

Review

Hydrogen Substitution for Conventional Fuels in High-Temperature Industrial Furnaces and Kilns: Key Technologies, Applications, and Future Prospects

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Abstract

Deep decarbonization of high-temperature industrial furnaces and kilns is essential for reducing greenhouse gas emissions in energy-intensive sectors. Hydrogen and hydrogen-enriched fuels are promising alternatives to conventional fossil fuels; however, their integration is not a straightforward fuel replacement. Owing to hydrogen's high laminar burning velocity, wide flammability limits, low volumetric heating value, and water-vapor-rich combustion products, hydrogen substitution can substantially alter flame stability, heat transfer pathways, pollutant formation, and material service behavior. This review systematically summarizes the key technologies and application progress of hydrogen-based fuel substitution in high-temperature industrial systems. First, the thermophysical and kinetic differences between hydrogen and hydrocarbon fuels are analyzed. Subsequently, core enabling technologies are discussed, including flashback prevention, low-NO_x combustion control, thermal-flow-field regulation, heat transfer optimization, and material compatibility under high-temperature, water-vapor-rich atmospheres. Application progress in representative scenarios—including metallurgy, heat treatment, petrochemical-fired heaters, waste treatment, rotary kilns, and cremation furnaces—is reviewed to identify scenario-specific constraints. The review indicates that successful hydrogen substitution requires a transition from isolated burner optimization toward system-level integration of combustion control, heat transfer management, emission mitigation, and material adaptation. Future research should prioritize integrated furnace design, long-term material service assessment, multi-fuel operating strategies, and data-driven control frameworks.

Keywords: hydrogen energy; industrial furnaces and kilns; conventional fuels; emissions; hydrogen substitution



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1. Introduction

Industrial decarbonization is essential for achieving global climate targets, as the sector accounts for approximately 40% of final energy consumption and a substantial share of energy-related CO₂ emissions [1–3]. Hard-to-abate industries such as steel, glass, ceramics, and petrochemicals rely heavily on high-temperature process heat, often above 1000 °C or even 1500 °C [4,5]. Although direct electrification can improve energy efficiency, its

deployment is constrained by power density, grid flexibility, and retrofit costs [6,7]. Hydrogen substitution is therefore regarded as a promising route for decarbonizing industrial high-temperature heat because it may be partly compatible with existing furnaces, kilns, and thermal infrastructure [8,9]. It should be noted that the decarbonization benefit of hydrogen substitution depends not only on combustion-side carbon elimination but also on the upstream hydrogen-production route. Hydrogen combustion can remove direct CO₂ emissions at the furnace or kiln, but fossil-derived hydrogen may shift part of the carbon burden to the production stage. Therefore, a low carbon-hydrogen supply, together with lifecycle carbon accounting, is a prerequisite for achieving deep decarbonization of industrial high-temperature heat. In this context, renewable hydrogen production through water electrolysis, photoelectrochemical water splitting, and water-oxidation catalysis provides an important enabling pathway for future hydrogen-fired furnace systems. Recent studies on photoelectrochemical oxygen evolution and water oxidation have demonstrated continued progress in catalyst and photoelectrode design, although large-scale furnace applications still require a stable, low-cost, and continuously available hydrogen supply [10,11].

Current studies and demonstrations mainly focus on hydrogen blending, while pure hydrogen combustion usually requires dedicated or substantially retrofitted systems. Compared with pure hydrogen firing, blending enables gradual carbon reduction with lower retrofit intensity, but high-ratio or pure hydrogen use imposes greater requirements on burner design, fuel supply, safety control, and material compatibility [12–14]. The motivation, transition pathway, and system-level challenges of hydrogen substitution are summarized in Figure 1.

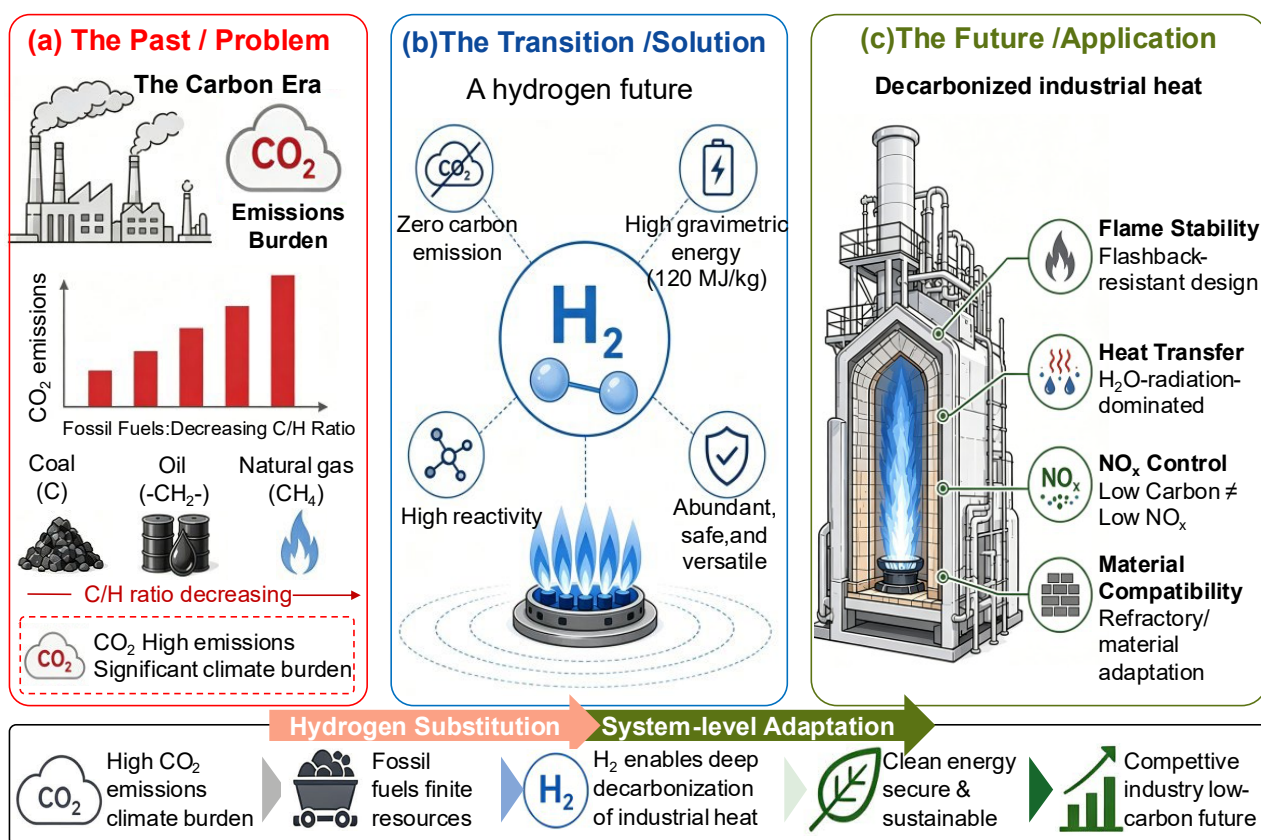


Figure 1. Hydrogen substitution for high-temperature industrial furnaces and kilns: motivation, transition pathway, and application challenges. (a) Decarbonization demand in hard-to-abate high-temperature process-heat sectors; (b) transition from fossil fuels to hydrogen enabled by carbon-free combustion and high-grade heat supply; (c) representative furnace applications and system-level challenges, including flame stability, heat transfer, NO_x control, and material compatibility.

In practical terms, hydrogen blending and 100% hydrogen operation represent two different deployment stages rather than only two fuel compositions. Low- to medium-ratio hydrogen blending can often be implemented as a transitional strategy because it provides partial combustion-side CO₂ reduction while retaining part of the original natural gas infrastructure and burner characteristics. However, its decarbonization potential is limited by the allowable blending ratio, fuel interchangeability, flame stability margin, and the carbon intensity of the supplied hydrogen. In contrast, 100% hydrogen firing offers the maximum potential for direct CO₂ elimination at the furnace, but it usually requires more substantial redesign of fuel nozzles, burner aerodynamics, flame stabilization methods, flashback protection, safety interlocks, NO_x-control strategies, heat transfer matching, and material adaptation under water-vapor-rich atmospheres. Therefore, blending is more suitable as a near-term retrofit pathway, whereas pure hydrogen operation should be regarded as a deeper decarbonization option requiring system-level redesign and validation.

However, hydrogen substitution in industrial high-temperature furnaces and kilns is not a simple fuel switch; it involves systematic changes in fuel thermophysical properties, combustion kinetics, and in-furnace heat transfer. Although hydrogen has a high gravimetric heating value of approximately 120 MJ/kg, its low density under ambient conditions gives it a volumetric heating value only about one-third that of natural gas [15–17]. Therefore, maintaining the same heat input with pure hydrogen or high-ratio hydrogen blending requires a much higher fuel volumetric flow rate, which directly affects burner jet momentum, equivalence ratio distribution, and the macroscopic furnace flow field [18–21]. Conventional fuel interchangeability indices, such as the Wobbe index, mainly describe the equivalence of overall heat input and are insufficient to capture changes in laminar burning velocity, chain-branching reactions, and preferential diffusion under high hydrogen blending ratios [22–24]. Thus, the impact of hydrogen introduction extends beyond heating-value differences and affects the coupled processes of combustion, flow, and heat transfer.

These differences create a series of coupled engineering challenges for hydrogen-containing industrial furnaces and kilns. First, in terms of flame stability, hydrogen has a high laminar burning velocity, short quenching distance, and low minimum ignition energy, making burners more susceptible to flashback, autoignition-induced instability, and thermoacoustic oscillations over wide operating ranges [25–30]. Second, for pollutant control, “low carbon” does not necessarily mean “low NO_x”. The higher adiabatic flame temperature of hydrogen can intensify nitrogen oxidation in high-temperature zones, thereby increasing the tendency for thermal NO_x formation [31–35]. Third, in heat transfer and material service, pure hydrogen or high-ratio hydrogen blending significantly changes radiative heat transfer: radiation from conventional hydrocarbon flames involves CO₂, H₂O, and soot, whereas hydrogen-rich combustion is increasingly dominated by H₂O radiation, affecting temperature distribution, heat flux density, and load-heating uniformity [36–40]. In addition, the higher water vapor partial pressure in hydrogen-rich combustion products alters the high-temperature atmosphere, imposing new requirements on oxidation/scale control of metallic loads and the long-term durability of refractory linings [41,42].

Overall, hydrogen substitution in high-temperature furnaces and kilns is not merely a fuel replacement but a system-level challenge involving combustion control, thermal-flow-field reconstruction, pollutant mitigation, and material adaptation. Although hydrogen combustion has been widely studied in gas turbines and other power systems [43,44], and preliminary assessments have been conducted for sectors such as steel and glass [45,46], systematic reviews focused on high-temperature industrial furnaces and kilns remain limited.

Existing studies have provided valuable insights into hydrogen combustion, hydrogen energy systems, and industrial decarbonization pathways. However, hydrogen substitution

in high-temperature fuel-fired furnaces and kilns involves coupled changes in combustion behavior, burner stability, heat transfer distribution, pollutant formation, material service conditions, and plant-level implementation. To address this gap, the present review examines hydrogen substitution from a furnace system perspective rather than as an isolated fuel or burner issue. Specifically, this review first compares hydrogen and conventional hydrocarbon fuels in terms of combustion kinetics, flame stability, radiative heat transfer, and combustion products. It then summarizes key enabling technologies, including flashback prevention, low-NO_x control, thermal-flow-field regulation, heat transfer optimization, and material adaptation. Representative applications in metallurgy, petrochemical-fired heaters, waste treatment furnaces, rotary kilns, and cremation furnaces are further reviewed to identify sector-specific constraints and provide guidance for low-carbon furnace design, retrofit, and safe long-term operation.

2. Combustion Characteristics in High-Temperature Furnaces and Kilns

High-temperature furnaces and kilns have long relied on conventional fossil fuels, particularly natural gas, to provide process heat. Owing to its high combustion efficiency, operational flexibility, and well-established combustion mechanisms, natural gas is generally regarded as the representative reference fuel for hydrogen substitution studies. Although liquid fuels such as heavy oil and diesel are still used as auxiliary or backup fuels in some furnace types, natural gas and its main component, methane, remain the most relevant benchmarks. Therefore, this section compares hydrogen with conventional hydrocarbon fuels, mainly natural gas/methane, in terms of combustion behavior, flame radiation, and product composition under high-temperature furnace conditions.

2.1. Fuel Characteristics and Combustion Behavior

Compared with conventional hydrocarbon fuels, hydrogen differs markedly in thermophysical properties and energy density, which affects fuel supply flow characteristics and burner aerodynamics. Although hydrogen has a high gravimetric heating value of approximately 120 MJ/kg, its low density gives it a volumetric heating value only about one-third that of natural gas [22]. Therefore, maintaining the same furnace heat load with high hydrogen blending requires a much higher fuel volumetric flow rate, altering nozzle jet momentum, local equivalence ratio distribution, and burner mixing behavior [16].

