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IMPACTS AND APPLICATIONS OF HYDROGEN INJECTION IN BLAST FURNACES: A REVIEW

IMPACTOS E APLICAÇÕES DA INJEÇÃO DE HIDROGÊNIO EM ALTOS-FORNOS: UMA REVISÃO

IMPACTOS Y APLICACIONES DE LA INYECCIÓN DE HIDRÓGENO EN ALTOS HORNOS: UNA REVISIÓN

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ABSTRACT

The steel industry is one of the largest contributors to global CO2 emissions, and the transition to low-carbon production methods is crucial to achieving climate goals. Hydrogen injection into blast furnaces (BFs) has emerged as a promising technology to reduce carbon emissions and improve the sustainability of steel production, especially when the hydrogen comes from non-fossil sources. This review comprehensively examines the impacts and applications of hydrogen injection in BFs, focusing on thermodynamic, operational and environmental aspects. By analyzing recent studies, it highlights the benefits, challenges and future directions by producing hot metal from hydrogen. The review synthesizes findings from more than 90 studies, providing an understanding of how hydrogen injection (HI) influences operations. Some parameters were emphasized, such as theoretical flame temperature (RAFT), oxygen enrichment (OE), coke consumption (CR), pulverized coal injection rate (PCI), blowing temperature (TS), top gas temperature (TGT) and CO_2 emissions. The potential of hydrogen to replace traditional carbon-based reducers was discussed. Overall, HI can reduce coke consumption and greenhouse gas emissions, increase process productivity, but will require technical care to meet expectations.

Keywords: CO_2 Emissions. Hydrogen. Injection. Blast Furnace.

RESUMO

A indústria siderúrgica é uma das maiores contribuintes para as emissões globais de CO2, e a transição para métodos de produção com baixas emissões de carbono é crucial para alcançar as metas climáticas. A injeção de hidrogênio em altos-fornos (BFs) surgiu como uma tecnologia promissora para reduzir as emissões de carbono e melhorar a sustentabilidade da produção de aço, especialmente quando o hidrogênio provém de fontes não fósseis. Esta revisão examina de

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forma abrangente os impactos e as aplicações da injeção de hidrogênio em BFs, com foco nos aspectos termodinâmicos, operacionais e ambientais. Ao analisar estudos recentes, ela destaca os benefícios, desafios e direções futuras da produção de ferro gusa a partir do hidrogênio. A revisão sintetiza as conclusões de mais de 90 estudos, proporcionando uma compreensão de como a injeção de hidrogênio (HI) influencia as operações. Alguns parâmetros foram enfatizados, como temperatura teórica da chama (RAFT), enriquecimento de oxigênio (OE), consumo de coque (CR), taxa de injeção de carvão pulverizado (PCI), temperatura de sopro (TS), temperatura do gás de topo (TGT) e emissões de CO_2. O potencial do hidrogênio para substituir os redutores tradicionais à base de carbono foi discutido. No geral, a HI pode reduzir o consumo de coque e as emissões de gases de efeito estufa, aumentar a produtividade do processo, mas exigirá cuidados técnicos para atender às expectativas.

Palavras-chave: Emissões de CO_2. Injeção. Hidrogênio. Alto-Forno.

RESUMEN

La industria siderúrgica es una de las que más contribuye a las emisiones globales de CO2, y la transición a métodos de producción con bajas emisiones de carbono es fundamental para alcanzar los objetivos climáticos. La inyección de hidrógeno en altos hornos se ha convertido en una tecnología prometedora para reducir las emisiones de carbono y mejorar la sostenibilidad de la producción de acero, especialmente cuando el hidrógeno procede de fuentes no fósiles. Esta revisión examina de forma exhaustiva los impactos y las aplicaciones de la inyección de hidrógeno en altos hornos, centrándose en los aspectos termodinámicos, operativos y medioambientales. Mediante el análisis de estudios recientes, destaca las ventajas, los retos y las perspectivas de futuro de la producción de arrabio a partir de hidrógeno. La revisión sintetiza los resultados de más de 90 estudios, lo que permite comprender cómo influye la inyección de hidrógeno (HI) en las operaciones. Se hicieron hincapié en algunos parámetros, como la temperatura teórica de la llama (RAFT), el enriquecimiento de oxígeno (OE), el consumo de coque (CR), la tasa de inyección de carbón pulverizado (PCI), la temperatura de soplado (TS), la temperatura del gas superior (TGT) y las emisiones de CO_2. Se discutió el potencial del hidrógeno para sustituir a los reductores tradicionales basados en el carbono. En general, la HI puede reducir el consumo de coque y las emisiones de gases de efecto invernadero, así como aumentar la productividad del proceso, pero requerirá cuidados técnicos para cumplir con las expectativas.

