



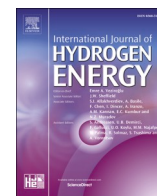
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Effects of hydrogen–coal mixing on NO_x formation during partial decarbonisation of rotary kiln iron ore induration - pilot-scale experiments using spectroscopy and video analysis

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ABSTRACT

This pilot-scale study examines hydrogen–coal co-firing at 0–65% hydrogen energy substitution in a 580-kW furnace representative of industrial iron-ore kiln systems. Five burner families, comprising six tested configurations, varied the relative positions, injection directions and velocities of hydrogen, coal and primary air. Relative to the pure-coal case, outlet NO_x decreased by 15–24% at 20% hydrogen substitution; at 40% substitution, the change ranged from a 5% reduction to a 31% increase; and at 60–65% substitution, NO_x increased by 42–97%. The emission performance is associated with changes in fuel NO_x and thermal NO_x formation, supported by apparent coal-ignition distance, apparent line-of-sight temperature, plume structure and local oxygen availability.

1. Introduction

Hydrogen–coal co-firing is investigated as a retrofit pathway for reducing direct CO₂ emissions from existing coal-fired industrial rotary kilns while retaining part of the installed fuel-delivery and combustion infrastructure. In regions with access to abundant low-carbon electricity, hydrogen may also constitute a possible longer-term fuel strategy, although broader techno-economic, infrastructure and regulatory conditions can affect its deployment [1,2]. Its environmental and economic performance also depends strongly on the hydrogen-production route and electricity prices [1,3].

Iron-ore pellets are principally indurated using either straight-grate or grate-kiln systems. The grate-kiln process consists of a travelling grate, a slightly inclined rotary kiln and an annular cooler [4]. In the rotary kiln, pellets are heated to the temperatures required for mineral reactions, sintering and the development of sufficient mechanical strength. Depending on ore mineralogy and operating conditions, pellet temperatures are generally within approximately 1250–1350 °C. Pulverised coal is commonly used as a thermal-energy source in grate-kiln plants, where the heat source interacts mainly radiatively and convectively with the refractory wall and moving pellet bed [5,6].

The rotary-kiln combustion environment differs from that of many

conventional boilers because it combines strongly preheated secondary air, large excess-air ratios, long radiative path lengths and interactions between turbulent combustion, refractory surfaces and the pellet bed [7, 8]. These conditions favour high NO_x emissions during pulverised-coal combustion and can promote even further NO_x formation when hydrogen is introduced [8,9]. Given their adverse environmental effects, NO_x emissions are subject to necessary regulatory limits, which may become more stringent in the future. This provides strong motivation to better understand NO_x formation across different coal–hydrogen fuel mixtures.

Replacing part of the coal-energy input with hydrogen directly decreases the carbon introduced with the fuel. Hydrogen combustion nevertheless differs fundamentally from pulverised-coal combustion because hydrogen has a low molecular weight, high mass diffusivity and broad flammability range. Its low minimum ignition energy [10] and short ignition-delay and reaction times at elevated temperature [11,12] additionally favour rapid ignition and oxidation. These properties can shift ignition and heat release closer to the burner [13,14], while hydrogen-injection geometry and jet interaction can modify entrainment and the spatial distribution of combustion [14,15].

Hydrogen contains no chemically bound nitrogen. However, rapid hydrogen oxidation in hot, oxygen-containing regions can establish

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conditions favourable to thermal NO_x formation through reactions initiated by the oxidation of molecular nitrogen [16]. Experimental and numerical studies of hydrogen and hydrogen-blended flames have shown that NO_x formation depends strongly on the local chemical and thermal conditions [17], burner mixing and flame structure [18,19], and residence time at elevated temperature [20].

Coal combustion produces NO_x through a more heterogeneous set of processes. Nitrogen chemically bound within the coal structure is partitioned between volatile compounds and the remaining char during particle heating and devolatilisation [21,22]. HCN and NH_3 are among the principal gaseous nitrogen-containing precursors. Their formation is influenced by coal characteristics and the original chemical forms of nitrogen [23,24], while the measured precursor yields are also sensitive to pyrolysis and reactor conditions [25]. The nitrogen retained within the char may subsequently form NO during char oxidation [26,27], while heterogeneous reactions involving char can simultaneously consume part of the NO formed in the gas phase [28]. Consequently, the conversion of coal nitrogen to NO_x is not determined solely by the fuel-nitrogen concentration. It depends on the coupled histories of particle heating, devolatilisation, volatile combustion, char oxidation and the local stoichiometric environment [22,29].

Three coupled groups of processes are therefore particularly relevant to hydrogen-coal co-firing. First, replacing coal with hydrogen decreases the fuel-nitrogen input. However, the resulting decrease in fuel NO_x does not necessarily follow a linear coal-replacement fraction [22,30].

Second, hydrogen combustion can increase the heating rate of neighbouring coal particles and shift their ignition closer to the burner [13,14]. Coal-particle ignition is controlled by particle heating and coal characteristics [31], while experimental studies demonstrate additional sensitivity to the oxidising environment and oxygen concentration [32,33]. Faster heating also changes the rate and timing of volatile release and has been shown to modify the partitioning of coal nitrogen between volatile-N and char-N [34,35]. Once released, HCN, NH_3 and related nitrogen intermediates may either be oxidised towards NO or converted towards N_2 . Their fate depends strongly on local temperature, stoichiometry, radical concentrations and residence time [16,22]. Fuel-rich or oxygen-lean regions can suppress the oxidation of nitrogen intermediates and strengthen reactions that reduce NO or convert reactive nitrogen towards N_2 [36,37].