The Wobbe Index has traditionally served as a primary criterion for thermal input equivalence in gas interchangeability. Franco et al. [5] investigated the thermodynamic behavior of natural gas–hydrogen blends, demonstrating that the Wobbe Index decreases non-linearly with increasing hydrogen fractions and reaches a local minimum at high blending ratios. However, Leicher et al. [4] and Xie et al. [47] evaluated the dynamic combustion characteristics of these mixtures. They pointed out that because of fundamental differences in reaction mechanisms, the Wobbe Index solely reflects thermal input. It fails to adequately characterize changes in laminar burning velocity, flame stability, and flashback sensitivity induced by hydrogen addition. Consequently, they concluded that the applicability of conventional interchangeability indices diminishes significantly at high hydrogen blending ratios.

At the chemical-kinetic level, hydrogen addition strongly affects the burning rate, ignition behavior, and flammability range of blended fuels. Previous studies have shown that hydrogen addition markedly increases the laminar burning velocity of premixed methane–hydrogen–air flames, mainly by enhancing chain-branching reactions and increasing H, O, and OH radical concentrations in the reaction zone [48–50]. Ren et al. [51] compared several kinetic mechanisms, including GRI-Mech 3.0 and USC-Mech 2.0, and further showed that hydrogen addition changes the dominant reaction pathways and

rate-controlling steps. In terms of ignition and flammability, experimental studies on flammability limits further showed that hydrogen blending lowers the lower explosion limit and raises the upper explosion limit, thereby broadening the flammable range of the fuel mixture [52,53]. These findings provide a kinetic basis for determining the safe operating window of hydrogen-enriched combustion systems.

Beyond one-dimensional burning characteristics, the thermophysical properties of hydrogen also affect multidimensional flame-front stability through preferential diffusion. Ern and Giovangigli [54] showed that, because of the low molecular weight and high mass diffusivity of hydrogen, hydrogen–methane mixtures, especially under lean conditions, usually exhibit an effective Lewis number below unity. This promotes hydrogen enrichment in positively curved flame-front regions, increasing the local equivalence ratio and flame temperature. Hu et al. [55] further showed that increasing hydrogen addition reduces the Markstein length and critical flame radius and may even shift the Markstein length from positive to negative values, indicating enhanced stretch sensitivity and stronger cellular instability driven by coupled diffusive–thermal and hydrodynamic effects.

These kinetic and diffusive effects directly influence the macroscopic flame stability of high-temperature burners. Preferential diffusion and wide flammability limits can improve blow-off resistance under lean conditions, whereas the high laminar burning velocity and short quenching distance of hydrogen increase the risk of flame propagation toward nozzles and walls. Kalantari and McDonell [56] reviewed boundary-layer flashback mechanisms, and Aniello et al. [27] showed that increasing hydrogen addition narrows the safe operating window of premixed burners. Hydrogen addition also changes burner aerodynamics. Zhao et al. [57] and Gee et al. [38] reported that the higher fuel jet momentum required to compensate for the lower volumetric heating value alters primary air entrainment. Without proper nozzle and air-supply adjustment, the mixture may shift toward stoichiometric conditions, further increasing flashback risk.

Overall, hydrogen substitution is not a simple fuel change but a coupled adaptation of fuel chemistry, diffusion behavior, and burner aerodynamics. Table 1 summarizes the key differences between hydrogen and methane/natural gas, highlighting why nozzle matching, flashback suppression, flame stability control, and flow-field organization must be re-optimized for hydrogen-enriched or pure hydrogen combustion.

Table 1. Key combustion parameters and engineering implications of hydrogen and methane/natural gas.

Category	Key Parameter	Hydrogen (H ₂)	Methane/ Natural Gas (CH ₄ /NG)	Engineering Implications and System-Adaptation Challenges	References
Basic thermophysical properties	Density at ambient temperature and pressure	~0.084–0.09 kg/m ³	~0.65–0.72 kg/m ³	A much higher fuel volumetric flow rate is required for the same heat load, which changes jet momentum and mixing behavior.	[15]
	Mass-based lower heating value (LHV)	~120 MJ/kg	~50 MJ/kg	Hydrogen has a high heat release per unit mass, but this does not imply superior volumetric heat-supply capacity.	[5,15]

Table 1. Cont.

Category	Key Parameter	Hydrogen (H ₂)	Methane/ Natural Gas (CH ₄ /NG)	Engineering Implications and System-Adaptation Challenges	References
Basic thermophysical properties	Volumetric lower heating value (LHV)	~10–11 MJ/m ³	~33–36 MJ/m ³	The volumetric heating value is only about one-third that of natural gas, requiring re-matching of nozzle diameter, jet momentum, and primary air entrainment ratio.	[15,38]
	Wobbe Index	~40.7–48.2 MJ/m ³	~47.0–53.4 MJ/m ³	Conventional thermodynamic fuel interchangeability criteria become less applicable under high hydrogen blending ratios.	[4,5]
Chemical kinetics	Laminar burning velocity	~209–325 cm/s	~38–45 cm/s	The flame propagation speed increases markedly, producing shorter and more compact flames and increasing boundary-layer flashback risk.	[48–50]
	Minimum ignition energy (MIE)	~0.02 mJ	~0.29 mJ	Ignition sensitivity increases substantially, requiring stricter explosion prevention in pipelines and anti-preignition burner design.	[15]
	Flammability limits in air	~4–75 vol%	~5–15 vol%	This favors lean combustion and wide-load flame stabilization but also expands the range over which flammable mixtures must be controlled.	[52,53]
	Adiabatic flame temperature in air	~2376–2400 K	~2220–2223 K	Local high-temperature zones are more likely to form, increasing the risks of thermal NO _x formation and localized overheating.	[15]
Multidimensional diffusion and stability	Effective Lewis number (Le)	~0.3–0.44 (<1)	~1.0	Preferential diffusion is enhanced, making local equivalence ratio and local flame temperature more likely to increase.	[54]
	Markstein length	Very small or even negative	Generally positive and larger	Flame-front sensitivity to stretch increases, intensifying cellular instability.	[55]

Table 1. Cont.

Category	Key Parameter	Hydrogen (H ₂)	Methane/ Natural Gas (CH ₄ /NG)	Engineering Implications and System-Adaptation Challenges	References
Multidimensional diffusion and stability	Quenching distance	~0.64 mm	~2.0 mm	Flames can propagate through narrower gaps, requiring re-evaluation of conventional flame-arresting and nozzle-gap designs.	[28,56]
	Blow-off resistance	Relatively strong	Relatively weak	This benefits ultra-lean operation, but the stable combustion window and operating boundaries must be redefined.	[27,55]
	Flashback sensitivity	Significantly higher	Relatively lower	Aerodynamic co-design is required to balance flashback prevention, overheating control, and low-NO _x operation.	[27,38,56]
	Primary air entrainment and jet characteristics	Higher jet momentum under high volumetric flow rates	Mature matching with existing burners	Hydrogen blending alters entrainment behavior, requiring re-matching of nozzle diameter and air-supply configuration.	[38,57]

1. The Wobbe index strongly depends on natural gas composition and reference conditions. 2. The laminar burning velocity values refer to typical peak ranges, usually measured near stoichiometric conditions at ambient temperature and pressure. 3. Methane is used as the representative component of natural gas; actual industrial natural gas may contain ethane, propane, nitrogen, carbon dioxide, and other species, which can affect the listed parameters.

2.2. Flame Radiation and Combustion Products

Beyond combustion behavior, hydrogen also changes flame radiation and heat flux distribution, as schematically illustrated in Figure 2a. Carbon-containing flames radiate through soot and CO₂/H₂O band emission, whereas soot-free hydrogen flames radiate mainly through H₂O bands [38,58,59]. Thus, hydrogen combustion reshapes the radiative–convective heat transfer balance rather than simply reducing radiation [36,42].

Gee et al. [38] reported that hydrogen addition removes soot radiation and can reduce flame radiative heat transfer in open burner configurations. However, in confined industrial furnaces, this reduction may be partly offset by enhanced convection from water-vapor-rich flue gas. Mabic et al. [36] showed that, in a 200 kW semi-industrial flameless furnace, hydrogen combustion increased the total heat flux to aluminum samples by about 19% under air firing and 6% under oxy-fuel firing. Kislinger et al. [37] and Schwarz et al. [18] further found that hydrogen-enhanced convection accelerated steel heating by approximately 13% and reduced the required fuel heat input from 94 kW for methane to 70 kW for hydrogen. These results suggest that hydrogen combustion redistributes radiative and convective heat transfer rather than simply weakening overall heat transfer (Figure 2a) [20,36,37].

Hydrogen's high laminar burning velocity also shortens the flame and concentrates heat release near the burner, as illustrated in Figure 2b. Guo et al. [34] measured wall heat flux distributions in a confined chamber and found that increasing the hydrogen blending ratio from 0 to 50 vol% shifted the peak heat flux location upstream from about 650 mm to 350 mm. Daurer et al. [20] further showed by CFD and OH* chemiluminescence imaging that hydrogen addition moves the main reaction zone closer to the nozzle and makes the flame more compact. Therefore, hydrogen substitution shifts heat release toward the burner

near field, requiring re-optimization of nozzle size, air distribution, and jet momentum to avoid local overheating or thermal damage.

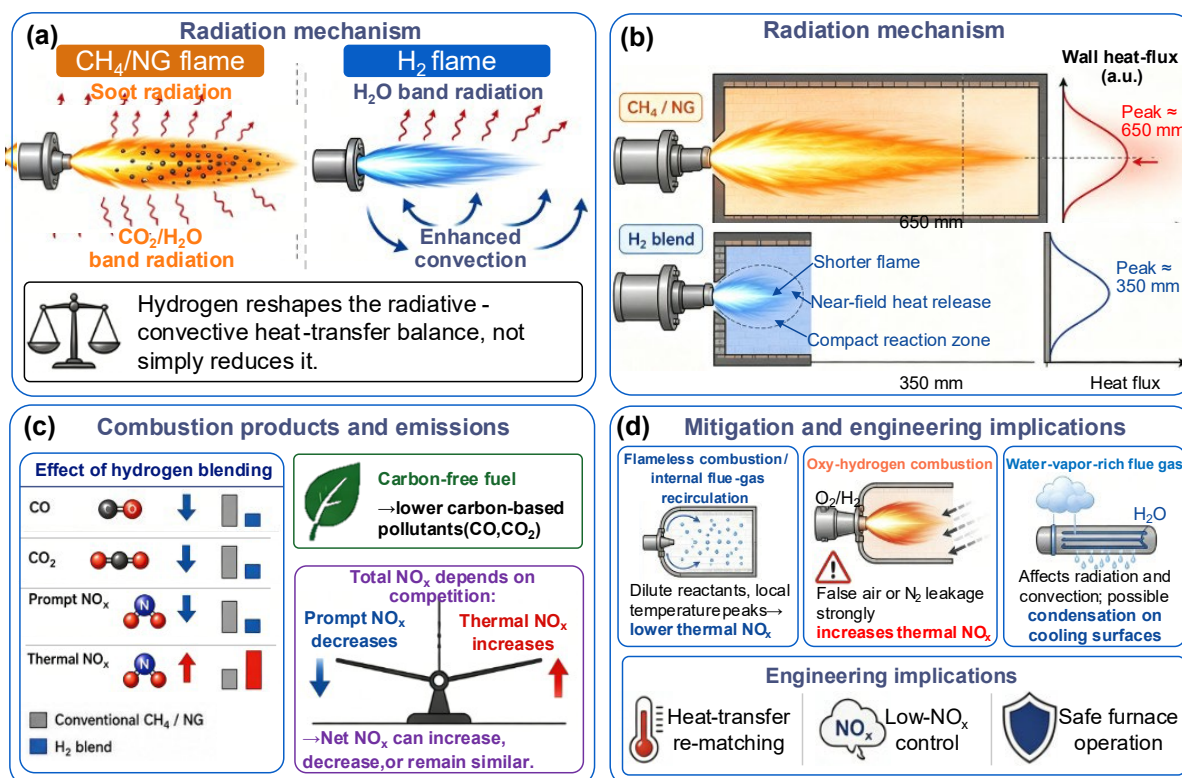


Figure 2. Effects of hydrogen substitution on flame radiation, heat flux distribution, combustion products, and emission-control strategies in high-temperature furnaces and kilns. (a) Radiation mechanisms of CH₄/natural gas and H₂ flames; (b) heat flux redistribution and upstream shift of the peak heat flux location under hydrogen blending; (c) changes in carbon-based products and NO_x formation pathways; (d) mitigation strategies and engineering implications for low-NO_x and safe furnace operation.