Palabras clave: Emisiones de CO_2. Inyección. Hidrógeno. Alto horno.

INTRODUCTION

The iron and steel sector is the largest CO_2 emitter among heavy industries and the second largest energy consumer, releasing 2.6–2.8 Gt annually (1–3). Its strong dependence on coal, responsible for 75% of energy demand and coke production, reinforces the role of blast furnaces

(BFs) for their efficiency and scale (4,5). Emission intensity varies among countries according to the share of electric arc furnaces (6).

In line with climate goals, low-carbon alternatives have gained prominence, such as biomass (7,8), hydrogen (9) and renewable electricity (10). Co-injection of H_2, O_2 and CO_2 with pulverized coal can raise productivity and reduce emissions (11). Using reactive coke with hydrogen has also proven effective (12). Hydrogen improves the reduction kinetics of iron oxides (13) and can partly replace coke, lowering carbon use and increasing efficiency (14–16), making it one of the main decarbonization paths (17). In China, hydrogen metallurgy could cut emissions by up to 62.53% by 2050 (18). Although natural gas injection is established, direct use of H_2 as a reductant requires further study, since its physical properties demand operational adaptations (19).

H_2 injection may reduce BF emissions by 16% or more (20), but faces challenges such as high renewable hydrogen costs (21,22) and thermal impacts (23). Trials have shown success with H_2-rich gas in different furnace zones (24,25) and with alternative carbonaceous injectants such as biomass residues (26–28). Large projects such as COURSE50 (Japan), ULCORED and HYBRIT (Europe) and U.S. initiatives explore H_2-based routes. Since 2010, Chinese efforts have reported significant reductions in fuel use and CO_2 (29,30).

Hydrogen affects flame temperature, slag composition, steel quality and coke performance (31), requiring adjustments such as oxygen enrichment (32). This review analyzes the operational and environmental impacts of H_2 injection in BFs, highlighting trends, challenges and perspectives for lower-carbon ironmaking.

METHODOLOGY

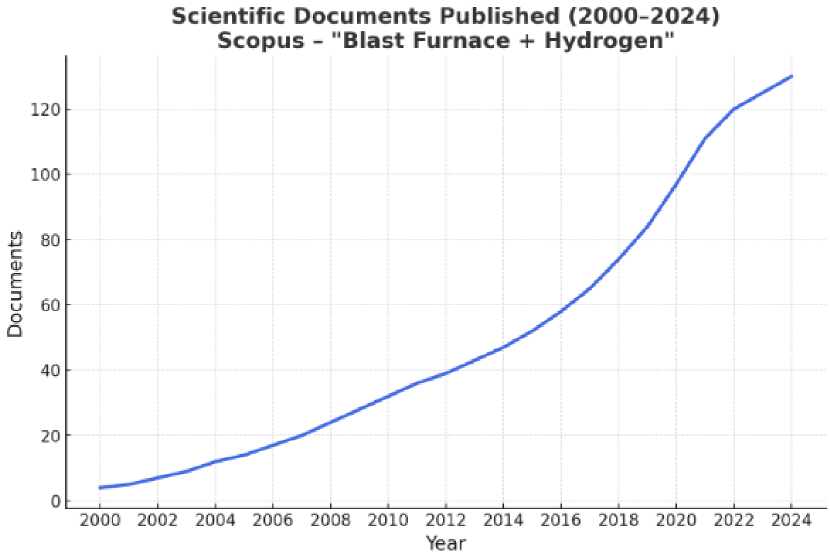
This study addresses gaps in knowledge on hydrogen injection in blast furnaces. A literature review was carried out in October 2024 with the following steps:

- Initial Scopus search (“blast furnace” + “hydrogen injection”) found 35 documents (1984–2024), 26 post-2020, considered insufficient.
- A broader Scopus search (“blast furnace” + “hydrogen”) returned 1031 results, 476 (46.2%) from 2020–2024.
- From these, 50 relevant works were filtered, totaling 76.
- Web of Science search added 22, of which 20 overlapped.

- Connected Papers portal was used to expand related references.
- Sectoral statistics were also consulted.