Third, increasing the hydrogen-energy fraction can increase the importance of gas-phase hydrogen oxidation and alter the extent of high-temperature reaction zones. NO production in hydrogen flames is highly sensitive to local high-temperature zones, oxygen availability and residence time, which together promote thermal NO formation, principally through the extended Zeldovich mechanism [16]. Experimental and modelling studies under high-temperature furnace conditions further demonstrate the sensitivity of NO formation to the resulting thermal and oxidising environment [38,39]. The magnitude of this contribution is sensitive to mixing and burner aerodynamics because these determine whether hydrogen reacts rapidly within oxygen-rich regions or over a larger, more distributed flame volume [18,19]. In this work, short-residence-time or rapid-quench combustion, in which the high-temperature residence time is limited to suppress thermal NO_x formation, was not investigated.

Previous experimental investigations by our research group have established several elements of coal-hydrogen interaction under rotary-kiln conditions. Johansson et al. reported that co-firing with 30% hydrogen energy substitution in an integrated burner decreased NO_x by 32% relative to pure coal and by 78% relative to pure hydrogen under the tested conditions [13]. The study also observed earlier coal ignition distance and a more compact flame, showing that hydrogen addition modifies coal-particle heating and the spatial distribution of heat release.

Colin et al. subsequently showed that changing the distance and angle of hydrogen injection relative to the coal stream could

approximately double the measured NO_x level [15]. This result demonstrated that geometric placement and jet interaction can be as important as nominal hydrogen fraction in determining the resulting emissions.

A further study by the present authors, conducted in the same pilot facility, investigated progressive hydrogen substitution using one principal burner concept and quantified changes in flame structure, apparent line-of-sight temperature, heat-release distribution and outlet NO_x [14]. Hydrogen substitution shifted ignition and heat release upstream, shortened the visible coal flame and produced a non-monotonic NO_x response. It has also been shown that it is possible to reduce NO_x emissions compared to pure coal up to 40% hydrogen replacement. However, that study did not systematically compare alternative spatial arrangements of coal, hydrogen and primary air.

Previous work has shown that replacing large fractions of pulverised coal with hydrogen may increase NO_x emissions, potentially limiting the extent of hydrogen substitution. Controlling NO_x formation is therefore a challenge for this application. Building on previous work, the present study investigates how the relative positions of coal, hydrogen and primary air, together with primary-air swirl, hydrogen-jet momentum and hydrogen-injection direction, influence combustion and NO_x behaviour at different hydrogen fractions. The study also develops macro-scale diagnostic methods selected for their potential transfer to full-scale kilns, where direct and spatially resolved measurements are considerably more difficult. The mechanistic discussion is therefore presented as an interpretation constrained by mutually consistent experimental observations rather than as a direct decomposition of chemical pathways.

2. Methods

2.1. Experimental philosophy

A recurring challenge in the combustion science of industrial-scale systems is the choice between mechanistic resolution, experimental cost, and operational representativeness. Full-scale rotary kilns operate under conditions that are difficult to isolate, because their thermal environment is shaped by the coupled interaction of turbulent combustion, radiative heat exchange with the pellet bed and refractory walls, gas-solid heat transfer, primary and secondary air flow rates and temperatures, as well as process and system-related factors such as fuel-flow variations, burner alignment, slag formation, production load, air leakage, etc. High-resolution mechanistic characterisation at full-scale is therefore both experimentally challenging and potentially difficult to generalise, since normal operation is not a fixed point, but a range of acceptable states. The 580-kW facility used here is approximately 1/100 of the power of an industrial kiln. It reproduces selected boundary conditions with near-horizontal firing, refractory confinement, pre-heated secondary air and large excess-air operation, but it cannot reproduce all full-scale residence-time distributions, radiative path lengths or turbulent length scales. Quantitative extrapolation of absolute values should consequently be made with caution, especially for particle-laden flames. Scale effects have been reported for solid-fuel combustion [40], pulverised-coal burner aerodynamics [41], industrial-flame heat transfer and pollutant formation [42], and NO_x scaling between burners and furnaces [43]. The influence of large excess-air operation on pulverised-fuel flame scaling has also been examined under conditions relevant to the present facility [7].

The diagnostics used in the present study were selected not only for their ability to provide mechanistic indicators in the pilot-scale furnace, but also with consideration of their potential applicability to full-scale kilns, where optical access to the flame is severely limited. Outlet NO_x provides the integrated result; fuel-N input constrains the maximum fuel-derived nitrogen supply; apparent ignition distance and particle-radiation temperature describe changes in coal heating and flame position; plume imaging indicates changes in near-burner dispersion; and

in-flame O_2 measurements constrain the local oxidising environment at the sampled locations. The sources, interpretation and principal limitations of each indicator are summarised in Table 1. The locations where the measurements were taken in the furnace are shown in Fig. 1. These measurements do not directly identify chemical pathways; instead, they are used to test whether the NO_x trends are consistent with changes in coal heating, local oxidising conditions and indirect indicators of hot gas-phase reaction zones. This macro-scale approach belongs to the experimental pillar of combustion science described by Williams [44].

2.2. Experimental setup and operating conditions

The experimental campaign was conducted in the LKAB Experimental Combustion Furnace in Luleå, Sweden. The 580-kW refractory-lined facility has an internal diameter of 0.65 m, a total length of up to 14 m and an approximately 4-m first section representing the downscaled rotary-kiln zone. The furnace is inclined by 3° . Earlier publications provide additional facility details [5,6,8,45]. The expression “rotary-kiln conditions” in this paper refers to the selected thermal and aerodynamic boundary conditions reproduced by the pilot facility and does not imply complete dynamic similarity with an industrial kiln.