Regarding combustion products and emissions, hydrogen addition reduces carbon-based pollutants but complicates NO_x formation, as summarized in Figure 2c. Cheng et al. [21] and Lan et al. [31] showed that, at 60% hydrogen blending, CO and CO₂ emissions decreased by about 70% and 37.5%, respectively, whereas thermal NO_x increased by up to 155% due to higher local flame temperatures and enhanced Zeldovich reactions. However, hydrogen also suppresses prompt NO_x formation by eliminating CH-related reaction pathways. Ditaranto et al. [60] and Weydahl et al. [61] reported that, in refinery-fired heaters, total NO_x under pure hydrogen firing may be lower than that from conventional refinery fuel gas under certain heat load conditions. Thus, NO_x emissions during hydrogen combustion depend on the competition between enhanced thermal NO_x and suppressed prompt NO_x, as well as furnace design and operating conditions. More specifically, the relative importance of different NO_x pathways varies with fuel composition, temperature field, dilution level, and feedstock characteristics. In high-temperature air-fired hydrogen or hydrogen-enriched flames, the extended Zeldovich mechanism is usually the dominant pathway because local high-temperature zones promote the oxidation of atmospheric nitrogen. In contrast, prompt NO_x associated with CH-related hydrocarbon radicals is progressively weakened as the hydrogen fraction increases and becomes negligible under pure hydrogen firing. The N₂O-intermediate pathway may become relevant under lean, highly diluted, staged, or flameless/MILD combustion conditions, where temperature

and radical distributions differ from those in conventional high-temperature flames. In addition, fuel-bound nitrogen should be distinguished from fuel-derived NO_x in hydrogen combustion. Although hydrogen itself contains no nitrogen, nitrogen-containing feedstocks or volatile species may contribute to NO_x formation in waste treatment furnaces, biomass-containing systems, and cremation furnaces. Therefore, the statement “low carbon does not necessarily mean low NO_x” is especially important for such applications, where NO_x may originate not only from the combustion air but also from the treated material or organic load. It should also be noted that NO_x values reported in the literature are expressed using different bases, including ppm, mg/m³, and mg/MJ. These values should not be directly compared unless the reference oxygen concentration, dry or wet basis, standard temperature and pressure, and fuel-input basis are specified. Therefore, in this review, reported NO_x values are mainly used to indicate the emission level within each specific study rather than to establish a direct quantitative ranking among different furnace systems.

To mitigate thermal NO_x increase under high hydrogen blending, combustion organization and flow-field dilution are commonly used to broaden the reaction zone and reduce local temperature peaks, as shown in Figure 2d. Lopez-Ruiz et al. [40] showed that flameless combustion of H₂/NG blends in a 2.5 MW industrial furnace maintained stable operation and good temperature uniformity even at 75% hydrogen blending, while keeping NO_x emissions below 86 mg/m³. Oxy-hydrogen combustion can avoid nitrogen introduction from air, but it is highly sensitive to false air or nitrogen leakage. Madhu et al. [39] and Hasche et al. [14] reported that, because reburning pathways are weakened in hydrogen-rich systems, only about 7% nitrogen ingress can increase NO_x emissions by a factor of 16. In addition, water-vapor-rich flue gas can alter heat transfer behavior and may induce condensation on cooling surfaces, which should be considered in efficiency assessment, heat-surface design, and lifetime evaluation [36,39].

Overall, hydrogen substitution reshapes flame radiation, heat flux distribution, and pollutant formation in high-temperature furnaces and kilns. Pure hydrogen or high-ratio hydrogen blending typically weakens soot radiation, enhances H₂O-dominated band radiation and convective heat transfer, shifts peak heat flux upstream, reduces CO₂/CO emissions, and complicates NO_x control. Therefore, hydrogen-enriched combustion requires coordinated optimization of heat transfer, thermal-flow-field matching, and low-NO_x strategies to ensure both decarbonization and safe furnace operation.

3. Key Technologies for Hydrogen Substitution in High-Temperature Furnaces and Kilns

Hydrogen substitution in high-temperature industrial furnaces and kilns is not merely a fuel switch but a system-level challenge involving combustion organization, pollutant formation, heat transfer redistribution, and material service conditions. Compared with natural gas, hydrogen has a lower minimum ignition energy, higher laminar burning velocity, wider flammability limits, and carbon-free but water-vapor-rich combustion products. These features directly affect burner stability, heat flux distribution, NO_x formation, and component durability.

Under high-ratio hydrogen blending or pure hydrogen operation, four common technical issues become critical: flashback prevention and flame stabilization, low-NO_x control, thermal-flow-field regulation, and material/system adaptation. Higher flame speed and shorter quenching distance increase flashback and thermoacoustic risks; higher local temperatures promote thermal NO_x formation; reduced soot radiation and increased H₂O radiation reshape radiative–convective heat transfer; and water-vapor-rich atmospheres challenge metals, seals, and refractory linings. Therefore, hydrogen substitution requires

coordinated optimization of safety, thermal performance, emissions, and long-term service reliability.

3.1. Flashback Prevention and Flame Stabilization

In hydrogen-enriched retrofits of industrial furnaces and kilns, the distinct combustion characteristics of hydrogen significantly increase instability risks. Compared with conventional hydrocarbon fuels, hydrogen has a higher laminar burning velocity and a shorter quenching distance, approximately 0.64 mm, making upstream flame propagation toward the nozzle more likely [22,27,56]. In addition, hydrogen addition broadens the flammability range and, through preferential diffusion associated with an effective Lewis number below unity, enhances intrinsic flame-front instability [56,62].

These features improve blow-off resistance under ultra-lean conditions, but they also shift the flame anchoring position upstream, modify recirculation zone behavior, increase near-wall heat loads, and raise the risks of boundary-layer flashback, combustion-induced vortex breakdown, near-wall autoignition, and thermoacoustic instability [25–27,56]. Therefore, burners for high-ratio hydrogen blending or pure hydrogen operation require integrated design for flashback prevention and flame stabilization, mainly through burner-structure optimization, combustion-flow-field control, and dynamic thermal management, as shown in Figure 3.

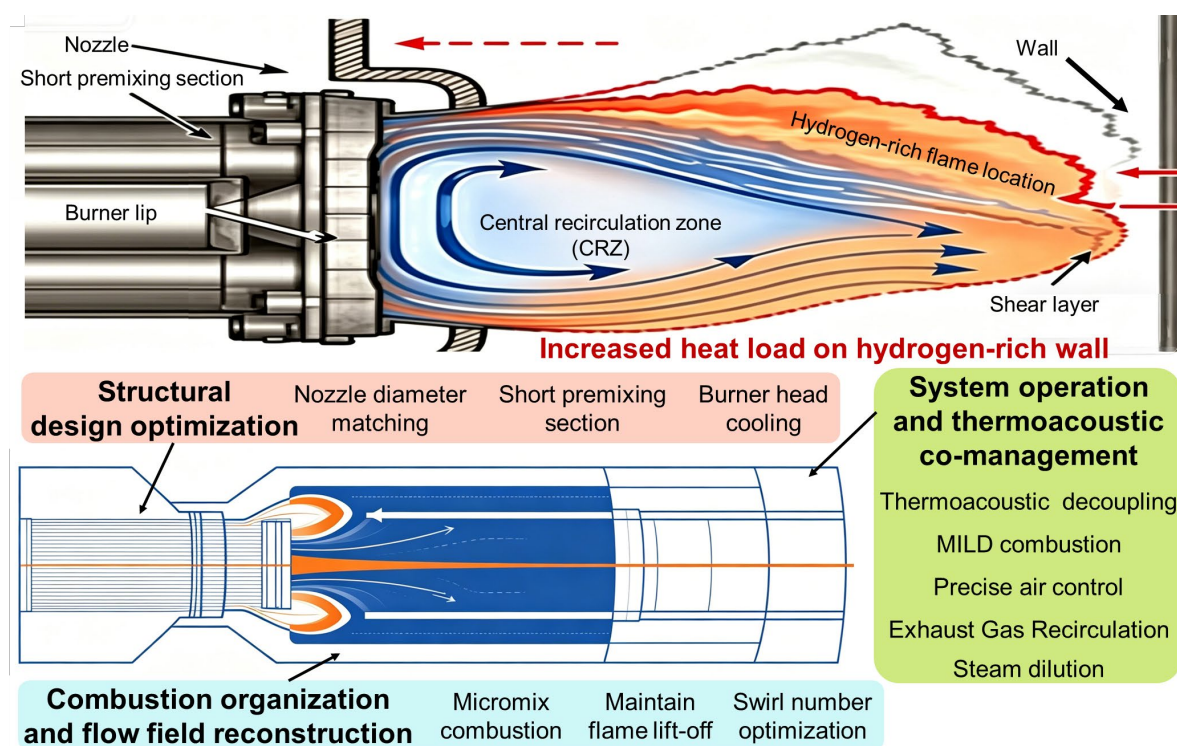


Figure 3. Schematic diagram of key technologies for flashback prevention and flame stabilization of hydrogen-rich burners in high-temperature furnaces and kilns.

3.1.1. Structural and Thermal Design for Flashback Suppression

In terms of hardware retrofitting, flashback suppression mainly depends on rematching nozzle diameter and outlet velocity while limiting upstream heat feedback. Gee et al. [38] investigated a commercial self-aspirating burner and showed that increasing the fuel–nozzle diameter, for example, from 4 mm to 12 mm, reduced primary air entrainment and reshaped the outlet velocity field. This expanded the flashback resistance from

approximately 50 vol% hydrogen blending to higher hydrogen fractions and even pure hydrogen operation.

Thermal–solid coupling is also critical. Fruzza et al. [30] performed conjugate heat transfer simulations using realistic burner geometry and showed that, with increasing hydrogen addition, the dominant flashback mechanism may shift from core-flow flashback to the more hazardous boundary-layer flashback. Pers et al. [28] further used high-speed optical diagnostics and found that, when the metal wall temperature exceeded a critical level of approximately 1000 K under high hydrogen blending, the flashback mode could shift from hole propagation to near-wall autoignition. Therefore, shortening the premixing path, enhancing burner-head cooling, and suppressing wall-attached flames are essential for high-hydrogen burner design.

Accordingly, representative strategies include short premixing ducts to reduce residence time [63], enhanced burner-head cooling, and asymmetric slit designs that redistribute solid-matrix heat and improve both flashback and blow-off limits [64].

3.1.2. Combustion and Flow-Field Control for Wide-Range Stability

At the combustion organization level, flame stability over a wide operating range can be improved by micromix combustion, recirculation zone control, and swirl optimization. Shi et al. [24] and Funke et al. [65] identified micromix combustion as an effective route for high-ratio hydrogen blending and pure hydrogen operation. By dividing a large flame into many small microflames through multi-nozzle arrays and orthogonal jets, this approach suppresses local fuel-rich hot spots and reduces flashback risks associated with large recirculation zones. For conventional swirl burners, hydrogen addition changes vortex structures and flame topology. Its high diffusivity allows the flame to penetrate the outer shear layer and move into the central recirculation zone, shifting the flame from a V-shape toward an M-shape closer to the nozzle [26]. Böncü et al. [66] showed that the flame lift-off height decreases at around 40% hydrogen blending and that flame attachment to the burner lip becomes more likely near 70% hydrogen. Therefore, reducing the swirl number or vane angle can help maintain flame lift-off and mitigate CIVB-induced flashback under high hydrogen blending.

3.1.3. System Dynamics and Thermoacoustic Control

At the system operation level, flashback prevention and flame stabilization must be coordinated with load regulation, air entrainment control, and thermoacoustic management. Zhao et al. [57] showed that the higher fuel jet momentum required for hydrogen firing can alter air entrainment and shift the premixed mixture toward stoichiometric conditions, increasing flashback risk during dynamic operation. Therefore, variable-load hydrogen combustion requires more precise control of primary air and false air.

When aerodynamic control is insufficient, dilution and exhaust gas recirculation provide important system-level stabilization. Lu et al. [67] and Sabia et al. [68] showed that steam dilution and flameless/MILD combustion with strong internal recirculation can reduce reaction intensity and flame temperature through thermal dilution and third-body effects. These strategies broaden the stable operating window, improve load flexibility, and help weaken thermoacoustic feedback in high-hydrogen furnace operation [25,26].

3.2. Low-NO_x Combustion Control

During the transition from conventional hydrocarbon fuels to hydrogen-enriched or pure hydrogen fuels in industrial furnaces and kilns, NO_x formation mechanisms change substantially. Although pure hydrogen combustion eliminates prompt NO_x pathways involving hydrocarbon radicals such as CH [69], its faster oxidation kinetics and higher flame temperature can promote thermal NO_x formation [70]. Therefore, achieving both

efficient heating and low NO_x emissions has become a key challenge in hydrogen combustion applications.

Current studies and engineering assessments mainly develop multidimensional low-NO_x strategies through deep flow-field dilution, burner–structure redesign, thermodynamic boundary control, and oxy-fuel or oxygen-staged combustion, as shown in Figure 4.