In total, 90 documents were analyzed, extracting gaps, objectives, methods, results and conclusions. Data were organized in a spreadsheet (authors, year, title, journal, database). Around 26% of studies used CFD (1D–3D), 21% laboratory experiments, 20% mathematical models, 14% reviews, 7% thermodynamic models, and the rest various simulations and BF trials. Figure 1 shows the growth in publications on “blast furnace” and “hydrogen” in Scopus (2000–2024).

Figure 1 – Growth in publications on blast furnaces and hydrogen.



Source: Prepared by the authors themselves.

THEORETICAL FRAMEWORK

I. Thermodynamic effects

Reduction of iron oxides by H_2 is endothermic, while by CO it is exothermic. For instance: $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$, $\Delta H = +100$ kJ (298 K); $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$, $\Delta H = -23.5$ kJ (298 K); $C + H_2O \rightarrow CO + H_2$ is also endothermic (33).

Thus, H_2 alters BF thermodynamics. It reduces oxides at lower temperatures than CO, lowering the cohesive zone (34–37). Reduction of FeO by H_2 is efficient below 1250 °C (up to 25% heat supplied by H_2), but excessive injection may cause incomplete reduction and higher coke use (4). Gas composition shifts, with more H_2 in the shaft, enhancing indirect reduction (16,38), though thermal stability in upper zones becomes harder to maintain.

Main effects: cooler upper furnace, thinner cohesive zone, higher ore/coke ratio, increased productivity, lower pressure loss and coke rate, and reduced emissions (14). Direct reduction decreases with higher H_2, while indirect reduction by H_2 rises, replacing part of CO reduction (16,39,40).

H_2 shifts the reserve zone equilibrium ($FeO + CO \leftrightarrow Fe + CO_2$) to lower temperatures. Its injection increases heat demand at the tuyere, usually compensated by higher O_2 or hotter blast. Above 1000 °C, H_2 mainly acts as a catalyst; below, it absorbs heat and affects the granular zone (23). It also shifts $H_2O + CO \leftrightarrow H_2 + CO_2$ equilibria. At high injection, gasification by H_2O raises CO in BF gas (14). Classic Chaudron diagrams show that below ~800 °C H_2 requires more moles than CO for full reduction, the reverse occurring at higher temperatures (41).

II. Effects on the Theoretical Flame Temperature (RAFT)

The theoretical (adiabatic) flame temperature (RAFT) is the temperature of gases leaving the combustion zone (CZ), influenced by fuel type, injection rate, blast conditions and material composition. With hydrogen, RAFT decreases due to its low inlet temperature and stronger cooling effect (≈5× that of natural gas, NG). In co-injection, H_2 lowers RAFT by ~–4.7 °C/kg; alone, the effect is –14 °C/kg for H_2 and –2.8 °C/kg for NG (38). A way of calculating the RAFT, considering hydrogen injection, is shown in equation 1.

Eq. 1 $$RAFT = 2239.643 - 15I_{\mathrm{H}} + 32.192F_0 - 0.629W_{\mathrm{c}} - 3248{,}12BH.$$

where

I_H is the hydrogen injection in kg/thm, F_o is the blowing enrichment rate in %, W_c is the PCI and BH is the blowing air humidity in m³/m³. (42)

Cold H_2 requires higher O_2 enrichment, significantly reducing RAFT. For instance, 250 m³/thm at 25 °C gave RAFT ≈1900 °C; with 350 m³/thm, enrichment rose from 3.76% to 24.56%. Preheating H_2 (450–1250 °C) reduces O_2 demand and coke rate, expanding the operating window: at RAFT 1900 °C and TGT 130 °C, max injection rose from 237 m³/thm (25 °C) to 350 m³/thm (1250 °C) (32). With 120 m³/thm H_2, RAFT fell from 2171.83 °C to 1900 °C, requiring 10.38% O_2 enrichment (14). Table 01 summarizes published RAFT values.

Greater O_2 enrichment enables higher H_2 injection, though with declining efficiency. Raising blast temperature also allows higher rates for the same O_2 level. However, above 29–30% O_2, Δtmin in the thermal reserve zone drops below 20 °C, impairing heat exchange and stability (43). Preheating H_2 reduces coke rate but not always CO_2, since heating consumes energy. The process of injecting coal together with H_2 preheated to 900 °C can increase the emissions reduction effect by around 30% with the use of green hydrogen (44).