Secondary air, representing the preheated air stream that enters the kiln from the cooler in the full-scale process, was supplied at a total flow of $2100 \text{ Nm}^3/\text{h}$. Following the dual-inlet configuration of industrial kilns, 40% of this flow was introduced through the lower inlet preheated to 980°C , and 60% through the upper inlet preheated to 1030°C . This preheating is critical for reproducing the thermal background against which co-firing NO_x formation must be assessed, since the high secondary air temperature significantly elevates the baseline thermal NO_x potential [49]. Before the experimental campaign, the furnace was heated for approximately three days to reach the operating temperature. During the campaign, after each change in fuel mixture or burner

setting, the furnace was operated under the new conditions for at least 6 h before measurements were conducted, allowing the system to stabilise.

Five burner families (m1–m5) were designed to vary the spatial relationship among coal, hydrogen and primary air. In the family m1, two variants were tested: m1a, representing the reference hydrogen-injection velocity, and m1b, with a hydrogen velocity approximately ten times higher. The hydrogen velocity is a theoretical value calculated from the flow rate and nozzle area and should be regarded as indicative. All burners used three concentric registers. Hydrogen energy fraction was calculated from the lower heating values of the fuel streams.

Family m1, representing the reference configuration, is designed with a coal injection placed along the centreline, enveloped by an annulus of primary air, and finally surrounded by hydrogen injected through the outermost register. This geometry deliberately separates hydrogen from coal by an intermediate air layer, establishing a baseline against other mixing strategies.

Family m2 is designed to probe the consequence of inverting this hierarchy. The coal centreline injection is preserved, but hydrogen is now placed immediately adjacent to the coal stream in the middle register, while primary air is displaced to the outer annulus. In doing so, m2 tests the hypothesis that closer hydrogen-coal proximity fundamentally alters the coal-particle heating indicator and assesses the change in local O_2 concentration in the coal jet.

Family m3 shares the spatial arrangement of m1 in every respect except for the primary air that is delivered with a swirl angle of 30° rather than straight. This single aerodynamic modification introduces stronger mixing between fuels and air and belongs to a flame-shortening strategy.

Families m4 and m5 occupy opposite ends of a geometric spectrum designed to isolate the directional influence of hydrogen injection relative to the coal stream. Family m5 injects hydrogen inward, angling

Table 1

Diagnostic measurements used as NO_x -relevant indicators, together with their physical interpretation and principal limitations.

NO_x relevance	Physical target	Measurement or interpretive indicator	Principal limitations
Thermal NO_x (H_2)	Hydrogen-flame temperature trend	Apparent line-of-sight (LOS) temperature; coal-ignition distance; qualitative flame visualisation Literature basis: LOS/optical temperature [45–47]; coal ignition [31–33,48]; flame visualisation [13, 14].	Local peak temperatures are not measured, and the LOS signal is spatially and temporally integrated.
Thermal NO_x (H_2)	Extension of oxygen-rich, high-temperature reaction zones	H_2 energy fraction used as an interpretive indicator Literature basis: thermal-N chemistry [16]; high-temperature H_2 furnace NO formation [38,39].	Increasing the H_2 fraction also changes the jet velocity and, consequently, the mixing and turbulence regime; the effect cannot therefore be quantified.
Thermal NO_x (H_2)	Fuel–air mixing intensity	Theoretical H_2 jet velocity and injection direction; coal-plume visualisation Literature basis: hydrogen-injection geometry [15]; H_2 flame mixing and structure [18,19].	Turbulence and mixing are inferred from the visible coal plume rather than measured directly.
Fuel NO_x	Fuel-bound nitrogen input	Coal ultimate analysis and coal mass-flow rate Literature basis: coal-N release and conversion [21, 22]; volatile/char-N contribution in rotary kilns [29].	The conversion of fuel-bound nitrogen to NO_x may vary significantly between operating conditions.
Fuel NO_x	Coal-particle ignition behaviour	Apparent ignition-distance visualisation Literature basis: general coal ignition [31]; oxidiser and O_2 effects [32,33]; ignition modelling [48].	Distance does not directly represent ignition time because the local particle and gas velocities are modified by hydrogen injection.
Fuel NO_x	Coal-particle radiative-temperature trend	LOS temperature Literature basis: pilot-furnace optical diagnostics [45,46]; grey-body/two-colour temperature basis [47].	The LOS temperature is averaged in time and space. Measurements at discrete ports may miss the local peak temperature and do not directly provide the maximum particle temperature.
NO_x reduction	Flame length and residence in fuel-rich regions	Coefficient of variation of the LOS temperature series; qualitative plume and flame visualisation Literature basis: air staging and reburning [36,37]; coal/ H_2 flame-length observations [13,14].	Radical concentrations and local chemical pathways are not measured, limiting validation of the proposed microscopic reduction mechanisms.
NO_x reduction	Local oxidising environment	In-flame O_2 mapping by gas sampling Literature basis: pilot-furnace gas sampling [45]; air-preheat effects on NO_x [49].	The O_2 field is measured only at discrete locations, and the mapping was performed at a slightly lower furnace power.
Total NO_x	Overall outlet NO_x trend	Exit flue-gas analysis (dry gas) Literature basis: rotary-kiln NO_x measurements [7, 8]; pilot-furnace diagnostics [45].	At higher hydrogen fractions, the increased water-vapour content may introduce additional uncertainty during gas drying and dry-basis correction, although the water-vapour content remains below 10 vol%.