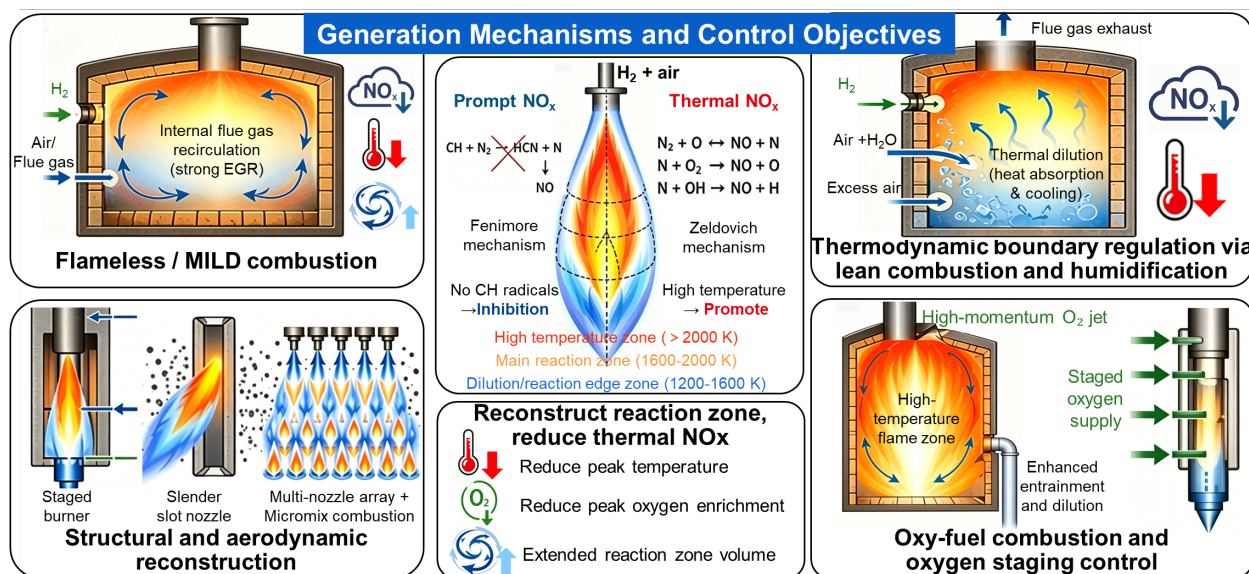


Figure 4. Schematic diagram of low-NO_x combustion control technologies for hydrogen combustion in high-temperature furnaces and kilns.

3.2.1. Deep Dilution via Flameless/MILD Combustion

Flameless/MILD combustion is considered an effective route for reducing NO_x emissions in high-ratio hydrogen combustion. By promoting strong internal exhaust gas recirculation, this approach deeply dilutes and thermally buffers the fuel–oxidizer mixture, thereby suppressing local high-temperature hot spots (Figure 4).

Lopez-Ruiz et al. [40] reported that flameless combustion of H₂/NG blends in a 2.5 MW industrial furnace maintained stable operation and good temperature uniformity even at 75% hydrogen blending, with NO_x emissions reported below 86 mg/m³ under the reporting conditions of that study. Mabic et al. [36] further demonstrated in a 200 kW semi-industrial furnace that NO_x emissions under pure hydrogen operation were reported below 12 mg/MJ in flameless air combustion and 3.8 mg/MJ in flameless oxy-fuel combustion. Ayoub et al. [71] also reported ultra-low NO_x emissions below 10 ppm for pure hydrogen flameless combustion without air preheating. Because these data were reported using different units and reference bases, they should be interpreted as evidence that flameless/MILD combustion can suppress NO_x under specific operating conditions, rather than as directly comparable emission limits.

3.2.2. Burner Geometry and Aerodynamic Control

Burner geometry optimization aims to disperse heat release and reduce local high-temperature zones by reshaping jet structure, mixing topology, and local oxygen distribution. Swaminathan et al. [33] studied an industrial burner and showed that adjusting the mass flow distribution between primary and secondary air reduced oxygen enrichment near high-temperature regions; when the primary/secondary air ratio was set to 0.4, the NO formation rate decreased by approximately 15.5%.

At smaller spatial scales, Kim et al. [32] developed a low-NO_x hydrogen burner with a high-aspect-ratio flame port and orthogonal fuel–air injection. The induced internal vortices

divided the large flame into multiple thinner flamelets, enhancing local convective cooling and lowering peak temperatures. Full-scale tests showed that NO_x emissions could be kept below 40 ppm under 100% hydrogen combustion. Shi et al. [24] further noted that micromix combustion, based on submillimeter multi-nozzle arrays, can suppress oxygen-rich zones and hot spots, reducing NO_x emissions from pure hydrogen combustion to below 10 ppm under optimized conditions. Daurer et al. [20] also reported in semi-industrial low-swirl burner tests that, at furnace temperatures below 1200 °C with cooling tubes installed, improved turbulent mixing under pure hydrogen combustion reduced NO_x emissions by approximately 20% compared with the natural gas baseline. These studies indicate that burner geometry design and local aerodynamic control are effective engineering strategies for low-NO_x hydrogen combustion.

3.2.3. Thermodynamic Control via Lean Combustion and Humidification

Reducing the reaction zone temperature through ultra-lean operation and high-heat-capacity diluents is a direct thermodynamic route for suppressing thermal NO_x. Under lean-burn conditions, excess air acts as a heat sink and lowers the peak flame temperature. Kim et al. [32] showed that, by exploiting the wide flammability range of hydrogen, stable pure hydrogen combustion could be maintained at a residual oxygen level of about 12%, while keeping NO_x emissions below 40 ppm and balancing CO and NO_x emissions under hydrogen-blended conditions.

Humidification of the oxidizer provides another effective strategy. Schmidt et al. [63] reported that, near stoichiometric conditions, increasing the relative humidity of combustion air to 95% reduced NO_x emissions from an improved hydrogen burner by approximately 22–28%. Lu et al. [67] further showed that, for micromix flames, NO_x emissions under steam dilution were typically only 20–50% of those under N₂ dilution, mainly because steam provides both stronger thermal dilution and chemical inhibition. These results indicate that lean operation and humidification suppress NO_x not merely by changing boundary conditions but by reshaping the thermodynamic state of the reaction zone.

3.2.4. Oxy-Fuel Combustion and Oxygen Staging

Replacing air with oxy-fuel combustion can reduce nitrogen input from the oxidizer at the source, providing a theoretical route toward low-NO_x and near-zero-carbon combustion. However, in practical industrial furnaces, even minor cold-air leakage can cause abnormal NO_x increases during pure hydrogen combustion. Madhu et al. [39] and Hasche et al. [14] studied 200 kW semi-industrial H₂/O₂ burners and showed that, because of the extremely high flame temperature of hydrogen–oxygen combustion, only about 7 vol% residual nitrogen in the oxidizer can increase NO_x emissions by a factor of 16. The sensitivity of NO_x to wet nitrogen content in the flue gas was also much higher than that under natural gas operation.

To address this issue, Schwarz et al. [72] proposed an industrial-scale oxygen-staging strategy based on high-momentum choked-flow oxygen lancing. By forming under-expanded oxygen jets to enhance flue gas entrainment and local dilution, this approach reduced NO_x emissions from pure hydrogen combustion by 72% compared with air–natural gas combustion and by 93% compared with conventional non-staged oxy-fuel combustion. These results indicate that, in hydrogen oxy-fuel systems, precise slight-positive-pressure control to limit false-air ingress should be combined with advanced oxygen-staging strategies to suppress thermal NO_x formation.

3.3. Thermal-Flow-Field Reconstruction and Heat Transfer Control

Hydrogen-enriched combustion produces soot-free flames and water-vapor-rich flue gas, shifting in-furnace heat transfer toward H₂O band radiation. Direct fuel switching

may redistribute radiative and convective heat transfer, shift peak heat flux, and cause local overheating. Therefore, the thermal-flow field must be re-evaluated and reconstructed for hydrogen-enriched furnace operation [34,42], as shown in Figure 5.

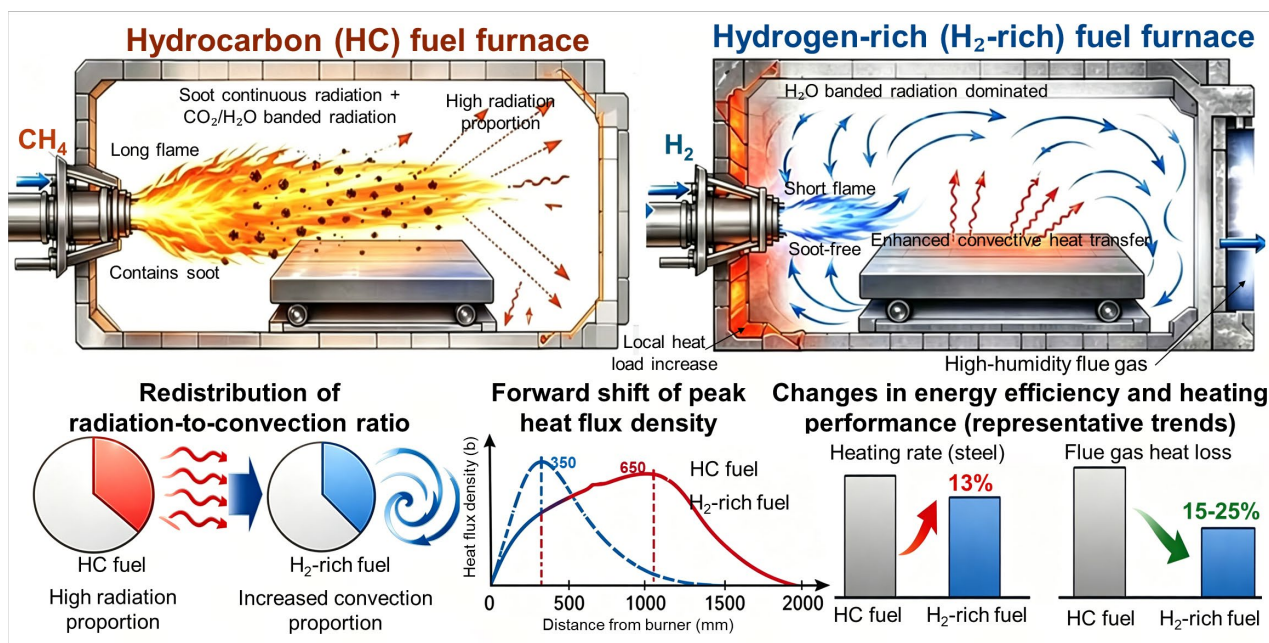


Figure 5. Schematic diagram of in-furnace thermal flow field reconstruction and heat transfer regulation technologies.

Guo et al. [34] studied a 35 kW commercial self-aspirating burner in a confined chamber and showed that increasing the hydrogen blending ratio from 0 to 50 vol% shortened the flame and shifted the peak wall heat flux location upstream from about 650 mm to 350 mm. At 150 mm from the burner, the wall heat flux under 50 vol% hydrogen blending was more than three times that of the natural gas baseline. Daurer et al. [42] further showed by fully coupled three-dimensional CFD simulations of a 3.9 MW oxy-fuel glass-melting furnace that pure hydrogen increased the average in-furnace velocity from 1.23 to 1.87 m/s, shortened the flame by more than 25%, and raised the average flame temperature by about 82 K. These results indicate that hydrogen substitution concentrates heat release near the burner, increasing the risk of local overheating and refractory thermal damage [19,34,42].

In heat transfer redistribution, the reduced radiation from soot-free hydrogen flames can be partly or even fully compensated by enhanced convection from water-vapor-rich flue gas [36,37]. Kislinger et al. [37] showed that pure hydrogen combustion increased the heating rate of 1.3520 steel by about 13%, reduced the required fuel heat input from 94 kW to 70 kW at the same target temperature, and lowered exhaust heat loss by 14.3%. Mabic et al. [36] reported that hydrogen combustion increased the total heat flux to aluminum samples by about 19% under air-fuel operation and 6% under oxy-fuel operation. Madhu et al. [39] further found that heat transfer to water-cooled tubes increased from 125 kW with natural gas to 141 kW with pure hydrogen, suggesting that condensation heat transfer under high water vapor partial pressure may affect efficiency assessment and heat-surface durability [36,39].

To restore or improve heat transfer uniformity and heating efficiency after hydrogen substitution, thermal-flow-field reconstruction is mainly achieved through combustion organization control, jet aerodynamic optimization, and flue gas recirculation. At the microscale jet level, Kim et al. [32] developed a hydrogen burner with a high-aspect-

ratio port and orthogonal fuel–air injection. This design divided the large flame into multiple thin flamelets, enhanced convective cooling at a high air velocity of 53.9 m/s, and dispersed local heat release through internal vortices, maintaining the pure hydrogen flame temperature at 1800–2000 K. Gee et al. [38] showed that, in a modified self-aspirating burner, increasing the fuel–nozzle diameter from 4 mm to 12 mm suppressed excessive primary air entrainment caused by the high jet momentum of hydrogen, enabling safe 100% hydrogen operation while improving the axial wall heat flux distribution. For flue gas recirculation and flameless combustion, Lopez-Ruiz et al. [40] demonstrated through full-scale numerical assessment of a 2.5 MW industrial reheating furnace that enhanced internal recirculation diluted the reaction zone. Even at 75% hydrogen blending, the flame expanded smoothly downstream, helping maintain a uniform temperature field and stable flameless operation in the large furnace chamber. From an engineering perspective, the heat transfer impact of hydrogen substitution should be evaluated using furnace-scale performance metrics rather than only flame appearance or radiation intensity. Key indicators include axial and radial wall heat flux profiles, peak heat flux location, convective/radiative heat transfer fractions, total heat flux to the load, load heating rate, temperature uniformity of the treated material, furnace thermal efficiency, exhaust heat loss, and the risk of burner-near-wall overheating or refractory hot spots. These metrics are particularly important because hydrogen-enriched combustion may reduce soot radiation while simultaneously increasing H₂O-dominated gas radiation, convective heat transfer, and near-burner heat release. Therefore, heat transfer re-matching should be performed together with burner aerodynamics, air/fuel staging, internal flue gas recirculation, and control-system optimization to avoid local overheating while maintaining heating efficiency and product temperature uniformity.