Compared with other H_2-rich gases, pure H_2 lowers RAFT most and raises TGT most, while COG and shale gas give more stable TGT. At 1100 °C blast and 25 °C preheating, max injection rates were 90 kg/thm (shale gas), 107.2 (COG) and 31.8 (H_2). At 1200 °C blast, they rose to 90.4, 108.3 and 32.9; with 600 °C preheating, to 94, 112.5 and 32.1 kg/thm (45). Injecting cold H_2 increases TGT, while reducing the coke/ore ratio and increasing O_2 reduces TGT. Preheating the H_2 widens the operating window, allowing higher injection rates without compromising RAFT and TGT (32).

Table 1 - RAFT

RAFT °C	EO_2 (%)	HI (m³/t)	HI (kg/t)	T Blow °C	PCI (kg/t)	Reference
2094	9	159	14,29	1273	120	(16)
2091	16,8	277	24,90	1273		
2098	15	304	27,33	1273		
2097	18,5	359	32,27	1273		
2040	12,4	160	14,38	1052	137	(46)
2051	4,03	217	19,54	1153	102,6	(36)
2051	4,03	217	19,54	1153		(47)
2051	3,65	209	18,82	1153		
2050	6,18	211	18,98	1153	104,1	
2051	0,49	159	14,29	1153	140	
2000	14	300	26,97	1041	167	(20)

Source: Prepared by the authors themselves

RAFT decreases ~14.2 °C per kg of H_2 injected, reaching 1910 °C at 35 kg/thm (38). With ΔTmin = 20 °C, RAFT ranged 2133–2266 °C with 0–12% enrichment at 1200 °C blast (35). Lower RAFT supports greater coke replacement and CO_2 reduction (48). Tuyere injection of reducing gas kept RAFT constant at 2314 °C despite higher O_2, preventing overheating in the lower furnace (49). For NG, preheating +100 °C increased RAFT by 17 °C, reduced TGT by 4.5 °C, and lowered coke rate by 7 kg/thm at 873 °C (50). The injection of hydrogenated gases is promising for reducing CO_2 and coke consumption. TGT is a limiting factor, with coke oven gas and pure H_2 being the most effective in reducing emissions (51). In general, TGT decreases with increasing H_2 content in the gas (5).

III. Fuel consumption

Hydrogen injection (HI) has strong potential to lower coke rate (CR). Reported results vary with injection mode (tuyere, shaft, co-injection). Comparative findings:

- Pure H_2 reduces CR more than COG or mixtures (16).

- Mass/heat balance simulations: max injection 19.5 kg/thm (RAFT/TGT limited), saving 37.5 kg/thm PCI (52).
- Increasing H_2 lowers chemical carbon use, but combustion consumption in CZ rises to supply heat (53).
- Tuyere injection reduces fuel rate at high O_2 (>35%), achieving lower values than BFs without injection (49).
- Higher H_2 volumes cut coke rate, while greater H_2 purity at constant volume may raise it (54).
- Coke rate decreases sharply with H_2 (33).
- Optimal CR reduction occurs at ~33.3% H_2; above this, CR rises again (40).
- One model estimated minimum coke consumption at 426 kg/thm under certain conditions. Reducing the degree of direct reduction from 27% to 21% would reduce consumption by 24 kg/thm (55).

Table 2 - Effect of Hydrogen Injection on Fuel Consumption

Hydrogen injection	**Reduction in consumption**	**Reference**
HI of 50 m³/thm	8.66% in CR.	(15)
HI between 7.9 and 10.9 m³/thm	Reduction of 1 kg/thm of CR, depending on the injection position (tuyere or shaft).	(43)
1 kg of H_2	Reduction of between 3 and 4 kg	(35)
12.2 kg/t of H_2	8% CR	(2)
For every 50 m³/thm of H_2 at 25 °C added, With the injection of,	10.9 kg/thm reduction in CR.	(32)
350 m³/thm of H_2	CR reduced from 300 kg/thm to 223.6 kg/thm.	(30)
300 m³/thm of H_2	CR reduced from 358 (with 167 PCI) to 285 (with 167 PCI).	(20)
10 m³/thm of H_2	CR reduced by 0.48%/0.46% at a constant/variable RAFT.	(39)
Increase H_2 injection from 10 kg/thm to 35 kg/thm	CR decreased by 60 kg/thm	(38)
HI (injection of 10 kg/thm) at 80 °C	CR 498.1 to 461.7 kg/thm	(48)
Increase in coke oven gas (COG) injection rate from 14.8 kg/thm (current) to 74.0 kg/thm, NG from 0.0 kg/thm (current) to 43.0 kg/thm and increase in H_2 injection rate from 0.0 kg/tHM (current) to 12.0 kg/tHM.	Reduction in CR from 308.1 kg/thm (current) to 277.1 kg/thm (COG), 272.1 kg/thm (NG) and 286.3 kg/thm (H_2).	(51)
Injection of 30 m³/s of hydrogen (shaft injection).	Reduction in CR from 323 kg/thm to 295 kg/thm	(56)
Co-injection of H_2 reduced the coke rate.	The lowest CR (285.8 kg-C/thm) and the highest coke replacement rate (4.1 kg-C/kg-H_2) being achieved with an H_2 injection ratio of 4:6 in the tuyere and shaft.	(5)
With a shaft injection rate of 10 Nm³/s.	The fuel rate decreased from 503 kg/thm to 445 kg/thm.	(57)