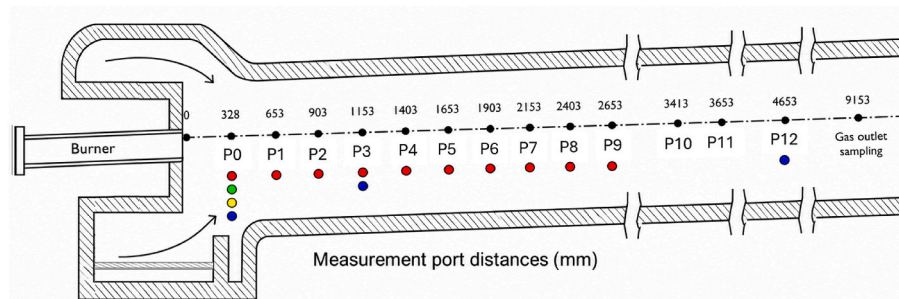


Fig. 1. Pilot furnace and diagnostic locations for outlet-gas sampling (last black point), in-flame gas sampling (blue points), spectroscopy (red points), and imaging with two cameras (yellow and green points). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the jets toward the centreline coal flow and thereby maximising mixing. Family m4 takes the opposing stance, injecting hydrogen radially outward into the secondary air stream, placing the hydrogen flame as far from the coal jet as the burner geometry permits and theoretically minimising the influence of hydrogen combustion on coal particle heating in the near-burner zone.

A summary of the five burner families and six tested configurations is presented in Table 2.

The coal used throughout this study was a sub-bituminous coal with a lower heating value of 30.5 MJ/kg. The as-received moisture content was 0.6%. On a dry basis, proximate analysis gave 12.5% ash, 18.5% volatile matter and 69.0% fixed carbon. Ultimate analysis on a dry basis gave 78.5% C, 4.0% H, 1.4% N, 3.5% O and 0.35% S; the small deviation from 100% after inclusion of ash results from rounding. The particle-size distribution is shown in Fig. 2.

2.3. Coal ignition diagnostics - apparent ignition distance

The apparent coal-ignition position was determined from images recorded through port P0 with a dedicated operational camera over a 20-s acquisition period (± 2 s). Here, “apparent ignition” denotes the first axial position at which coal devolatilisation produces a detectable increase in the spatial and temporal variation of image intensity. It is not a direct measurement of single-particle ignition delay. The method follows the physical basis used in optical coal-ignition studies: particle heating, devolatilisation and oxidation produce a rapid increase and fluctuation of radiation intensity in visible light range once ignition begins [31–33,48]. Because hydrogen emission is weak in the visible range under the selected camera settings and furnace conditions (highly radiative wall), the diagnostic identifies the response of the coal plume rather than the hydrogen flame. In certain cases, coal particles heated by the hydrogen flame may reach temperatures high enough to emit visible radiation before ignition. Such particles increase the measured light intensity but do not necessarily produce the temporal intensity fluctuations associated with active ignition and combustion.

Fig. 3 presents each step of the procedure used to determine the ignition distance. For each frame, a fixed sampling line was drawn from the burner outlet along the coal-jet centreline. The intensity profile was smoothed with a moving-average window of 50 pixels, and the variance between the raw and smoothed profiles was calculated. The ignition location was determined using a semi-automated variance-based method. Ignition onset was identified as the first axial position at which the variance exceeded a prescribed threshold and remained above this threshold over a minimum persistence distance. Both the variance threshold and the required persistence distance were adjusted for each operating case according to the characteristic image intensity and variance profile, and the selected values were then kept constant for all analysed frames within that case. The variance threshold was typically within approximately 80–120, while the persistence criterion was selected to exclude short isolated threshold crossings and retain only a

sustained increase in variance. This adjustment was necessary because the camera exposure time and aperture were automatically adapted to the recorded light intensity, resulting in variations in the overall image intensity between operating conditions. A background-intensity correction was applied using a region of refractory material located behind the burner, as far as practicable from the flame and exposed only to the secondary-air flow, which remained at approximately constant temperature. However, although this region was not directly exposed to flame radiation, radiative emission from the flame could still influence the measured background intensity. The background correction could therefore not fully compensate for differences in image intensity between cases. For example, at high hydrogen fractions, the visible intensity decreases as the coal flame becomes shorter and less dense. Each case was therefore verified by comparing the recorded images with the corresponding variance profile. Despite the case-specific threshold and persistence settings, the same characteristic behaviour was observed across the analysed cases, as illustrated in Supplementary Data 1 for the cases m1a and m2. The variance remained initially low and relatively stable before increasing sharply at a very distinct axial position. The onset of this sustained increase was defined as the apparent coal-ignition location. The method is therefore intended to provide a comparative indicator of ignition location rather than an absolute measurement of individual-particle ignition delay. The results were normalised over the detected range (0 = burner outlet; 1 = no ignition detected within the P0 field of view).

2.4. Fuel-bound nitrogen assessment

The fuel-nitrogen mass flow was calculated from the ultimate analysis data and the measured coal flow rate at each operating condition. The resulting values are presented in Table 3, falling from 0.960 kg N/h at 0% H₂ to 0.384 kg N/h at 60% H₂.

2.5. Spectroscopic measurement of apparent LOS temperature

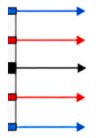
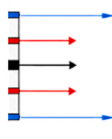
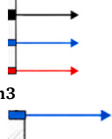
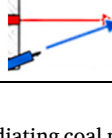
The spectroscopic measurement provides an apparent line-of-sight (LOS) temperature dominated by coal-particle and wall emission. It is used as an indicator of coal-particle heating, flame position and particle loading, but does not measure local gas-phase or hydrogen-flame temperature due to radiation properties. Since thermal NO_x depends on local gas temperature and residence time, these quantities are not measured directly. The approach follows Wiinikka et al. [46] and Colin et al. [14].