Overall, hydrogen substitution reshapes heat-release distribution, modifies the balance between radiative and convective heat transfer, and requires thermal-flow-field reconstruction through burner optimization, flue gas recirculation, and control-system adjustment. The objective is not only to maintain the required heat duty, but also to control wall heat flux distribution, exhaust heat loss, load temperature uniformity, and refractory hot-spot risk, as summarized in Figure 5.

3.4. Material and Component Adaptation in Water-Vapor-Rich Atmospheres

During hydrogen-enriched combustion, increased water vapor in the flue gas creates a high-temperature, water-vapor-rich furnace atmosphere. This environment alters flue gas properties, gas–solid reactions, oxide-scale growth, and mass transport, thereby affecting the durability of metallic surfaces, heated workpieces, and refractory linings. Fuel supply and combustion components may also face hydrogen embrittlement risks, making material and component adaptation essential for hydrogen furnace retrofits [73–75], as shown in Figure 6. However, the dominant material risk mechanism depends strongly on the component location and service temperature. For fuel supply systems, valves, regulators, piping, pressure vessels, seals, and cold or moderately heated metallic components, hydrogen embrittlement, hydrogen-assisted cracking, leakage, and pressure-cycle fatigue are primary concerns. In contrast, inside the hot furnace chamber, classical hydrogen embrittlement is usually less dominant than high-temperature oxidation, steam-assisted corrosion, oxide-scale growth and spallation, water-vapor-enhanced mass transport, and refractory degradation. Therefore, material adaptation for hydrogen-fired furnaces should distinguish between hydrogen service compatibility in the fuel delivery system and high-temperature durability in water-vapor-rich furnace atmospheres.

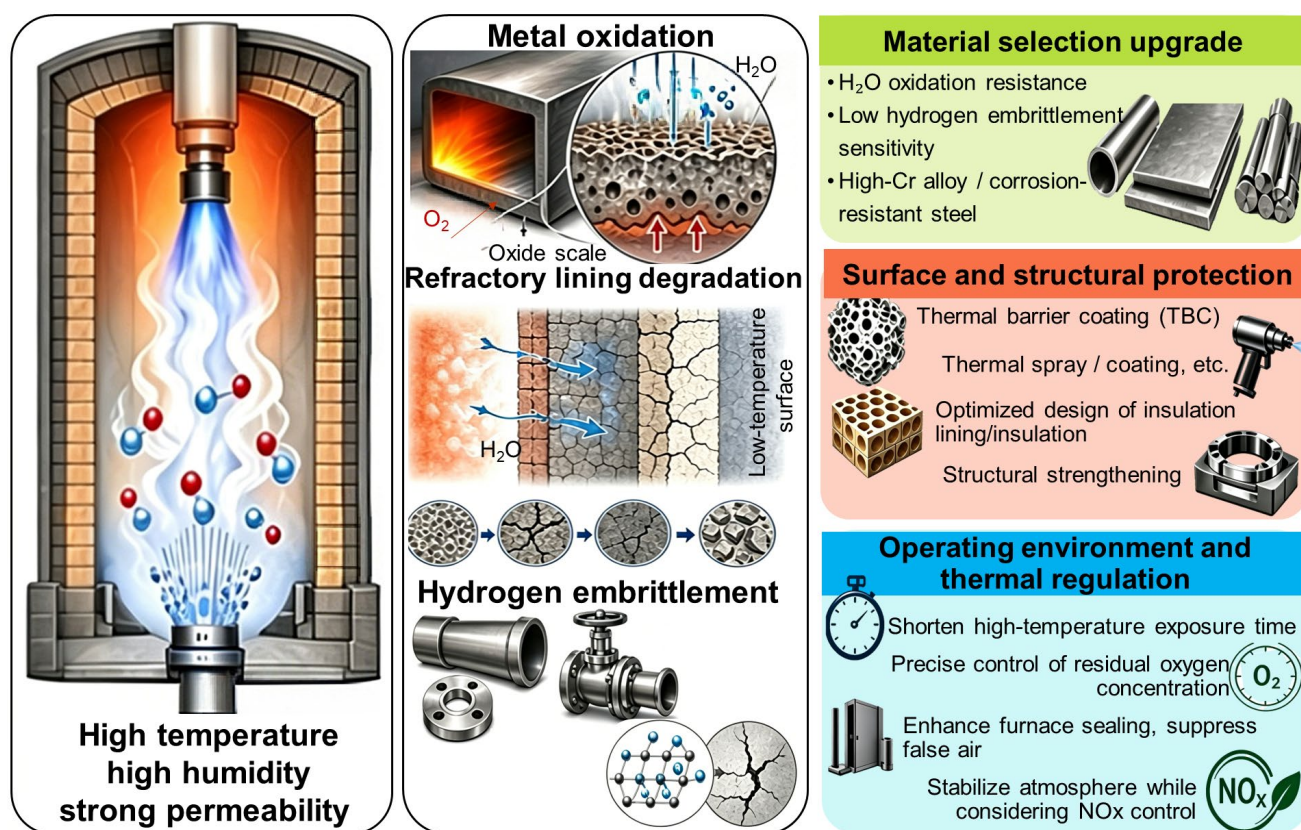


Figure 6. Schematic diagram of material and component adaptation technologies under high-temperature water vapor environments.

3.4.1. Oxidation and Microstructural Evolution of Metallic Components

High water vapor partial pressure can significantly alter oxidation kinetics and oxide-scale evolution in metallic materials. Airaksinen et al. [41] investigated dynamic heating of low-carbon steels up to 1180 °C and showed that the water-vapor-rich atmosphere produced by hydrogen combustion increased porosity within the oxide scale and promoted pore migration toward the oxide–gas interface. They also found strong steel-grade dependence: when switching from methane–air to hydrogen–oxy-fuel combustion, the oxidation mass gain increased by about 18% for low-Mn steel, but by 41% and 65% for high-Mn–Si and high-Mn steels, respectively. This indicates that alloy composition strongly affects material loss and adaptation difficulty under hydrogen-rich heating conditions.

Temperature and oxidizer type further influence oxidation behavior. Radünz et al. [76] tested EN 1.4307 (AISI 304L) austenitic stainless steel under semi-industrial conditions and found that, at 1200 °C with 1–7% residual oxygen, switching from natural gas–air to hydrogen–air combustion increased the specific mass gain by about 15%, while hydrogen–oxy-fuel combustion increased it by about 40%. Schwarz et al. [77] further tested 12 steel grades at 1250 °C and showed that the rise in furnace moisture from 17.7% under natural gas–air combustion to 99% under hydrogen–oxy-fuel combustion was a key driver of accelerated oxidation. However, high-Cr super-austenitic steel 1.4539 and duplex steel 1.4462 showed relatively low mass gains under several water-vapor-rich atmospheres, suggesting better oxidation resistance and adaptation potential.

3.4.2. Moisture-Induced Degradation of Refractories and Insulation Systems

In addition to metallic loads, water-vapor-rich atmospheres can also affect refractory linings and insulation systems. Leicher et al. [4] noted that material and product degradation in practical operation is often driven not by hydrogen itself but by the substantially

increased water vapor partial pressure in the furnace atmosphere. Poirier, Walter, and co-workers [78,79] further suggested, based on assessments of industrial systems such as glass-melting furnaces, that high-temperature humid atmospheres can penetrate deep into refractory linings and react with specific refractory components, thereby altering their physicochemical properties. Such moisture-induced oxidation/corrosion may accelerate microstructural degradation and macroscopic spalling during long-term thermal cycling, weaken insulation performance, and ultimately affect furnace efficiency and operational stability [4,78–80]. The vulnerability of refractories to hydrogen-enriched combustion should therefore be assessed according to both material family and furnace atmosphere. Different refractory systems may respond differently to high water vapor partial pressure, alkali-containing vapors, molten slags, and repeated thermal cycling. Table 2 summarizes the potential degradation mechanisms of representative refractory and insulation materials under water-vapor-rich furnace atmospheres.

Table 2. Potential degradation mechanisms of refractory and insulation materials under hydrogen-enriched, water-vapor-rich furnace atmospheres.

Refractory or Insulation Family	Possible Vulnerability Under H ₂ -Enriched Combustion	Main Degradation Mechanisms	Typical Engineering Concerns
Silica refractories	Sensitive to thermal cycling and chemically active humid atmospheres, especially in alkali-containing flue gas	Steam-assisted corrosion, alkali volatilization/reaction, phase-transformation-related expansion, thermal shock	Spalling, dimensional instability, reduced lining lifetime
Aluminosilicate refractories	Affected by water vapor, alkali vapors, and glassy-phase degradation at high temperature	Steam-assisted corrosion, alkali attack, mullite/glassy-phase alteration, microcrack growth	Strength loss, increased porosity, insulation degradation
Magnesia-based refractories	Vulnerable when hydration/dehydration and slag penetration occur	MgO hydration/dehydration, slag interaction, chemical spalling, pore-network corrosion	Cracking, peeling, slag-line corrosion, reduced corrosion resistance
Zirconia-containing refractories	Generally high-temperature resistant, but sensitive to thermal shock and phase-stability issues under cycling	Thermal-shock cracking, phase transformation, steam/impurity-assisted degradation	Crack propagation, local lining damage, reduced thermal-cycle reliability
Spinel refractories	Relatively stable, but degradation depends on slag chemistry and impurity penetration	Slag corrosion, alkali/sulfur/chlorine interaction, thermal mismatch, microstructural coarsening	Corrosion at slag-contact zones, lining thinning, hot-spot formation
Insulating fiber materials	Sensitive to long-term high-temperature humidity and repeated heating/cooling	Fiber shrinkage, devitrification, moisture-assisted embrittlement, binder degradation	Loss of insulation performance, dusting, local heat loss, shell overheating

Accordingly, refractory selection for hydrogen-fired furnaces should not be based only on nominal maximum service temperature. Long-term compatibility with water-vapor-rich atmospheres, alkali/slag chemistry, thermal cycling, and local heat flux redistribution should also be considered, especially in rotary kilns, waste-treatment furnaces, and batch-operated special-purpose furnaces where refractory linings are exposed to strongly fluctuating chemical and thermal environments.

3.4.3. Hydrogen Service Compatibility and Integrated Adaptation Strategies

In response to these changes in service environment, current engineering adaptation mainly focuses on material selection, surface protection, and operating atmosphere control. First, on the fuel delivery side, hydrogen service compatibility is mainly associated with low- and moderate-temperature metallic components rather than the hot furnace atmosphere. Because hydrogen has a small molecular size and high diffusivity, fuel supply pipelines, valves, regulators, pressure vessels, welded joints, burner fuel passages, and sealing components should preferentially use materials and joining schemes with low sensitivity to hydrogen embrittlement, hydrogen-assisted cracking, leakage, and pressure-cycle damage. This requirement is particularly important for high-pressure storage, pressure-reduction units, flexible connections, and frequently operated valves in hydrogen-enriched furnace retrofits [81].

Second, inside the hot furnace chamber, material adaptation should focus on high-temperature oxidation resistance, steam-assisted corrosion resistance, oxide-scale stability, and refractory durability under water-vapor-rich atmospheres. As noted above, alloy composition strongly affects oxidation mass gain and scale stability; therefore, material design should consider not only conventional high-temperature strength, but also long-term stability under humid oxidizing conditions.

Finally, operating atmosphere control is essential for slowing material degradation. Radünz et al. [76] showed that shortening high-temperature exposure and strictly controlling residual oxygen can reduce oxidation loss. Madhu et al. [39] and Hasche et al. [14] further emphasized that false-air ingress must be minimized in hydrogen-rich combustion systems, because even minor nitrogen leakage can disturb the furnace atmosphere and greatly increase thermal NO_x emissions. Therefore, material and component adaptation should be integrated with furnace sealing, atmosphere management, and operating-regime optimization.

4. Representative Applications in Furnaces and Kilns

The application of hydrogen fuels in high-temperature furnaces is highly scenario-dependent. While large-scale sectors like metallurgy have explored this extensively, sensitive processes remain cautious. Hydrogen substitution is not a simple fuel swap but a system-level adaptation. Its unique combustion alters heat flux distribution, atmospheres, and moisture levels, which can significantly impact surface quality when gases directly contact materials. Consequently, the feasibility of hydrogen must be evaluated within specific industrial contexts rather than generalized across all furnace types.