Source: Prepared by the authors themselves

IV. Combustion Efficiency and Substitution Rate

Hydrogen injection slightly improves pulverized coal burn (PCI) up to 30 m³/thm, but above that the burn rate decreases (15). Hydrogen combustion is more efficient and faster than PCI, being completely consumed 0.5 m from the tip of the injection lance (34). The increase in H_2 in the co-injected gas speeds up its combustion, heats up the PCI and anticipates its devolatilization and combustion, compensating for the capture of O_2 by the gas (58). The combustion of H_2 raises the local temperature, promoting the early release of volatiles and greater burnout of the biochar (59). Increasing the injection of natural gas (NG) increases the fraction of H_2, reducing CO_2 emissions, but also O_2 in the raceway, impairing the burning of PCI. The PCI burn rate fell from 70.11% to 68.31% when NG injection was increased from 47 to 67 m³/thm (60).

The combustion efficiency of PCI is affected by the consumption of O_2 by fuels rich in H_2. Burnout was highest with recycling top gas (RTG) (81.76%), followed by H_2 (79.86%), COG (78.04%) and NG (75.72%). NG generated more unburned particles, affecting the permeability of the coke bed (61). Burnout increases along the centerline as the distance from the injection lance extends and is greater around the particle plume. With high NG injection and low PCI, the burnout at the exit of the combustion zone ranges from 64.12% to 68.11% (62). Both the final burnout along the centerline of the vent and the average burnout of the raceway surface increased with increasing hydrogen injection rate (63).

The PCI substitution rate varies between 1.9 kg-PCI/kg-H_2 and 1.64 kg-coke/kg-H_2 for HI of 19 kg/thm (44). Coke replacement ranges from 4 kg/kg-H_2 (with 5 kg/thm of H_2) to 3 kg/kg-H_2 (maximum injection) (35). With 69 kg/thm of H_2, the total consumption of reducing agent was 376 kg/thm (307 kg of coke), compared to 332 kg of coke and 150 kg of PCI in conventional BF (64). The substitution ratio ranges from 0.86 to 5.49, with the highest value for 5 kg/thm of H_2 at 1200 °C (48). Typical substitutions: NG (0.8-0.9 kg/m³), COG (0.4-0.45 kg/m³), H_2 (1.9-2.0 kg/kg) (65).

Blowpipe injection is ideal for small quantities and low O_2 contents (up to 30%), improving PCI burnout. Direct injection into the raceway is more suitable for large volumes and high O_2 contents (40-50%), promoting diffusion, temperature increase and burnout (66). Smaller PCI particles perform better. However, large volumes of reducing gas can cause tuyere erosion, requiring further study.

V. Impact on primary slag and the Softening and Melting Zone

The injection of hydrogen-rich gas reduces the FeO content and the amount of primary slag. With 10% H_2 in the reducing gas, the slag decreased by around 10% (01). The FeO content fell to 1.73%, below the 10-30% of conventional operation, and the cohesive zone took on an irregular V shape, descending to the bosh (67). Enrichment with H_2 alters slag formation, reducing the amount of wustite and forming new mineral phases. Without H_2, the slag contained wustite, hortonolite and $FeTiO_3$; with 10% H_2, the wustite disappeared and calcium-magnesium olivine and melilite appeared. The amount of primary slag fell with increasing H_2: 1290 kg/tFe (0%), 919 kg/tFe (5%), 618 kg/tFe (10%) and 512 kg/tFe (15%) (37).

With more H_2, the reduction rate of the ore increases, reducing the FeO content and raising the slag formation temperature, which increases the initial softening temperature (T_A). The continuous reduction of FeO to Fe raises the softening end temperature (T_{40}) and the melting start temperature (T_S) of the mixed charge. The melting point of the slag also increases with the H_2 content (68). In the oxygen blast furnace (OBF) process with H_2, the reduction index (RI) must be improved, and the T_A can be reduced to 1050-1100 °C, while in conventional BF, the T_A can exceed 1100-1150 °C (64).

