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Review paper

THE ROLE OF HYDROGEN BASED SHAFT FURNACES IN STEEL INDUSTRY DECARBONIZATION

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Abstract

This study provides a systematic review of current hydrogen-based metallurgical processes, analyzing their technical pathways across multiple dimensions including raw material preparation, reaction mechanisms, critical equipment design, and system integration. A comparative evaluation reveals the distinct advantages and limitations of each technological route. The paper highlights HBIS Group's pioneering HyMEX demonstration project - the world's first industrial-scale application of coke oven gas direct reduction without reforming. This breakthrough technology eliminates the conventional dependence on natural gas for reducing gas production and achieves the highest hydrogen utilization rate among operational shaft furnace processes. The successful implementation establishes a new benchmark for hydrogen metallurgy industrialization. Furthermore, this analysis examines China's unique position for hydrogen metallurgy development, considering both policy frameworks and resource characteristics. With abundant coke oven gas resources and dominant steel production capacity, China possesses distinctive advantages for scaling hydrogen-based ironmaking. The study concludes that as hydrogen infrastructure matures and production costs decline, shaft furnace hydrogen metallurgy will likely become a cornerstone technology for the industry's low-carbon transformation, providing critical technical support for national climate commitments.

***Keywords**: low-carbon transition; hydrogen direct reduction; alternative ironmaking; coke oven gas zero-reforming; industrial demonstration*

1. INTRODUCTION

Amid global energy restructuring and climate challenges, hydrogen energy has emerged as a clean, high-efficiency solution for sustainable development [1-3]. The steel industry, a major CO_2 emitter (1.7B+ tons annually in China, 70% from blast furnaces [4, 5]), faces urgent decarbonization needs. While blast furnaces dominate (90% of China's production), their carbon reduction potential is limited even with hydrogen substitution [6-7]. Non-blast furnace processes (direct reduction, molten reduction) offer greater decarbonization potential by maximizing hydrogen use and eliminating coke. Hydrogen-based shaft furnaces are mature, while fluidized bed reduction - enabling fast, pellet-free processing - gains traction. Smelting reduction remains developmental. This paper reviews global non-blast furnace technologies and highlights China's pioneering coke-oven-gas-to-hydrogen demonstration project. It proposes tailored hydrogen metallurgy pathways to guide the industry's low-carbon transition.

2. DEVELOPMENT STATUS OF NON-BLAST FURNACE TECHNOLOGY

2.1 Development status of smelting reduction iron making

The original intention of developing molten reduction was to use non-coking coal as the energy source or reducing agent to reduce iron oxides in a high-temperature molten state. After the separation of slag and iron, molten iron was obtained. Coal could be used instead of coke and fine ore could be directly smelted to simplify the ironmaking process and reduce pollutant emissions. However, from the actual operation results, both the COREX and FINEX processes that have achieved commercial operation require a small amount of coke, and the fuel consumption is as high as over 850 kg/t. The HISMELT process was jointly developed by CRA of Australia (now Rio Tinto) and MIDREX of the United States and was sold to Shandong Molong of China in 2012. During the introduction process, Shandong Molong combined the production practice of the original Australia and optimized and improved the mineral powder pretreatment, high-temperature flue gas treatment system, etc. The process was renamed ML-HISMELT. The transformation and upgrading relocation and renovation project of Xingsteel introduced the ML-HISMELT technology of Shandong Molong. It is planned to build three new ML-HISMELT melting reduction furnaces with a total pig iron production capacity of 1.65 million tons per year. Currently, the engineering construction is underway. HBIS Group has also developed a new full-oxygen hydrogen-rich carbon cycle ironmaking process with independent intellectual property rights. A 30 m^3 pilot demonstration line has been built, and the feasibility verification of the process is awaiting. Comparison of different smelting reduction iron-making processes are shown in Table 1.

Table 1. Comparison of different smelting reduction iron-making processes [8-10]