This section reviews representative applications in metallurgical and heat-treatment furnaces, petrochemical-fired heaters, waste treatment furnaces, rotary kilns, and cremation furnaces, with emphasis on their key process constraints and engineering challenges.

To provide a more balanced cross-sector comparison, Table 3 summarizes the role of hydrogen, main technical benefits, application constraints, NO_x/material-related concerns, indicative technology maturity, and decarbonization potential for representative high-temperature furnaces and kilns. This comparison highlights that hydrogen substitution should not be evaluated using a single criterion. Instead, its feasibility depends strongly on the thermal function, operating mode, fuel switching route, emission-control requirements, and material service environment of each furnace category.

Table 3. Comparison of hydrogen substitution in representative high-temperature furnaces and kilns.

Furnace/Kiln category	Operating Characteristics	Main Role of H ₂ Substitution	Potential Benefits	Main Technical Limitations	NOx and Material Concerns	Indicative Maturity/TRL	Decarbonization Potential
Metallurgical and heat-treatment furnaces	Continuous or semi-continuous heating; strict temperature uniformity and surface-quality requirements	H ₂ blending or pure H ₂ firing for reheating and heat treatment	Direct CO ₂ reduction, faster heating, compatibility with high-temperature process heat	Upstream shift of heat flux, local overheating, scale formation, burner retrofit	Thermal NOx, oxide-scale growth, water-vapor-enhanced oxidation, refractory hot spots	Medium-high; pilot and industrial demonstrations increasing	High, especially when low-carbon H ₂ is available
Petrochemical and refinery-fired heaters	High-duty process heating; radiant/convection sections; existing hydrogen networks at some sites	H ₂ -rich refinery fuel gas, H ₂ blending, or dedicated H ₂ burners	Use of existing H ₂ infrastructure, reduced carbon emissions from fuel combustion	Heat load redistribution, tube-wall temperature control, coking risk, fuel network adaptation	Thermal/prompt NOx balance, tube overheating, material lifetime, thermoacoustic stability	Medium-high; retrofit feasibility is relatively strong	Medium-high, depending on hydrogen source and process integration
Municipal solid waste incinerators	Heterogeneous feedstock; variable moisture and calorific value; strict burnout and flue gas treatment	Auxiliary H ₂ for ignition, flame stabilization, and heat load compensation	Lower fossil auxiliary fuel use, improved transient combustion stability, reduced incomplete combustion risk	Feedstock variability, complex pollutant formation, integration with existing flue gas cleaning systems	Fuel-bound nitrogen, NOx from waste volatiles, PCDD/F control, fly ash and corrosion issues	Low-medium; mainly conceptual or auxiliary-fuel potential	Moderate; mainly through replacement of auxiliary fossil fuel
Medical and hazardous waste rotary kilns	Multiphase reactions; long residence time; secondary combustion chamber required	Auxiliary or co-firing fuel for thermal stabilization and tail gas burnout	Stable high-temperature destruction of hazardous organics and pathogens; lower fossil fuel support	Coupling of kiln, afterburner, and emission-control system; safety and flame stability constraints	Fuel-bound nitrogen, acid gases, refractory corrosion, water-vapor-rich flue gas	Low-medium; further validation needed	Moderate; site-specific and strongly limited by waste composition
Cement and mineral rotary kilns	Long axial temperature gradient; large thermal inertia; flame length and kiln coating stability are critical	Partial H ₂ substitution or co-firing with alternative fuels	Reduced fossil carbon contribution from kiln fuel; potential integration with multifuel burners	Shorter H ₂ flames, near-burner heat concentration, disturbance of axial heat profile, and clinker quality	Thermal NOx, front-end refractory overheating, kiln coating instability, alkali/sulfur/chlorine interactions	Low-medium; early-stage demonstrations and modeling	Medium-high, but technically challenging
Cremation furnaces	Batch-type, intermittent operation; transient and heterogeneous thermal load; secondary combustion required	Zero-carbon auxiliary fuel for transient heat buffering and rapid flame stabilization	Reduced fossil fuel use, improved combustion completeness, potential support for low-carbon public-service facilities	Frequent start-stop cycles, ignition reliability, odor control, safety management, integration with exhaust treatment	NOx from nitrogen-containing volatiles, PCDD/F control, heavy-metal/fly ash migration, refractory durability under humid flue gas	Low; specialized demonstrations and system-level validation are still needed	Moderate; important for specialized public-service decarbonization

4.1. Metallurgical and Heat-Treatment Furnaces

In the steel and nonferrous metallurgical industries, reheating furnaces and heat-treatment furnaces are typical facilities that rely on fossil fuels to provide high-temperature process heat [4,82]. These large-scale, continuously operated industrial furnaces generally require high-grade heat in the range of 1000–1300 °C. Unlike the role of hydrogen as a chemical reducing agent in upstream metallurgical processes, downstream reheating and heat-treatment processes mainly utilize hydrogen as a thermal fuel. Existing technology assessments suggest that hydrogen fuel burners and supporting systems for such process-heating applications have reached a relatively high level of technological maturity, making them one of the more practically feasible near-term fuel-substitution scenarios in industry [82]. However, moving from simple heat source replacement to long-term commercial operation still requires addressing two key issues in metallurgical reheating furnaces: reconstruction of the thermal flow field and control of workpiece surface quality, as shown in Figure 7.

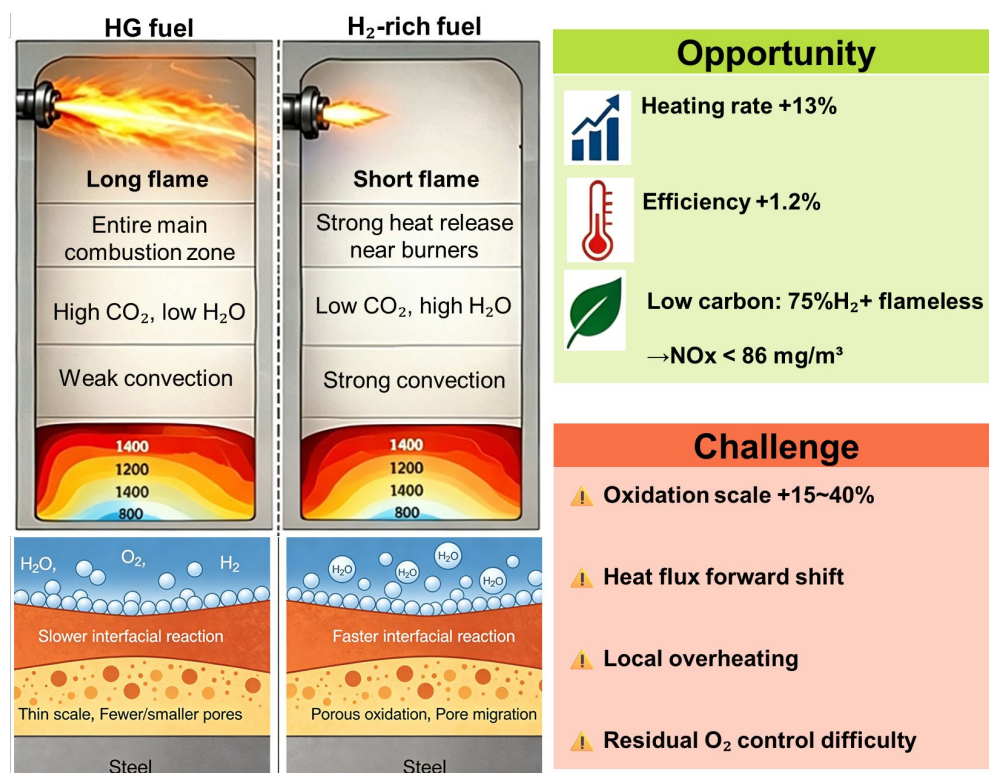


Figure 7. Hydrogen combustion in metallurgical and heat treatment furnaces: opportunities and main challenges.

4.1.1. Thermal Flow Field and Efficiency Assessment

In practical industrial applications, the focus has gradually shifted from laboratory-scale verification of flame stability to the evaluation of temperature-field uniformity and overall thermal efficiency in large furnace chambers. Mayrhofer et al. [83] conducted a systematic study on industrial heat-treatment furnaces and showed that, owing to changes in the properties of high-moisture flue gas, a hydrogen blending ratio of 40 vol% led to a slight increase of approximately 1.2% in the overall system efficiency compared with pure natural gas operation.

Regarding transient heating behavior, Kislinger et al. [37] and Daurer et al. [20] performed comparative tests on 1.3520 steel (100CrMnSi6-4) specimens in a semi-industrial furnace. Their results showed that, after switching to pure hydrogen combustion, the

enhanced convective heat transfer associated with high water vapor concentrations could partly compensate for the reduced radiation from carbon-free, soot-free flames. To reach the same target temperature of 1060 °C, the required fuel heat input under pure hydrogen operation was substantially lower than that under natural gas operation, decreasing from 94 kW to 70 kW, while the steel heating rate increased by approximately 13%.

In addition, Lopez-Ruiz et al. [40] carried out CFD and experimental assessments of a real 2.5 MW industrial reheating furnace. Their results demonstrated that, by adapting flameless combustion technology, the system could maintain a broad reaction zone through strong internal flue gas recirculation even at hydrogen blending ratios as high as 75%. Under these conditions, the overall heating capacity was preserved, while NO_x emissions were controlled below 86 mg/m³.

4.1.2. Scale Formation Control in Water-Vapor-Rich Atmospheres

Although hydrogen fuel shows promising potential for improving thermal efficiency, the influence of high water vapor partial pressure on metal surface quality remains one of the most critical process barriers in direct-fired heating, where combustion products are in direct contact with the workpiece. Airaksinen et al. [41] and Cirilli et al. [84] reported that, during the high-temperature heating of low-carbon steels and stainless steels, the water-vapor-rich atmosphere produced by hydrogen combustion significantly accelerates gas–solid interfacial reactions, increases porosity within the oxide scale, and promotes pore growth toward the gas–scale interface. This promotes increased porosity within the oxide scale, with pore size tending to increase toward the gas–scale interface.

Radünz et al. [76] and Schwarz et al. [77] further examined austenitic stainless steels, including EN 1.4307, under semi-industrial conditions at approximately 1200 °C. Their results showed that changing the furnace atmosphere from natural gas–air combustion to hydrogen–air or hydrogen–oxygen combustion increased the specific oxidation mass gain by approximately 15–40%. This increase is mainly attributed to the enhanced interfacial oxidation reactions caused by the higher water vapor partial pressure. Schmitz et al. [85] further noted that such intensified oxidation not only directly increases metallic material loss but also imposes stricter requirements on precise residual oxygen control in the furnace chamber, as well as on subsequent descaling and hot-rolling operations.

Overall, hydrogen has shown clear technical feasibility as an alternative fuel in metallurgical reheating and heat-treatment applications, particularly in improving heating rates and supporting low-carbon fuel substitution. Its large-scale deployment, however, depends not only on burner retrofit but also on integrated process optimization involving scale formation control, local thermal-load management, and coordinated regulation of dynamic furnace operating conditions.

4.2. Petrochemical and Refinery Furnaces

The petrochemical and refining industries are among the sectors with the most intensive demand for high-temperature process heat and represent one of the most practical industrial scenarios for hydrogen fuel substitution [1,8]. Unlike in metallurgy, where hydrogen may also serve as a reducing agent, hydrogen use in the petrochemical sector is mainly associated with fuel replacement. A key advantage is that many petrochemical sites already have relatively well-developed hydrogen production, distribution, and by-product hydrogen recovery infrastructure. Therefore, industrial efforts toward hydrogen fuel substitution in this sector have mainly focused on large-capacity, continuously operated heating equipment, such as process-fired heaters and steam methane reforming (SMR) furnaces [86], as shown in Figure 8.