The injection of H_2 can improve the permeability of the cohesive zone due to the lower presence of wustite and the higher melting point of the slag (23). With 15% H_2, T_S increased from 1305 °C to 1485 °C and the dripping temperature (T_D) from 1413 °C to 1497 °C (69). The cohesive zone becomes narrower horizontally and shorter vertically with more H_2 (40). The formation of high melting point compounds and the carburization of iron raised the dripping temperature, shifting the cohesive zone downwards (37). The height of the cohesive zone fell below the baseline with 23.75 kg/thm of H_2 (38).

With 15% H_2, T_A rose from 1112 °C to 1176 °C, T_{40} from 1220 °C to 1377 °C, T_S from 1323 °C to 1465 °C, and the width of the cohesive zone fell from 141 °C to 27 °C (68). With the injection of H_2 into the shaft, the apex of the cohesive zone rose, the base remained stable and the profile became more concave towards the shaft (52), this can be considered positive for the process because it improves thermal and reduction conditions, accelerates reduction, and increases the degree of reduction of iron oxides. These changes reduce fuel consumption.

VI. Productivity

Productivity increased by 145% (from 4000 to ~9800 thm/day) with the option of maintaining the RAFT by enriching the blowing air with oxygen, when the HI went from 0 to

585 m^3/thm. The increase in productivity was less significant when lower RAFTs were allowed. Compared to other gases, HI resulted in a 48% increase in productivity, natural gas in 30% and coke oven gas in 14%, while maintaining the RAFT between 1800 and 2200 (39). Hydrogen injection increased blast furnace productivity by up to 13.7%, depending on the level of oxygen enrichment (40). BF productivity increases with hydrogen enrichment, but the rate of increase decreases at higher hydrogen contents (37). Productivity increases with increasing oxygen content in the blow, but the increase is less significant in oxygen blast furnaces (OBFs) with injection in the tuyeres due to the reduction in the blow rate. (53). Partially replacing PCI with enriched blast furnace gas (with H_2) resulted in a significant increase in productivity, with the best-case scenario predicting an increase of 20.5% (70).

VII. Combustion Zone

The combustion zone (CZ), or raceway, can be altered in size with hydrogen injection (HI), but there is disagreement in the literature as to its actual extent.

Some studies indicate that the CZ is smaller with HI compared to pulverized coal injection (PCI), due to the lower density of hydrogen. This characteristic reduces the drag force on the coke particles, limiting the expansion of the CZ and favoring a more peripheral distribution of the gases generated. It was observed that the width and height of the CZ gradually decreased by around 32% and 55%, respectively, as the concentration of injected hydrogen increased from 1.5% to 4.5%. The hydrogen burns near the injection nozzle, releasing a large amount of water vapor, and the oxygen is quickly consumed due to the simultaneous combustion of hydrogen and carbon. As a result, CO is formed by the gasification of carbon with H_2O and CO_2 on the periphery of the CZ (71). On the other hand, other studies point to the opposite behavior, suggesting that HI results in a significantly larger CZ than that observed with PCI. According to these studies, the depth of the CZ expands from 1.1 m to 1.4 m, the width from 0.45 m to 0.7 m and the height from 0.76 m to 1.45 m. The total volume of the SZ under HI can reach 0.19 m^3, around four times greater than that of the PCI (0.05 m^3). In this condition, a higher temperature is observed at the front of injection lance, but lower temperatures in deeper regions of the CZ. This effect is attributed to the intense endothermic reaction of coke gasification, promoted by the large amount of water vapor generated during hydrogen combustion (34).

The gas velocity in the tuyere varies significantly with the type of fuel injected. The decreasing order of speed is: COG (313.89 m/s), NG (308.13 m/s), RTG (297.08 m/s) and H_2 (282.14 m/s), and the speed of the gas affects penetration into the coke bed. COG, due to its higher velocity, has the highest penetration, while H_2 has the lowest (61). Injecting H_2 can reduce carbon emissions, but requires additional measures to increase the gas velocity in the combustion zone.

VIII. Reducing CO_2 emissions

One of the main drivers of hydrogen injection in BFs is CO_2 mitigation. Studies report reductions of up to 20–30%, depending on injection rate and operating conditions. The benefits, however, depend on H_2 origin: if produced from fossil fuels without CCS, overall emissions may not fall significantly (1). Thus, integration with renewable sources or CCS is essential. Table 03 summarizes published results.