The method used an Ocean Optics HR-6XR300-10 spectrometer (300-line composite blaze grating, 10- μ m slit) covering the wavelength range 200–1100 nm, operated with OceanView software. For each measurement position, 500 spectra were recorded, providing a statistically robust sample of the temporal variability in particle emission.

LOS emission spectra were recorded through two diaphragms that restricted the viewed volume and reduced detector saturation. The

Table 2

Specification of the five burner families and six tested configurations (m1a, m1b and m2–m5). Hydrogen energy fraction is based on lower heating value. The theoretical velocities should be regarded as indicative. The burner is shown in a longitudinal cross-sectional view through its centreline to provide a clearer representation of the mixing between the different streams. Coal injection is represented by the black arrow, hydrogen injection by the blue arrows, and primary-air injection by the red arrows.

Mixing configuration	Central register	Register 2	Register 3
m1a (reference) 	Coal; straight injection; 25 m/s	Primary air; straight injection; 150 m/s; 40 Nm ³ /h	H ₂ ; multi-hole; straight injection; 20% H ₂ : 100 m/s; 40% H ₂ : 200 m/s; 60% H ₂ : 300 m/s
m1b (high-velocity H₂) 	Coal; straight injection; 25 m/s	Primary air; straight injection; 150 m/s; 40 Nm ³ /h	H ₂ ; multi-hole; straight injection; 20% H ₂ : 1000 m/s; 40% H ₂ : 2000 m/s
m2 	Coal; straight injection; 25 m/s	H ₂ ; multi-hole; straight injection; 20% H ₂ : 100 m/s; 40% H ₂ : 200 m/s; 60% H ₂ : 300 m/s	Primary air; straight injection; 150 m/s; 40 Nm ³ /h
m3 	Coal; straight injection; 25 m/s	Primary air; 30° swirl; 150 m/s; 40 Nm ³ /h	H ₂ ; multi-hole; straight injection; 20% H ₂ : 100 m/s; 40% H ₂ : 200 m/s; 60% H ₂ : 300 m/s
m4 	Coal; straight injection; 25 m/s	Primary air; straight injection; 150 m/s; 40 Nm ³ /h	H ₂ ; multi-hole; outward injection; 20% H ₂ : 100 m/s; 40% H ₂ : 200 m/s
m5 	Coal; straight injection; 25 m/s	Primary air; straight injection; 150 m/s; 40 Nm ³ /h	H ₂ ; multi-hole; inward injection; 20% H ₂ : 100 m/s; 40% H ₂ : 200 m/s

radiating coal particles and furnace wall were assumed to behave as grey bodies over the 500–800 nm range [47]. Spectra were fitted with Planck's law over approximately 500–740 nm after excluding the Na doublet near 589 nm, K emission lines and strong H₂O/CO₂ absorption regions. Exposure time was 100 ms. Because the LOS integrates over coal particles and the furnace wall, a normalised average temperature position was used as a composite indicator: In combustion zones, a low normalised position reflects dominant wall contribution (either low coal density or unignited coal), while a high position indicates strong particle emission and, by inference, elevated particle temperatures or density. The coefficient of variation of the LOS temperature series provides an independent measure sensitive to flame length: high values indicate

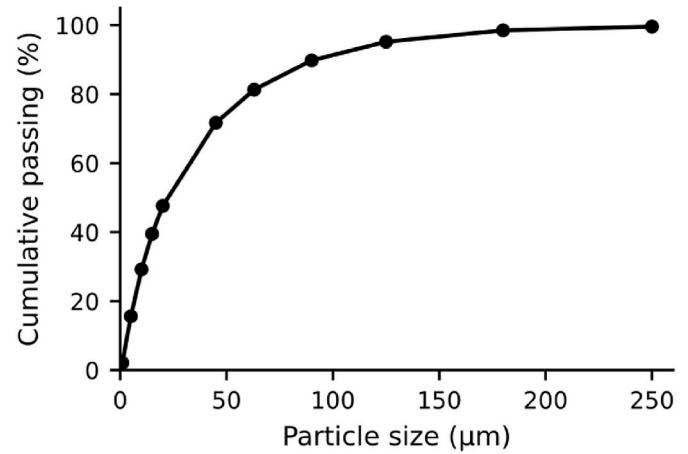


Fig. 2. Cumulative particle-size distribution of the coal used in the experimental campaign.

large fluctuations between particle and wall temperatures, characteristic of either ignition events or flame tail.

2.6. In-flame O₂, outlet O₂ and NO_x

Outlet NO_x was sampled on the furnace centreline at 9.153 m from the burner, where the gas was sufficiently mixed to represent the bulk flue gas. The sample was extracted hot and transported through a heated line to avoid condensation and dehumidified before analysis. NO and NO₂ were quantified by NDUV method in a LIMAS analyser. Total NO_x emissions were expressed as NO₂ equivalent and normalised by the fuel-energy input as follows:

$$NO_x \left[\frac{mg}{MJ} \right] = 2.053 \frac{(NO_{ppm} + NO_{2,ppm}) (\dot{V}_{flue})}{\dot{Q}_{fuel}}$$

In this equation, NO_{ppm} and NO_{2,ppm} are the measured dry-basis volumetric concentrations of NO and NO₂, respectively; $\dot{V}_{flue}$ is the dry flue-gas volumetric flow rate (Nm³/h); and $\dot{Q}_{fuel}$ is the total fuel thermal input (MJ/h), calculated independently for each operating condition from the measured coal and hydrogen flow rates and their respective lower heating values. The factor 2.052 converts the summed NO and NO₂ concentration from ppmv to mg/Nm³ when NO_x is expressed as NO₂ equivalent. It is obtained from the molar mass of NO₂ (46.0 kg/kmol) divided by the ideal-gas molar volume at normal conditions (22.414 Nm³/kmol): 46.0/22.414 = 2.052. Because ppmv is a molar (volume) fraction, NO and NO₂ can be added directly on a ppmv basis before conversion to NO₂-equivalent mass concentration. Multiplication by $\dot{V}_{flue}$ gives the NO_x mass flow in mg/h, and division by $\dot{Q}_{fuel}$ gives the final emission factor in mg/MJ. The dry flue-gas volumetric flow rate was calculated from the measured inlet air and fuel flows on a normal-volume basis. The combustion-air flow was corrected for inlet moisture, and the fuel contributions were converted using the stoichiometric air requirement and corresponding dry flue-gas production for each fuel. Air leakage was neglected because of the enclosed tubular geometry of the pilot facility, for which no significant leakage was expected under the operating conditions.