Technology	COREX	FINEX	HISMELT	New technology of HBIS
Developer	Voestalpine	Voestalpine and POSCO	Rio Tinto	HBIS and Northeastern University
Application unit	Baosteel Group Xinjiang Bayi Iron & Steel Co., Ltd., etc	POSCO	Shandong Molong Group introduced technology re-innovation	HBIS
Monomer maximum (10000 t/a)	150	200	80	Pilot test (about 2)
Ingredients	pellet and lump ore (6.0-16.0 mm)	Sinter powder under sieve (0.5-1.0 mm)	Ore powder (＜6.0 mm)	Pellet, sinter and lump ore
Fuel	Coke and coal	Coke, pulverized coal and briquette	Non-coking coal (＜3 mm)	Coke and hydrogen
Prereductor	Shaft furnace (Metallization rate 50%)	Fluidized bed (Metallization rate 65-80%)	Rotary kiln (Metallization rate 15%)	Upper part of reactor (Metallization rate 85%-90%)
Final reductor	Molten gasifier	Molten gasifier	SRV furnace	Lower part of reactor
Fuel consumption	about 1 000 kg/t Fe	about 850 kg/t Fe	about 850 kg/t Fe	Coke: about 307 kg/t Fe hydrogen: about 369 Nm^3/t Fe
Oxygen consumption /(Nm^3/t-Fe)	550 (Pure oxygen)	530 (Pure oxygen)	Air consumption 2600, oxygen volume fraction 39%	180 (Pure oxygen)
Main component of hot metal /%	C: 3.5-4.0 Si: 0.8-1.5 S: about 0.025 P: about 0.120	C: 3.5-4.0 Si: 0.6-1.2 S: about 0.030 P: about 0.120	C: 3.5-4.0 Si: trace S: about 0.156 P: about 0.035	C: about 4.5 Si: 0.4-0.5 S: about 0.020 P: about 0.100
Advantage	The adaptability of raw materials is broad	Reduction temperature is low; There are no strict restrictions on the composition and variety of iron ore	Wide range of raw materials, can smelt high phosphate rock, vanadium titanium magnetite and so on	Hydrogen-rich carbon cycle smelting, large carbon reduction range
Drawback	Fusion gasifier high temperature flue gas dust bonding plugging	Low reduction efficiency	The FeO content in slag is high, the yield of molten iron is low, and the life of furnace cylinder is short	Pending confirmation of validity

2.2 Development status of fluidized bed reduction

Fluidized direct reduction ironmaking method refers to the method of reducing iron ore powder in a fluidized bed using gas, reformed natural gas or hydrogen. The basic process flow is as follows: the reducing gas is heated to 400-900 ℃ and passes through 2 to 4 stages of fluidized beds step by step. Under the interaction of gravity and reducing gas flow, the iron ore powder enters the preheating, pre-reduction and reduction stages of fluidized beds in sequence. The reduced sponge iron powder is pressed into blocks and used in the subsequent smelting process. FIOR/FINMET and CIRCORED are typical fluidized bed reduction processes. The reduction part of the FINEX process adopts a fluidized bed device, but essentially falls within the category of molten reduction ironmaking. The HyREX process is an improvement based on the FINEX technology. The reducing agent uses natural gas instead of coal combustion to produce gas for reduction, and the fluidized bed reduction process is retained. Replace the original melting gasifier with an electric furnace. Overall, the fluidization direct reduction ironmaking technology has been industrialized and commercialized. However, issues such as the loss of flow due to the reduction and bonding of mineral powder during the production process, the stable operation of fluidization equipment, and the availability of reduction gas resources have hindered the rapid development of fluidization reduction technology. In terms of production scale and stability, it still cannot be compared with the gas-based shaft furnace reduction process, and it is difficult to surpass the scale of the gas-based shaft furnace in the short term. Comparison of different types of fluidized direct reduction iron making processes are shown in Table 2.

Table 2. Comparison of different types of fluidized direct reduction iron making processes [11, 12]

Technology	FINMET	CIRCORED	FINEX	HyREX	Fluidized bed of Ansteel
Developer	Voestalpine	Lurgi Metallurgical Company	Voestalpine and POSCO	POSCO and Primetals Technologies	Institute of Process Engineering, Chinese Academy of Sciences
Application unit	BHP	Cleveland-Cliffs Inc. and partners	POSCO	POSCO	Ansteel Bayuquan
Monomer maximum (10 000 t/a)	100	50 (Idle state)	200	30 (Production is scheduled in 2026)	about 1 (Not in service)
Number of fluidized beds	4	3	4	4	2
Melting furnace	None	None	Molten gasifier: Pulverized coal is burned with oxygen to generate heat to melt DRI	ESF furnace with electric melting	None
Ingredients	Ore powder (0.1-8.0 mm)	Ore powder (0.2-8.0 mm)	Sinter powder under sieve (0.5-1.0 mm)	Sinter powder under sieve (0.5-1.0 mm)	Pellet (0.5-1.6 mm)
Reduction gas consumption/(m^3/t DRI)	(Natural gas: about 450	Hydrogen: about 1 000	Melt gasifier gas: 1 350-1 480	Natural gas: about 404	Hydrogen: about 890
Parameter	1) Reactor temperature: R4 (550-570 ℃); R1 (780-800 ℃) 2) Reactor pressure (1.1-1.4 MPa)	1) Reactor temperature: Primary preheated circulating fluidized bed (850-950 ℃); Two stage pre-reduction fluidized bed (630-650 ℃); Three stage horizontal bubbling fluidized bed (630-650 ℃) 2) Reactor pressure:	Reactor temperature: R3 (about 450 ℃); R2 (600-700 ℃); R1 (about 750 ℃)	Reactor temperature: R4 (441 ℃); R3 (636 ℃); R2 (706 ℃); R1 (758 ℃) 2) Reactor pressure (0.5 MPa)	Reactor temperature: First stage (about 700 ℃); Second stage (about 700 ℃)