Additional findings include: reformed COG injection reduced CO_2 by 34.62%; higher H_2 content raises BFG calorific value, improving energy recovery and lowering emissions (56); combining H_2 injection with TGT recycling cuts CO_2 by up to 30%, and potentially 100% with CCS (75); COG and pure H_2 achieved ~8% and 6% reductions, respectively, versus conventional BF (51); replacing PCI with enriched BFG reduced emissions by up to 14.8% (70); and H_2 injection achieved 13.03 $kgCO_2/kgH_2$ avoided (76).

Table 3 - Potential Reduction in CO_2 Emissions

Potential Reduction	**H_2 injection**	**Reference**
16% reduction	359 Nm^3/thm	(16)
Reduction of CO_2 emissions by up to 262 m^3/thm (an OE of the blowing air of 9% and integrating CO_2 capture, the final emission was 278 m^3/thm of CO_2).	80 m^3/thm	(43)
Direct CO_2 reduction of 10.2%-17.8% (decarbonization potential was estimated in the range of 9.4 to 9.7 tCO_2/tH_2).	HI 19.0 and 28.3 kg/thm.	(35)
HI reduced direct emissions by 8% with a total emissions reduction of 110 kg-CO_2eq/thm.		(44)
14.4% reduction in CO_2 emissions.	359 m^3/thm	(45)
26.1% reduction in CO_2 emissions .	350 m^3/thm	(32)
Can reduce CO_2 emissions by 16%, 7% and 6%	300, 200 e 100 m^3/thm (H_2, COG and NG).	(20)
9.46% reduction in CO_2 emissions.	19.5 kg/thm	(54)
21.3%/25.9% reduction in emissions at a constant/variable RAFT [Every 10 m^3 of H_2 reduces CO_2 production by 0.49 and 0.51% (constant and variable RAFT)].	The increase in H_2 consumption from 150/100 to 585/600 m^3/thm	(39)
Potential 11% reduction in CO_2 emissions.	Increase in H_2 from 10 to 35 kg/thm	(38)
Potential reduction of between 5.5-12.1%.	27.5 kg/thm of H_2	(72)
21.4% reduction in CO_2 emissions compared to the reference case using 120 kg/thm of PC.	27.5 kg/thm of H_2 are injected at 1200 °C	(48)
Reduction of CO_2emissions by 82 kg/thm, representing 5.4%.	Co-injection of 95 kg of NG with 15 kg of H_2	(73)
Reduced emissions by 9.8% (from 1397 kg/thm to 1259 kg/thm)	29 kg/thm of H_2	(74)

Source: Prepared by the authors themselves

IX. Other operational impacts

The injection of hydrogen reduced the Maximum Pressure Difference (MPD) in all the volume fractions tested, indicating an improvement in the permeability of the process (69), and at higher rates with 35 kg/thm of H2, the pressure drop across the furnace increased significantly (38). The S value (permeability index) decreased significantly with increasing hydrogen content, from 238.78 to 19.29 kPa °C (68). The increase in hydrogen content in the reducing gas reduced the pressure drop in the furnace, despite the decrease in the coke layer (33).

Stable blast furnace operation can be achieved with H2 injection of up to 30 kg/thm alone and up to 15 kg/thm in combination with NG (68). For a blast temperature of 1200°C, the maximum hydrogen injection rate, limited by the value of Δtmin = 20°C, is 19.0 kg of H2/thm for 2% oxygen enrichment and 28.3 kg of H2/thm for 12% enrichment (35). The H2 residence time decreases with increasing HI and with increasing injection temperature (77).

X. Raw materials

The addition of hydrogen to the reducing gas significantly increases the reduction rate of iron ore above 600-700 °C for all charges (lump, sinter and pellets) (78). Mixing H2 with CO improves gas diffusion, promoting deeper reduction in the particles and the formation of cracks, which can intensify degradation. Just 2% of H_2 in CO significantly increases RDI-2.8, especially for sinter (50% increase) and pellets (137% increase) (79).

In blast furnaces, at around 900 °C, H2 favors the reduction of pellets, with the formation of radial cracks that facilitate the penetration of the reducing gas (80). The presence of H2/H2O improves reduction kinetics without causing significant disintegration (26). In the sinter, H2 can inhibit or intensify disintegration, depending on the kinetics in relation to the gas mixture. Reduction with H2 is kinetically more favorable than with CO, forming dense, interconnected layers of iron, while CO generates smaller fragments (23).