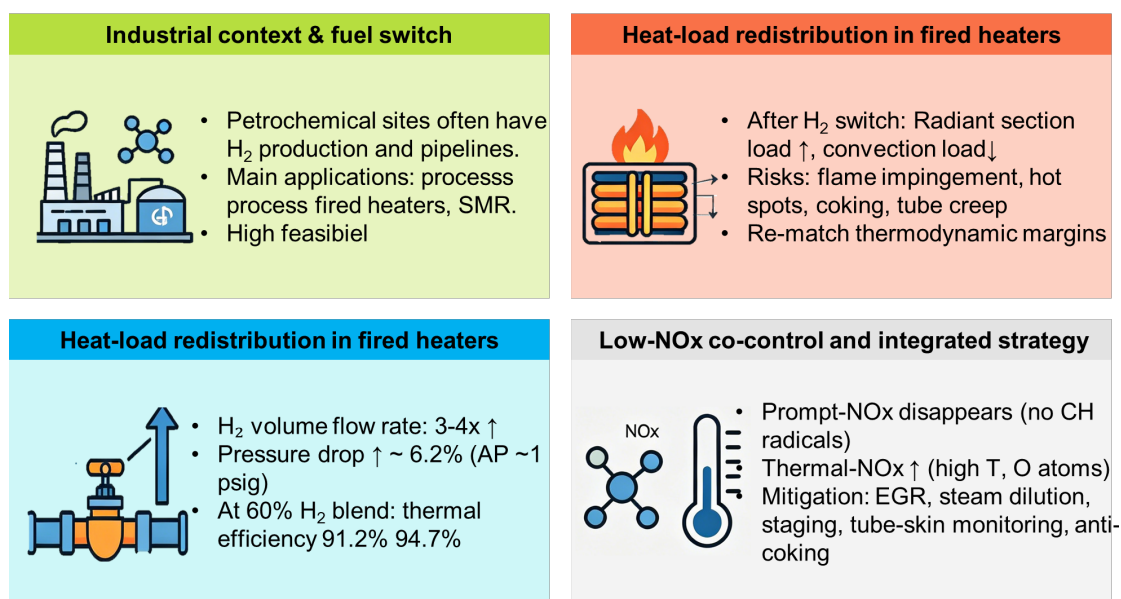


Figure 8. Hydrogen-fired petrochemical and refinery furnaces: opportunities and engineering challenges (the upward arrow represents an increase in value, and the downward arrow represents a decrease in value).

4.2.1. Fuel Switching and Heat Load Redistribution

Unlike metallurgical furnaces, which mainly heat solid workpieces, petrochemical-fired heaters typically transfer heat to high-temperature, high-pressure, multicomponent fluids flowing rapidly inside process tubes. Therefore, heat must be delivered to the process coils as uniformly as possible. Any flame impingement on the tubes or formation of local hot spots may induce thermal cracking and coking of the process fluid, further accelerating high-temperature creep of the tube material and even increasing the risk of failure [60,61].

Ditaranto et al. [60] and Weydahl et al. [61] used CFD to evaluate refinery-fired heaters in pre-combustion carbon-capture retrofit scenarios. They found that replacing conventional refinery fuel gas with pure hydrogen had little adverse effect on the overall furnace thermal performance but led to a substantial redistribution of in-furnace heat flux. Lowe et al. [87] further showed that hydrogen firing tends to shift more heat load to the radiant section while reducing heat absorption in the convection section. This implies that, during engineering retrofit, the thermal margins and temperature matching between the radiant and convection heat transfer surfaces must be re-evaluated.

4.2.2. Fuel Supply and Flow Adaptation

In terms of fuel network adaptation for long-term stable operation, the extremely low volumetric heating value of hydrogen imposes more stringent requirements on the retrofit of existing fuel supply and control systems. Lowe et al. [87] showed that maintaining the same process heat duty with pure hydrogen requires a fuel volumetric flow rate several times higher than that of conventional refinery fuel gas. The higher flow demand increases pressure losses in fuel headers and valve trains, and may exceed the flow capacity of existing nozzles and piping networks.

Existing tests showed that the pressure drop from the mixing drum to the fired-heater fuel network increased by approximately 6.2%, corresponding to an absolute increase of about 1 psig. Although this increase was not sufficient to cause a fundamental loss of flame stability, it indicates that nozzle orifice size, pipe diameter, and valve flow area must be re-evaluated and resized for high-load refining and petrochemical units.

Meanwhile, Lan et al. [31] numerically studied hydrogen-enriched combustion in an industrial-fired heater and found that, under unchanged inlet temperature and operating conditions, increasing the hydrogen blending ratio to 60% intensified the in-furnace flow circulation. This was attributed to the higher burning velocity and stronger thermal expansion of the blended fuel. As a result, the thermal efficiency increased from 91.2% under pure natural gas operation to 94.7%. Mu et al. [88] further showed that efficiency improvement in refinery-fired heaters is closely linked to flue gas condensing waste-heat recovery and the associated pressure-drop penalty, rather than fuel substitution alone.

4.2.3. Low-NO_x Control in Refinery Furnaces

In terms of emission compliance, the higher adiabatic flame temperature of hydrogen generally tends to promote thermal NO_x formation. However, in specific refinery-fired-heater applications, this does not always lead to an absolute increase in total NO_x emissions [89]. Ditaranto et al. [60] showed through experiments and simulations that, for conventional carbon-containing refinery fuel gas, prompt NO_x associated with CH-radical chemistry can contribute substantially to total NO_x, while thermal NO_x may remain a minor pathway under certain baseline conditions.

After switching to pure hydrogen combustion, the prompt-NO_x formation pathway is eliminated, and the total NO_x emissions on a mass basis may therefore become lower than those from conventional refinery fuel gas combustion. Furthermore, the introduction of steam dilution reduced the peak flame temperature by approximately 140 K, leading to an additional NO_x reduction of nearly 50%. These findings indicate that low-NO_x control in refinery applications should not be simply interpreted as “hydrogen inevitably increases NO_x”. Instead, it should be evaluated comprehensively by considering furnace configuration, baseline fuel composition, and dilution strategy [90].

Overall, hydrogen fuel substitution in petrochemical and refinery furnaces has shown strong engineering feasibility in thermal conversion and system efficiency. Its commercial deployment, however, is shifting from basic flame stability verification toward integrated process optimization, including heat load redistribution between radiant and convection sections, fluid-dynamic adaptation of high-flow-rate fuel networks, and coke prevention and lifetime management of furnace tubes.

4.3. Special-Purpose Furnaces and Kilns

Waste treatment systems and certain public-service high-temperature combustion facilities represent one of the most scenario-specific categories for hydrogen fuel application. Unlike metallurgical or petrochemical heating processes, where material properties are relatively stable and thermal loads are generally continuous, these special-purpose furnaces and kilns often face systematic challenges, including highly heterogeneous feed-stock composition, large fluctuations in heating value, and coupled multiphase chemical reactions [91–93]. Therefore, the role of hydrogen in these scenarios should not be simply regarded as an equivalent replacement for conventional thermal fuels. Instead, it needs to be assessed independently according to the physical configuration and specific process constraints of each furnace type [94–96]. Among these special-purpose systems, cremation furnaces are retained as a representative batch-operated public-service furnace rather than as a marginal example. Their intermittent operating mode, strong transient heat-load fluctuation, secondary-combustion requirement, odor-control demand, and strict exhaust treatment constraints make them substantially different from continuous metallurgical furnaces and petrochemical-fired heaters. Therefore, hydrogen-assisted combustion in cremation furnaces provides a useful case for evaluating whether hydrogen can support

transient heat compensation, low-carbon auxiliary firing, and stable emission control in specialized high-temperature furnace systems.

At present, engineering demonstrations and mechanistic assessments involving hydrogen are mainly focused on representative equipment such as municipal solid waste incinerators, medical and hazardous waste rotary kilns, cement and specialty mineral calcination rotary kilns, and cremation furnaces [97–99], as shown in Figure 9.

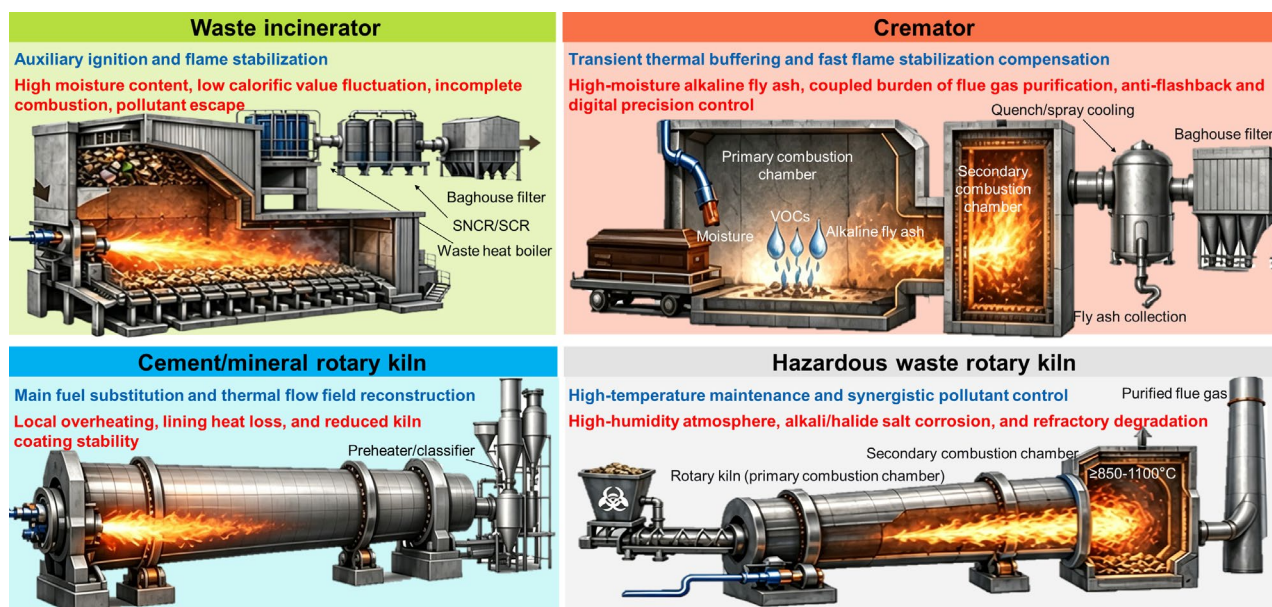


Figure 9. Typical scenarios and key challenges of hydrogen substitution in special application furnaces and kilns.

4.3.1. Municipal Solid Waste Incinerators

In mechanical stoker-grate and fluidized-bed systems for municipal solid waste incineration, hydrogen is more suitably regarded as an auxiliary ignition and flame stabilization fuel rather than the primary energy source. Lombardi et al. [100] reviewed waste-to-energy technologies and pointed out that incineration performance is strongly affected by feed-stock moisture content and lower heating value. For municipal solid waste with high moisture content and low calorific value, unstable heat release can cause delayed ignition, local flame instability, and incomplete combustion [101,102].

In this context, hydrogen can serve as a zero-carbon auxiliary fuel to reduce fossil fuel consumption during ignition and flame stabilization [103]. Owing to its wide flammability limits and low ignition energy, hydrogen can rapidly compensate for transient decreases in waste heat load and expand the stable combustion boundary under lean or unstable conditions. Related assessments of medical waste treatment and biomedical waste gasification further emphasize that sufficient and stable thermal input is essential for efficient thermochemical conversion and pollutant control [104,105]. Therefore, hydrogen-assisted combustion may help reduce the risks of flameout, incomplete combustion, and hazardous pollutant release in waste-incineration systems.

4.3.2. Medical and Hazardous Waste Rotary Kilns

In the thermal treatment of medical and hazardous wastes, rotary kilns and their secondary combustion chambers are designed not merely for low-grade heat recovery but primarily to ensure the complete destruction of polycyclic aromatic hydrocarbons, toxic components, and pathogens [102,106]. Previous studies have shown that, to suppress the formation and residual release of persistent pollutants such as dioxins and furans

(PCDD/Fs), the flue gas temperature in secondary combustion chambers must generally be maintained at a high level with sufficient gas-phase residence time [107–109].

Under these strict environmental requirements, hydrogen is mainly valuable as an auxiliary fuel for rapidly compensating thermal deficits and improving tail gas burnout. Wang et al. [19] experimentally investigated hydrogen-enriched propane/air combustion in a model furnace equipped with a rotary kiln burner. Their results showed that, under constant total heat release, hydrogen addition improved combustion boundary conditions and helped reduce CO and NO_x emissions. Gaurav et al. [110] also used CFD to analyze the temperature field in rotary kilns, highlighting the importance of properly organized temperature profiles for multiphase reactions and treatment performance.

However, hydrogen-enriched auxiliary combustion also introduces material challenges under water-vapor-rich conditions. In hazardous waste rotary kilns, where refractory linings are already exposed to severe corrosion from alkali metals, halogen salts, and molten slags, the increased water vapor partial pressure may promote the penetration of corrosive gaseous species into refractory micropores, potentially inducing phase-transformation expansion, chemical spalling, and microstructural degradation [111]. Therefore, the long-term application of hydrogen in hazardous waste treatment facilities depends not only on its ability to provide rapid, high-temperature compensation but also on system-level adaptation of refractory materials resistant to water-vapor-rich and alkaline corrosive environments [78–80].

4.3.3. Cement and Mineral Rotary Kilns

Unlike waste or hazardous waste treatment systems, where hydrogen is mainly considered as a transient thermal buffer, hydrogen use in cement and specialty mineral rotary kilns is primarily aimed at deep substitution of the main fuel [8]. Sectoral assessments by Zhu et al. [1] and Bataille et al. [3] indicated that cement clinker production requires extremely high-temperature process heat, making hydrogen attractive because of its ability to directly provide high-grade thermal energy.

