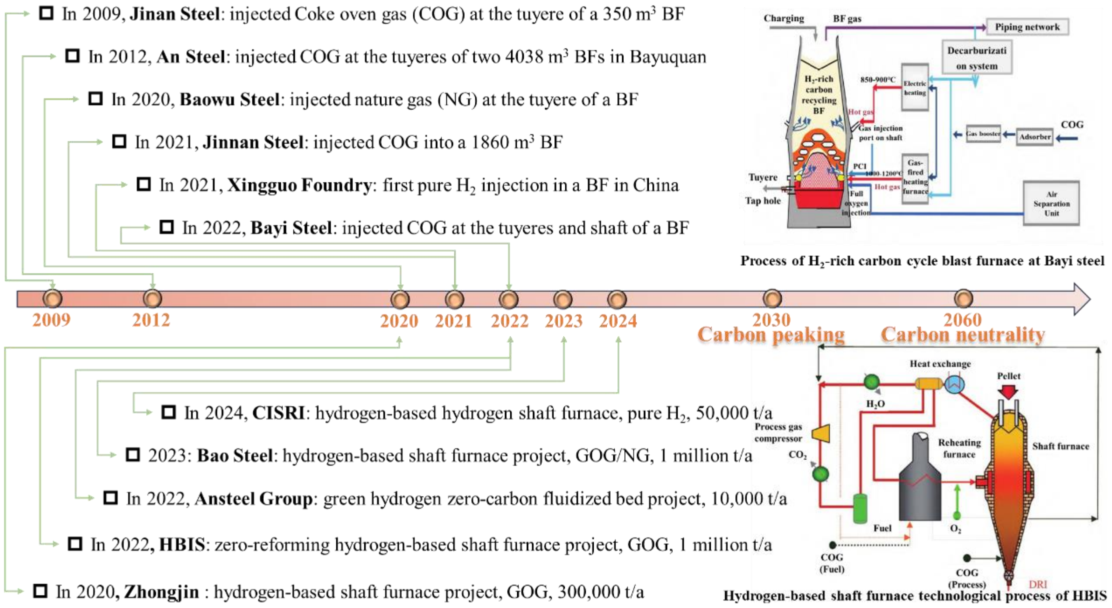

Figure 2. Schematic Diagram of Hydrogen Metallurgy Industrial Practices in China

3. ANALYSIS OF HYDROGEN SOURCES FOR HYDROGEN METALLURGY IN CHINA

The large-scale development of hydrogen metallurgy requires a hydrogen supply that is both low-cost and low-carbon. Currently, hydrogen sources mainly include fossil fuels (coal and natural gas), industrial by-product hydrogen, water electrolysis, and biomass-based hydrogen production. At present, China's hydrogen production is predominantly based on fossil fuels, with 62% derived from coal, 19% from natural gas, and approximately 18% from industrial by-product hydrogen. Hydrogen produced via water electrolysis accounts for only 1% [6]. To systematically compare the economic performance and CO_2 emission reduction potential of different hydrogen sources, this study normalizes hydrogen share, unit cost, and CO_2 emissions, and presents a ternary comparison diagram (figure 3). Coal-based hydrogen benefits from China's abundant coal resources and mature industrial system, offering a significant cost advantage (0.45-0.78 CNY/Nm^3) [7]. However, its high CO_2 emission (25-30 kg CO_2/kg H_2) [8] makes its share expected to decrease to 20% by 2025 [1]. Industrial by-product hydrogen and natural gas-based hydrogen also face challenges related to high CO_2 emission.

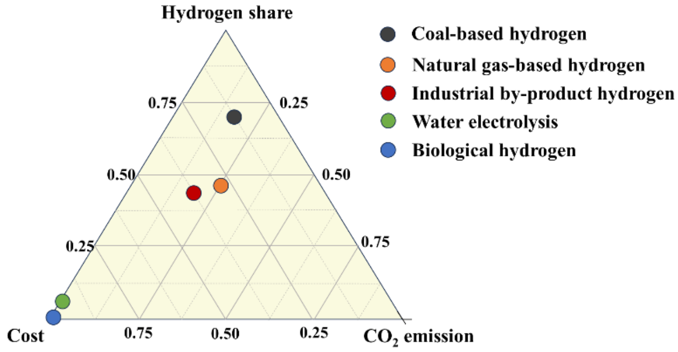

Figure 3. Ternary diagram of share-cost-carbon emissions for different hydrogen sources

In the future, water electrolysis is expected to become the major hydrogen source for hydrogen metallurgy in China. Its share is projected to increase to approximately 15% by 2030 and reach 70% by 2050 [1]. However, the current cost of hydrogen produced by electrolysis is relatively high at 2.69 CNY/Nm^3, which is two to three times that of fossil fuel-based hydrogen [8]. Moreover, over 50% of China's power generation still relies on coal, resulting in a carbon emission of 9-12 kg CO_2/kg H_2 for coal-based hydrogen production. In contrast, electrolysis powered by renewable energy (solar and wind) can achieve near-zero emissions, making it the most promising pathway for green hydrogen. Therefore, the Chinese steel industry should strengthen the integration of renewable energy-powered electrolysis with hydrogen metallurgy technologies. This integration should rely on renewable hydrogen production processes to support the development of hydrogen metallurgy, improve energy efficiency of electrolysis, and expand hydrogen production capacity to significantly reduce green hydrogen costs. Besides electrolysis, emerging technologies such as nuclear-based and biomass-based hydrogen production also hold potential. Nuclear-based hydrogen production boasts thermochemical efficiencies above 50% but faces challenges related to equipment costs, safety, and high-temperature materials. Biomass hydrogen production remains at the research stage with costs as high as 25-33 CNY/kg, making industrial application difficult.

4. CONCLUSION

Under the "dual carbon" goals, China has made notable progress in both hydrogen metallurgy research and industrial application. Over the past five years, the number of hydrogen metallurgy related papers and patents in Chinese databases has steadily increased. Chinese steel enterprises have successively implemented industrial practices including H_2-rich blast furnace and hydrogen-based shaft furnace, promoting the industrialization of hydrogen metallurgy technologies. However, current hydrogen sources are dominated by grey hydrogen with high CO_2 emissions and green hydrogen production remains costly. Achieving low-cost, large-scale green hydrogen production is urgently needed to underpin the rapid development of hydrogen metallurgy in China.

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