Coke is 20-30% more reactive with H2O than with CO2, and the reaction rate is 2-4 times higher (81). The H2 generated by the injection of hydrogen-rich gas promotes the coke gasification reaction, increasing the solution loss reaction rate (82). When the fraction of H2 in the oven increases from 0 to 10%, the coke gasification rate increases significantly. Gasification with H2O is 1.3-3.2 times faster than with CO2, with a 37 °C lower limit temperature (54). The addition of 10% and 25% H2 increases coke gasification from 27.05% to 33.98% and 42.83%, respectively, and reactivity from 22.3% to 28.4% and 35.8% (83). The effect of H2 on gasification is more relevant at low temperatures, becoming negligible above 1300 °C (84). H2O reacts preferentially with coke up to 1092 K, shifting gasification to lower temperatures (85).

H_2-rich blast furnaces alter the coke's deterioration mechanism, promoting the reduction process in low-temperature areas and lower production of H2O and CO2 at high temperatures. The strength of the coke after reaction drops from 66.4% to 59.4% with 10% H2, and to 50.4% with 25% (83). The addition of H2O increases the formation of micropores at low temperatures and macropores at high temperatures, with greater porosity at the edges of the coke compared to CO2 (81). With 10% H2, the porosity of the coke rises from 57.9% to 83%, while that of the center drops to 40% (83).

XI. Future research directions

Future research should prioritize the optimization of hydrogen injection into blast furnaces (BFs), with a focus on developing advanced models capable of predicting its operational effects, as well as investigating new materials and technologies for storage and injection. In addition, it is essential to carry out industrial-scale studies to assess the long-term performance of this technology, especially with regard to furnace stability and the quality of the end product. Several technical challenges still need to be overcome, such as recycling the top gas containing N2, the operational difficulties associated with high levels of oxygen in the blowing air and the limitation of the indirect reduction rate in conventional blast furnaces, currently restricted to 70%, which compromises the potential for reducing carbon emissions (86).

Direct hydrogen injection has limitations, including low utilization efficiency, difficulties in the thermal balance and safety concerns regarding handling and storage. In this context, the methanation of BFG, a process that converts CO and CO2 into CH4, has emerged as a promising alternative for the indirect introduction of hydrogen, with superior potential for mitigating CO2 emissions (74).

The integration of hydrogen injection with low-carbon technologies, such as carbon capture and storage (CCS) and the use of renewable energy sources, represents a relevant complementary strategy. In an integrated steel plant with capacity of 2.54 million tons/year, the estimated cost of capturing 99% of the CO2 is $80.3 per ton (87).

Other aspects that require investigation include optimizing the H2/CO2 ratio in the methanation process (CO2 + 4H2 = CH4 + 2H2O and CO + 3H2 = CH4 + H2O) to maximize coke replacement (88), and developing materials that are resistant to hydrogen embrittlement. In addition, the H2/CO ratio must be adjusted to optimize NO reduction and minimize NOx emissions, since excess hydrogen can compromise the regeneration of the active sites in the coke, reducing the efficiency of the process (89).

Finally, the success of the transition to hydrogen-based steelmaking will depend on the availability of green hydrogen, the expansion of renewable electricity and the necessary infrastructure. It is estimated that, in the most ambitious scenarios, global electrolysis capacity will need to be increased by more than a thousand times compared to current levels (90).

CONCLUSION

The injection of hydrogen into blast furnaces represents a promising way to reduce CO2 emissions in the steel industry while maintaining production efficiency. However, successful implementation requires careful optimization of operating parameters, as well as the development of new materials and technologies to overcome technical challenges. This technology in blast furnaces shows potential for reducing CO2 emissions by more than 30%, as well as reducing coke consumption by more than 10% and increasing productivity, but it requires strict control of parameters such as RAFT, oxygen enrichment, top gas temperature, combustion and cohesive zone shape and raw material quality. Given the current production costs of the entire green hydrogen chain, replacing coal and coke is not financially advantageous. Efforts from the government, academia, and industry are needed to find ways to overcome these difficulties.

This review has highlighted the main impacts and applications of hydrogen injection in BFs, including its effects on temperature profiles, gas composition, coke consumption and CO2 emissions. While there has been significant progress in understanding the potential of hydrogen injection, more research is needed to address the remaining challenges and unlock the full potential of this technology. By continuing to advance and understand the production of iron from hydrogen, we can move closer to achieving a sustainable, low-carbon future for the steel industry.

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