The outlet values are reported on a dry basis. The instruments were calibrated before the experimental campaign using calibration gases, resulting in differences below 2%. The plotted mean corresponds to approximately 30 min of stable operation selected manually; the shaded/min–max range describes temporal operating variability and is not presented as a complete uncertainty interval. Post-flame conversion between the near-flame zone and the outlet may occur similarly to that in full-scale operation; the outlet result should therefore be interpreted

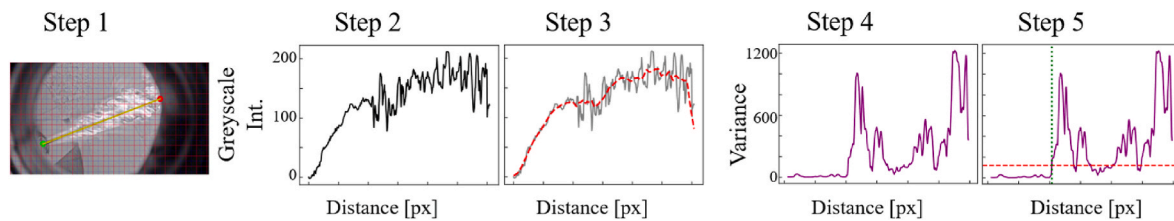


Fig. 3. Image-processing workflow used to determine the apparent coal-ignition position. Step 1: A sampling line is defined along the coal jet. Step 2: Grayscale intensity is extracted along the line. Step 3: A moving-average trend is calculated. Step 4: The residual variance is determined. Step 5: Apparent ignition is defined at the first sustained increase in variance above the selected threshold over the required persistence distance.

Table 3

Fuel-nitrogen flow as a function of hydrogen energy fraction.

	% of H ₂	0%	12%	20%	40%	60%
FUEL-N FLOW	kg N/h	0.960	0.845	0.768	0.576	0.384

as the integrated furnace emission. Outlet NO_x concentrations were measured at 4.2 m to assess possible differences along the exhaust duct. No significant difference was observed between the measurements at 4.2 and 9.153 m. Furthermore, cross-sectional sampling at 9.153 m confirmed that the exhaust gas was homogeneous, showing a consistent concentration profile across the diameter of the furnace.

In-flame O₂ was measured with a traversing probe and a HORIBA analyser at P3, P7 and P12. These measurements were performed at 510 kW rather than 580 kW while maintaining the same global air-to-fuel ratio. The outlet NO_x values, expressed in mg/MJ, were very similar at 510 and 580 kW. They are therefore used only as qualitative evidence of the sampled local oxidising environment. They are not used to derive quantitative information or to imply that different power levels produce identical flames.

For validation, the outlet O₂ concentration was measured at the same location as the outlet NO_x, and the corresponding O₂ results are presented in Supplementary Data 2. The outlet O₂ concentration varied by less than 0.5 percentage points for pure coal and below 0.3 percentage points in cofiring between burner configurations, indicating relatively similar conditions.

2.7. Coal plume visualisation

Finally, coal-plume visualisation was used to assess changes in the visible coal-particle flame structure, including plume spreading, intermittency, and apparent flame-edge wrinkling. An RGB FORGE 5GigE CMOS camera (FG-P5G-50S4C-C, 2448 × 2048 pixels) was operated at 114 fps through port P0. The recorded images were converted to grayscale, normalised, and Gaussian-smoothed to reduce image noise. Apparent flame/plume-edge structures were then extracted by applying a Sobel gradient-magnitude filter followed by thresholding. These structures provide qualitative indications of shear-layer deformation but cannot be interpreted as measurements of the turbulence regime.

3. Results and discussion

Fig. 4 presents the central experimental result: outlet NO_x as a function of hydrogen energy fraction and burner configuration. The accompanying range represents the observed temporal (approximately 30 min) minimum and maximum and mainly reflects operational variation, including coal-feeding fluctuations.

A common non-monotonic trend is observed. Except for m4 and m1b, outlet NO_x decreases from pure coal to 20% hydrogen substitution and then increases at higher hydrogen fractions. The magnitude of this response depends strongly on burner geometry and hydrogen momentum. The discussion of the relationship between mixing strategy and NO_x emissions is organised into five sections. Section 3.1 discusses

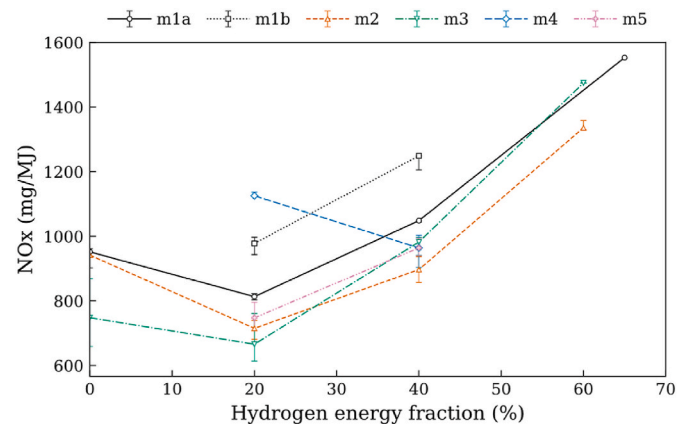


Fig. 4. Outlet NO_x as a function of lower-heating-value hydrogen energy fraction. Points show approximately 30-min means; ranges show temporal minima and maxima.

apparent coal ignition and the inferred coal-particle heating indicator. Section 3.2 examines turbulence and coal-plume structure, Section 3.3 presents the apparent LOS temperature and flame characterisation, and Section 3.4 discusses the in-flame O₂ concentration. Finally, Section 3.5 synthesises these observations by comparing each burner configuration with the reference case.