		about 0.4 MPa			
DRI metallization rate/%	93	93	65-80	about 85	≥92 (predict)
Advantage	High metallization rate of DRI	The choice of ore and reducing agent is flexible	The reduction temperature is low, and there is no strict restriction on the composition and variety of iron ore	Strong adaptability to raw materials, low quality ore can be used	It is claimed that it can solve the problems of bonded loss of flow and slow loss of flow of powdered iron ore
Drawback	It is easy to cause adhesive plugging in the fluidized bed. The process is more complicated	The reduction time of bubbling fluidized bed is long and the efficiency is low	High investment cost and operating cost, low metallization rate, easy to bond plugging	Pending confirmation of validity	Pending confirmation of validity

2.3 Development status of hydrogen-based shaft furnace

Since the WIBERG process was developed in Sweden at the beginning of the 20th century, more than ten gas-based reduction processes have emerged successively. However, the MIDREX process and HYL process are currently widely adopted. These two processes are recognized as relatively mature and stable large-scale production processes with output comparable to that of the blast furnace process. In 2024, the two processes will produce nearly 100 million tons of DRI. It accounts for more than 70% of the total output. Compared with the MIDREX process, the HYL/ENERGIRON process, due to the high H_2 content in the reducing gas, has a large space for carbon reduction and its future capacity share may show an increasing trend. In China, due to the large amount of coke oven gas produced by integrated steel enterprises, the HyMEX shaft furnace hydrogen metallurgy process with zero reforming of coke oven gas has development potential. Comparison of reduction processes of different types of hydrogen-based shaft furnaces are shown in Table 3.

Table 3. Comparison of reduction processes of different types of hydrogen-based shaft furnaces [13-15]

Technology	MIDREX	HYL/ENERGIRON	HyMEX
Developer	Midrex Technologies, Inc., America	HYLSA, Mexico	HBIS Group Zhangxuan technology
Classification	STANDARD: Conventional natural gas reforming and reduction AREX: Natural gas zero-reforming without reforming furnace MXCOL: Non-catalytic partial oxidative reforming of coke oven gas MIDREX H_2: Pure hydrogen shaft furnace reduction technology	HYL-III: Natural gas reforming HYL-ZR: Zero reforming of natural gas or coke oven gas	Zero reforming of coke oven gas
Monomer maximum (10000 t/a)	250 Algerian Qatari Steel Company; Tosyari Company; Thyssenkrupp Steel Duisburg steel plant (Production is scheduled in 2026)	250 Nucor Steel; Jindal Steel Group Volcan Green Steel; Suez Steel Company (Production is scheduled in 2025)	—
Ingredients	The main stream uses 9-16 mm pellet, and a small proportion of 10-35 mm lump ore can be added	The main stream uses 9-16 mm pellet, and a small proportion of 10-35 mm lump ore can be added	9-16 mm pellet
Reduction gas consumption	Natural gas: 280-290 m^3/t DRI	Natural gas: 275-290 m^3/t DRI	Coke oven gas: 550 m^3/t DRI
Parameter	750-900 ℃ 0.2-0.3 MPa	960-1080 ℃ 0.4-0.8 MPa	1000-1050 ℃ 0.7-0.8 MPa

	$\varphi_{H_2} / \varphi_{CO} < 2$	$\varphi_{H_2} / \varphi_{CO}$ = 4-8	$\varphi_{H_2} / \varphi_{CO} \approx 8$
Advantage	Low working pressure and temperature; The process is simple and easy to operate	High production efficiency; High H_2 ratio with large carbon emission reduction range	
Drawback	Low production efficiency	Harsh conditions with high temperature and high pressure operation	

3. HBIS's Zero-Reforming Hydrogen Metallurgy Breakthrough

Leveraging regional advantages, HBIS launched the world's first zero-reforming coke oven gas hydrogen metallurgy project at Zhangxuan Tech. (process flow shown in Figure 1), achieving stable operation in May 2023. The 600,000-ton/year DRI facility sets industry benchmarks:Metallization rate ≥94%, carbon content 2.5-3.0%; 29.3% lower gas use (from 750 to 530 m^3/t); 30.3% power reduction (from 330 to 240 kWh/t).