However, the key engineering challenge for these large rotary kilns is not simply whether the target temperature can be reached, but how hydrogen alters flame structure and spatial heat flux distribution. Previous studies have shown that, because of its high laminar burning velocity, hydrogen can transform the long, radiation-dominated flames produced by pulverized coal or natural gas into shorter, more concentrated jet flames with stronger near-field heat release [112,113]. Such changes in the spatial heat transfer profile may cause local overheating of the front-end refractory lining and affect the dynamic stability of the clinker kiln coating, which protects the metallic kiln shell.

Meanwhile, modern cement production increasingly relies on multifuel burners and large fractions of solid recovered fuels and waste plastics [114]. Hercog et al. [115] further showed that, in complex multifuel combustion systems, a major aerodynamic challenge is to achieve stable hydrogen injection, reliable delivery of solid alternative fuels, and a long, smooth calcination temperature gradient within the same burner–kiln configuration. This remains a critical issue for advancing hydrogen substitution in cement and mineral rotary kilns.

4.3.4. Cremation Furnaces

In public health and municipal services, cremation furnaces provide hygienic and dignified body disposal and represent a typical public service scenario for low-carbon fuel substitution [116,117]. Unlike continuous waste incineration, cremation involves highly transient and heterogeneous thermal loads. Guo and He et al. [118,119] reported that a standard human body contains approximately 65% free water, 15% lipids, and 14% proteins,

which can cause delayed ignition, local quenching, and incomplete combustion. Large-scale measurements further showed that cremation workshops and flue gases contain CO, NO_x, VOCs, PCDD/Fs, and heavy metals, raising long-term environmental and occupational-health concerns [120–123]. These features make cremation furnaces a representative batch-operated high-temperature combustion system for evaluating hydrogen-assisted transient heat compensation, flame stabilization, and emission-control compatibility under highly variable organic and nitrogen-containing load conditions.

To suppress PCDD/F formation and ensure pollutant destruction, standards such as GB 13801-2015 and DB11/1203-2015 require the secondary combustion chamber to remain above 850 °C or even 1000 °C [117,124–126]. However, Zhou and Yin et al. noted that air leakage, excessive residual oxygen, and rapid moisture evaporation can disturb the high-temperature combustion boundary in conventional oil-fired cremators [123,124]. In this context, hydrogen is more valuable as a zero-carbon auxiliary fuel for transient heat buffering and rapid flame stabilization than as a simple replacement fuel. Its low ignition energy and fast oxidation kinetics can help compensate for temperature drops caused by moisture evaporation and reduce the risk of incomplete combustion and pollutant escape [122,127]. In mobile cremation units, hydrogen-assisted combustion combined with secondary air preheating may further improve combustion completeness under space-limited conditions [128,129].

Nevertheless, hydrogen-assisted cremation still faces coupled challenges in material degradation, pollutant migration, and control-system adaptation. Luo et al. [130] showed that captured ash from crematory flue gas purification systems contains high PCDF contributions and heavy metals such as Zn and Cd with leaching risks. A hydrogen-rich, water-vapor-rich atmosphere may further affect pollutant condensation, enrichment, and migration, increasing the load on dust removal, flue gas scrubbing, and wastewater denitrification systems [131,132]. In addition, Chang, Huang, Shi, and co-workers emphasized that low-carbon cremation equipment requires digital and intelligent upgrading [133–135]. Future systems should integrate high-frequency monitoring of chamber pressure, oxygen concentration, and combustion-state fluctuations to support rapid fuel-valve regulation, flashback prevention, and stable low-emission operation [136–138].

Overall, hydrogen-assisted cremation offers a promising route to stabilize transient combustion and improve pollutant control, but routine deployment requires integrated optimization of heat compensation, alkaline fly ash control, and digital thermal management [133,139].

5. Conclusions and Outlook

Hydrogen substitution for conventional fuels offers a technically feasible pathway for the deep decarbonization of high-temperature furnaces and kilns. However, it is not a simple fuel switch but a system-level challenge involving fuel properties, combustion kinetics, thermal flow field organization, pollutant formation, and long-term material durability. The key issue is therefore not whether hydrogen can burn but how to balance safety, emissions, thermal efficiency, heating uniformity, and service lifetime, as shown in Figure 10.

Although the reviewed studies generally support the feasibility of hydrogen substitution in high-temperature furnaces and kilns, the available evidence also reveals several inconsistencies and unresolved challenges. First, the reported NO_x trends are not uniform: hydrogen addition can suppress prompt NO_x by reducing hydrocarbon-radical pathways, but it can also intensify Zeldovich thermal NO_x when local flame temperatures and near-burner hot spots increase. Second, the heat transfer effect of hydrogen is furnace-dependent. Soot radiation may decrease, whereas H₂O-dominated gas radiation, convective heat trans-

fer, and near-burner wall heat flux may increase, leading to different conclusions depending on whether flame radiation, total heat flux, load heating rate, or temperature uniformity is used as the evaluation metric. Third, many reported benefits have been obtained under laboratory, pilot-scale, or CFD-based conditions, while long-term industrial validation remains limited. For CFD-based studies, the level of validation also varies substantially. Some simulations are validated against global quantities such as outlet temperature, flue gas composition, or overall heat duty, whereas local wall heat flux, near-burner temperature fields, transient flame behavior, and NO_x spatial distribution are less frequently validated. In addition, predicted results may be sensitive to turbulence–chemistry interaction models, radiation models, NO_x submodels, boundary conditions, mesh independence, and assumptions regarding wall emissivity and refractory properties. In particular, burner durability, refractory degradation, fuel system safety, transient operation, NO_x-control stability, and lifecycle carbon reduction still require further verification under realistic operating conditions. Therefore, future research should move beyond isolated burner or single-parameter studies toward integrated furnace-level demonstrations combining combustion stability, heat transfer matching, emissions control, material durability, and techno-economic assessment.

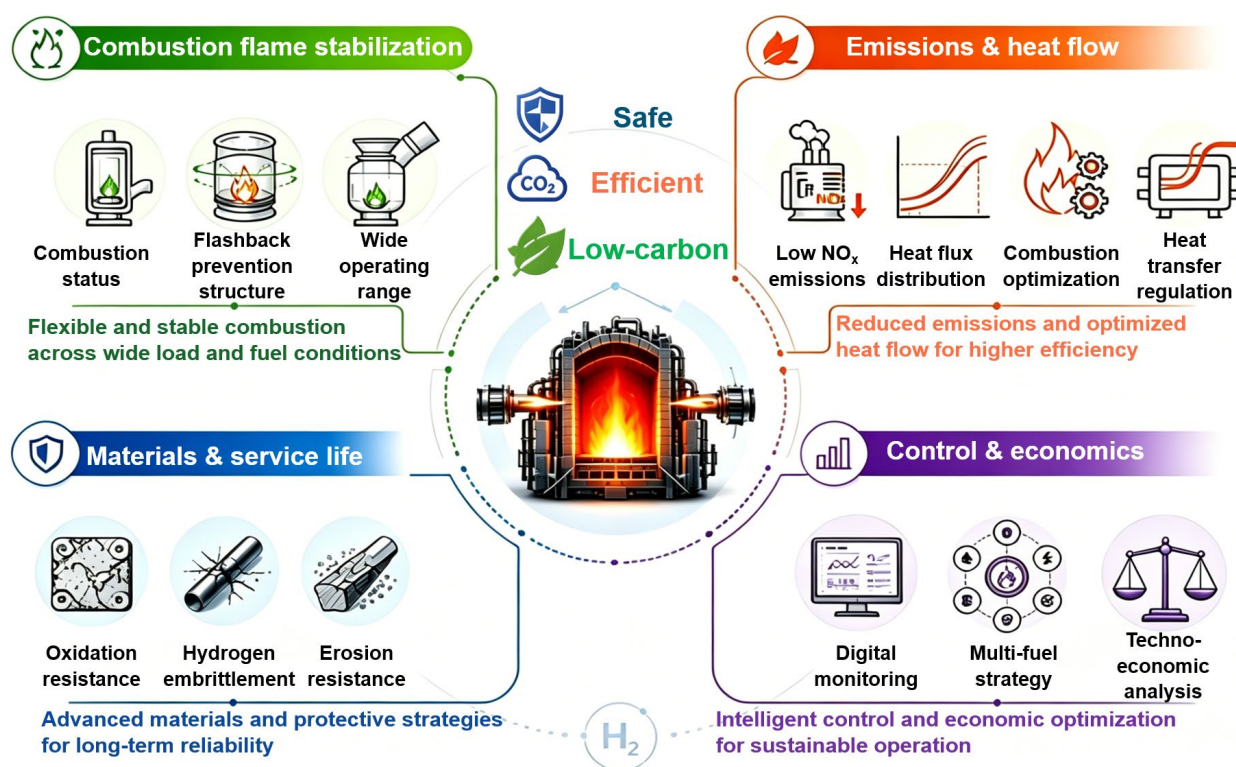


Figure 10. Hydrogen substitutes in high-temperature furnaces and kilns—conclusions and outlook framework.

From an implementation perspective, economic feasibility is another key barrier to large-scale hydrogen substitution. The cost of hydrogen-fired furnace operation depends not only on the unit price of hydrogen but also on the hydrogen-production route, electricity price, natural gas price, carbon pricing policy, supply continuity, and site-specific fuel network conditions. Compared with simple low-ratio hydrogen blending, high-ratio blending or 100% hydrogen firing usually requires more extensive retrofitting of burners, fuel trains, metering systems, pressure-regulation units, leak-detection devices, safety interlocks, control logic, and sometimes NO_x after-treatment systems. Additional costs may also arise from hydrogen storage or on-site generation, pipeline compatibility assessment, downtime

during retrofit, operator training, and safety certification. Therefore, hydrogen substitution should be evaluated not only by combustion performance or direct CO₂ reduction, but also by total implementation cost, retrofit complexity, infrastructure availability, and the expected carbon-reduction benefit over the service life of the furnace.

(1) Hydrogen substitution has shown clear engineering potential. Existing studies have demonstrated progress in flashback prevention, flame stabilization, low-NO_x combustion, thermal flow field regulation, heat transfer control, and material adaptation in water-vapor-rich atmospheres. Technologies such as staged combustion, swirl control, micromix combustion, flameless combustion, flue gas recirculation, and surface protection indicate that hydrogen utilization is moving from basic combustibility verification toward equipment-oriented controllability and operability.

(2) The main challenges are strongly furnace-dependent. In metallurgical and heat-treatment furnaces, the focus is on temperature uniformity, scale formation, and long-term continuous operation. In petrochemical-fired heaters, key issues include heat load redistribution, tube-wall temperature control, coking risk, and thermoacoustic stability. In waste treatment and special-purpose furnaces, hydrogen is more suitable as an auxiliary or co-firing fuel, with application limited by wide-load flame stabilization, flashback prevention, coupling with flue gas treatment systems, and refractory durability.

(3) Future research should shift toward system-level integration. Further work should clarify the coupling among fuel supply, burner design, furnace flow field, heat load distribution, pollutant control, and material degradation. Particular attention should be paid to the migration of flashback limits, thermoacoustic instability, NO_x fluctuations, and thermal flow field reconstruction under variable-load and start–stop conditions.

(4) Industrial deployment requires long-term validation and techno-economic assessment. Future demonstrations should evaluate material oxidation, corrosion, refractory degradation, and structural reliability under high-temperature water-vapor-rich atmospheres. In parallel, techno-economic and lifecycle-carbon studies should consider the upstream hydrogen-production route, low-carbon hydrogen availability, plant gas network compatibility, retrofit intensity, process window tolerance, and carbon pricing conditions. Moreover, the practical emission-reduction value of hydrogen substitution should be evaluated by distinguishing direct furnace-side CO₂ reduction, lifecycle carbon reduction, NO_x-control performance, and the reduction of incomplete combustion products such as CO and unburned hydrocarbons. Only when hydrogen is supplied through sufficiently low-carbon pathways, such as renewable electricity-driven electrolysis or other low-carbon production routes, can combustion-side CO₂ elimination be translated into substantial lifecycle carbon reduction.

Based on the above analysis, the highest-priority research needs for hydrogen substitution in high-temperature furnaces and kilns can be summarized as follows. First, low-carbon hydrogen supply and lifecycle carbon accounting should be integrated into furnace decarbonization assessments to avoid shifting emissions from the combustion stage to the hydrogen-production stage. Second, flashback-safe, low-NO_x, and load-flexible hydrogen burners should be developed for both blending and 100% hydrogen operation. Third, furnace-level heat transfer reconstruction should be investigated using engineering metrics such as wall heat flux profiles, convective/radiative heat transfer fractions, load temperature uniformity, exhaust losses, and refractory hot-spot risk. Fourth, long-term material and refractory durability should be validated under water-vapor-rich atmospheres, repeated thermal cycling, and realistic impurity/slag conditions. Fifth, CFD models and digital-twin control frameworks should be validated against experimental and industrial-scale data, including local heat flux, temperature fields, NO_x emissions, and transient stability. Finally, sector-specific demonstrations and techno-economic analyses are needed

to identify where hydrogen blending can serve as a near-term retrofit pathway and where 100% hydrogen firing can provide deeper decarbonization benefits.

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