3.1. Apparent coal ignition distance

The apparent ignition position in Fig. 5 is an indirect indicator of coal-particle heating and near-burner mixing. A shorter distance is consistent with faster heating and/or improved access to hot oxidising gas, whereas a longer distance may reflect slower heating, reduced

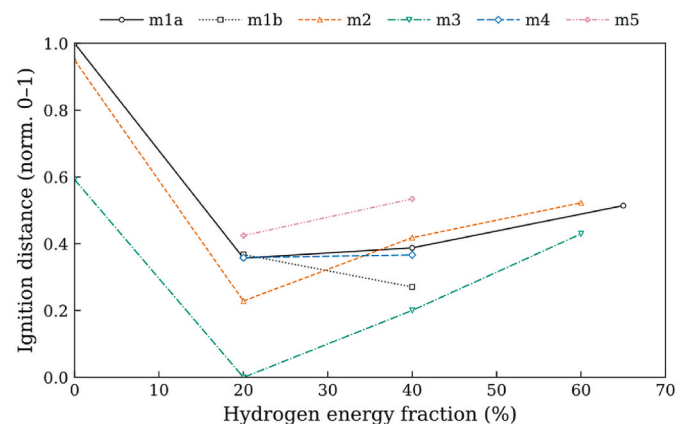


Fig. 5. Normalised apparent coal-ignition position obtained using the semi-automated variance-based method with case-specific threshold and persistence criteria.

sampled O_2 , or changes in particle trajectory and axial velocity. Because the velocity field is not measured, the apparent ignition position is not equivalent to the ignition-delay time of individual particles.

Hydrogen and coal differ strongly in their ignition sequence. At high temperature, hydrogen–air induction times can range from microseconds to milliseconds and the minimum ignition energy is low [10–12, 50]. Coal particles must first heat, evaporate moisture and devolatilise before the released gases and char ignite; reported characteristic times under relevant laboratory conditions extend from milliseconds to fractions of a second and depend on particle size, temperature and O_2 concentration [31–33,48]. During the present campaign, coal type, moisture content and nominal particle-size distribution were held constant. Under these conditions, differences in apparent ignition position are interpreted primarily through changes in thermal history, local oxidising environment and transport, while acknowledging the uncertainty of the optical criterion. Higher temperature shortens the ignition time [33,48] and lower oxygen availability elongates the ignition time [33].

Fig. 5 presents the normalised apparent coal ignition distance and shows that partially substituting coal with hydrogen shifts the detected ignition position upstream. Except for m1b, the earliest apparent coal ignition is observed at 20% hydrogen. This observation is consistent with rapid hydrogen ignition and increased heat transfer to coal particles. At larger hydrogen fractions, the detected position moves downstream compared to 20% hydrogen. This may result from two coupled effects: increased hydrogen momentum changes the near-burner velocity field and particle trajectories, and higher hydrogen flow consumes more local O_2 , causing the coal particles to experience a more fuel-rich environment in the first part of the flame. Due to the change of the velocity field, a downstream shift in ignition distance should not be interpreted directly as a longer ignition time.

To separate the effect of hydrogen substitution from the effect of mixing strategy, the following section compares the ignition behaviour of each mixing strategy against the reference configuration.

At 20% H_2 , m2 gives a shorter apparent ignition position than m1a, consistent with closer hydrogen–coal proximity and stronger early particle heating. At higher hydrogen fractions, m2 shifts slightly downstream relative to m1a. This is compatible with a higher oxygen consumption around the coal jet, which can delay coal ignition spatially, a mechanism that could become significant at high hydrogen content.

The 30° primary-air swirl in m3 produces the earliest detected ignition under pure-coal operation and generally shortens the apparent position at low hydrogen fraction. This is consistent with enhanced entrainment of hot surrounding gas. At 40–60% H_2 , the values converge toward m1a and m2. This convergence is partly a limitation of the variance-threshold method: in m3, some coal particles entrained by the swirl appear to ignite near the burner outlet, but because they do not belong to the main coal jet, their contribution to the intensity variance is weak. The result is a two-stage ignition pattern, with early ignition of entrained particles and later ignition of the main coal jet.

Outward hydrogen injection (m4) gives an apparent ignition position similar to m1a. However, the m4 may not fully capture the expected physics of this configuration. Supplementary Data 1 shows a high-intensity zone close to the burner outlet and extending a few centimetres along the coal jet at both 20% and 40% H_2 , although the zone is weaker at 40% H_2 . A plausible interpretation is that part of the hydrogen is entrained by the primary-air momentum and brought into contact with the coal jet. Coal particles entering this local high-temperature zone emit visible radiation but may not yet be ignited. Thus, even with outward hydrogen injection, some hydrogen still contributes to coal-particle heating, but the effect appears to weaken as hydrogen momentum increases.