Through the digestion and absorption of the "zero Reforming Direct reduction Technology for coke oven Gas", HBIS Group has successfully developed the following key technologies: (1) The hydrogen shaft furnace process utilizes high-quality pellets featuring a pelletizing rate exceeding 95%, along with superior reduction characteristics including ≤15% expansion rate and $I_{RD, <3.2mm}$ less than 10% for optimal smelting performance; (2) The advanced purification process achieves exceptional gas quality with H_2/CO ratio exceeding 8, while delivering industry-leading impurity removal rates of 98% for H_2S and 85% for hydroxyl sulfur. Notably, naphthalene content is reduced to just 5mg/m^3 while maintaining a competitive purification cost of 0.1¥/m^3; (3) The DRI-EAF breakthrough enables stable production of premium steel grades (including auto slabs and bearing steel) at 20-45% DRI ratios, achieving >80% yield while reducing nitrogen content by 20ppm compared to traditional processes; (4) The near-zero CO_2 utilization system achieves annual capture of 60,000 tons at 230¥/ton, producing 99.999% pure food-grade CO_2 while enabling innovative microbial protein synthesis from flue gas at 10kg/m^3/day productivity.

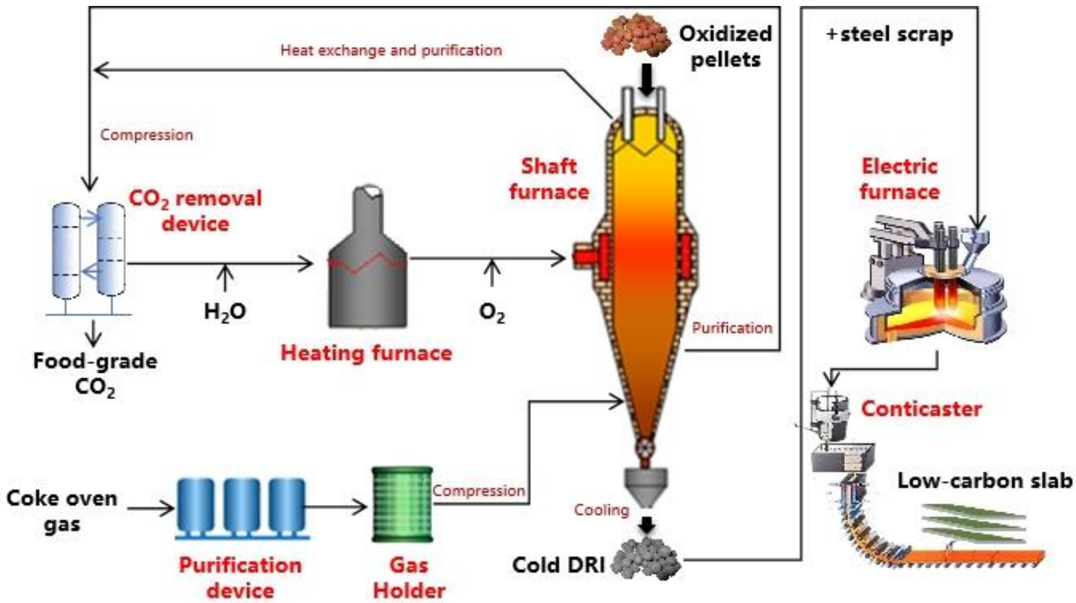

Figure 1. The process flow chart of hydrogen metallurgy based on coke oven gas in HBIS

4. CONCLUSION

Hydrogen metallurgy is internationally recognized as a revolutionary pathway for low-carbon steel production, offering a fundamental solution to energy and emission challenges while enabling the development of low/zero-carbon steel products. Among various technologies, gas-based shaft furnace direct reduction stands out for its high hydrogen utilization, environmental friendliness and compact process flow, having established a mature global technical system. Given China's limited natural gas resources, coke oven gas-based hydrogen metallurgy with zero-reforming technology currently represents the most viable and scientifically sound approach aligned with domestic resource endowments. Looking forward, as hydrogen metallurgy and supporting EAF technologies mature alongside renewable hydrogen production advances, green hydrogen is poised to become the primary hydrogen source for shaft furnaces, accelerating the steel industry's transition toward zero-carbon emissions.

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