Inward hydrogen injection (m5) gives a longer apparent ignition position than m1a. Penetration of hydrogen into the coal plume is likely simultaneously increasing local heating, consuming O_2 and changing particle trajectories and velocity. The spatial ignition position shifts

downstream, although the coal ignition delay time may not necessarily be longer.

The response to the m1b high-momentum nozzle depends on hydrogen fraction. At 20% H_2 , the coal ignition distance remains close to that observed at low hydrogen velocity, suggesting that the higher hydrogen momentum has only a limited influence on the coal jet. At 40% H_2 , however, the increased momentum may enhance the mixing sufficiently to promote earlier coal ignition, which is consistent with the coal-plume images discussed below.

3.2. Turbulence and coal-plume structure

Fig. 6 presents five representative processed frames for selected co-firing cases, used to visualise the near-burner structure of the coal plume. The pure coal case is not included because coal ignition occurs downstream of port P0 and the visible turbulent structures are weak or absent in the observation window. These images show the response of the coal-particle cloud to the surrounding flow field and are interpreted as qualitative indicators of hydrogen-induced mixing, plume deformation, and near-burner coal dispersion. However, they do not provide a direct measurement of turbulence intensity, nor do they visualise the hydrogen flame itself, which emits weakly in the visible range against the furnace background.

For the m1a configuration, increasing the hydrogen fraction clearly modifies the early coal-plume structure. At 20% H_2 , the coal plume remains relatively coherent and elongated, with large-scale shear-layer structures along the plume boundary. These structures resemble a roll-up instability at the interface between the coal jet and the surrounding flow, suggesting moderate hydrogen-induced entrainment while the coal jet core remains preserved. At 40% H_2 , the plume becomes shorter, more compact, and more radially dispersed. The coherent jet-like structure observed at 20% H_2 is partly lost, indicating stronger perturbation of the coal flow. At 60% H_2 , the plume no longer appears as a continuous coal jet, but rather as an intermittent compact cluster of particles near the end of the observation window. This suggests a further increase in near-burner dispersion and unsteadiness as the hydrogen flow rate and associated momentum increase.

The transition from a coherent plume at 20% H_2 to a more fragmented and compact structure at higher hydrogen fractions may be explained by two coupled effects. First, increasing the hydrogen fraction increases the hydrogen jet momentum, which modifies the local momentum balance and enhances shear between the hydrogen, coal, and primary-air streams. Second, the larger hydrogen flame volume may generate stronger local gas expansion and entrainment, increasing the unsteadiness experienced by the coal particles. Together, these effects are believed to promote stronger coal-particle dispersion and a less ordered near-burner flame structure.

The effect of increasing hydrogen velocity from m1a to m1b differs from that of increasing the hydrogen fraction within m1a. At both 20% and 40% H_2 , the m1b cases appear more axially stretched and somewhat more coherent than the corresponding low-velocity cases. This suggests that the higher hydrogen momentum increases jet penetration and shifts part of the hydrogen–coal interaction downstream, rather than immediately producing stronger radial dispersion close to the burner. In other words, high hydrogen velocity may intensify mixing, but not necessarily at the same axial location or in a way that produces a more compact flame at port P0. The changes in mixing and flame structure are consistent with the ignition results. Increasing the hydrogen velocity alone (m1a versus m1b) does not necessarily delay apparent ignition, while increasing the velocity through a higher hydrogen fraction does not necessarily advance it.

At 20% H_2 , outward and inward injection produce visibly different plume responses. The m4 plume has larger wavy edge structures, whereas the m5 plume is straighter and more sharply bounded, with smaller but visually more intense edge perturbations. This suggests that the two configurations produce different turbulence structures: m4 is

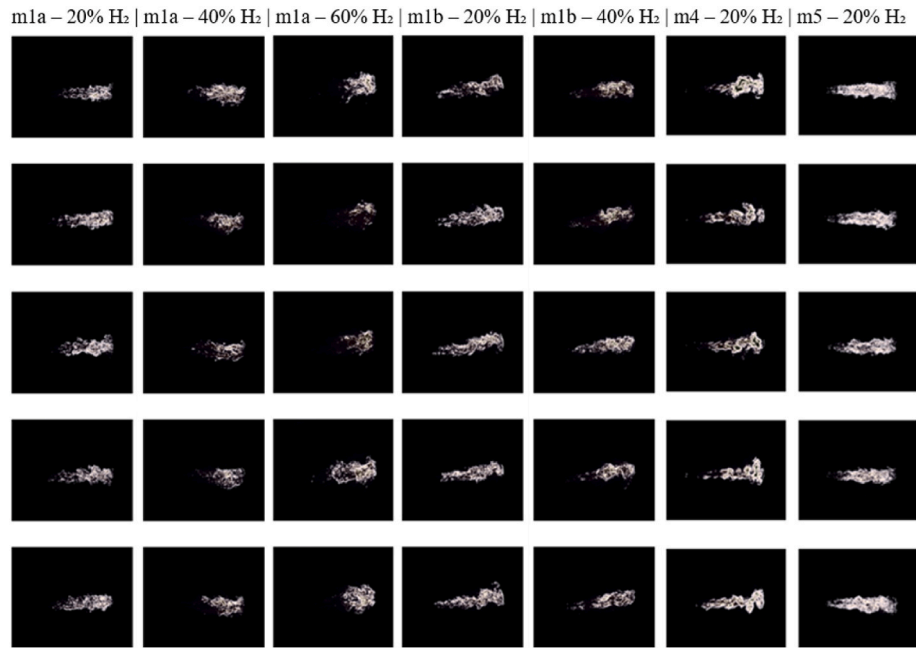


Fig. 6. Representative processed near-burner coal-plume frames for selected co-firing cases.

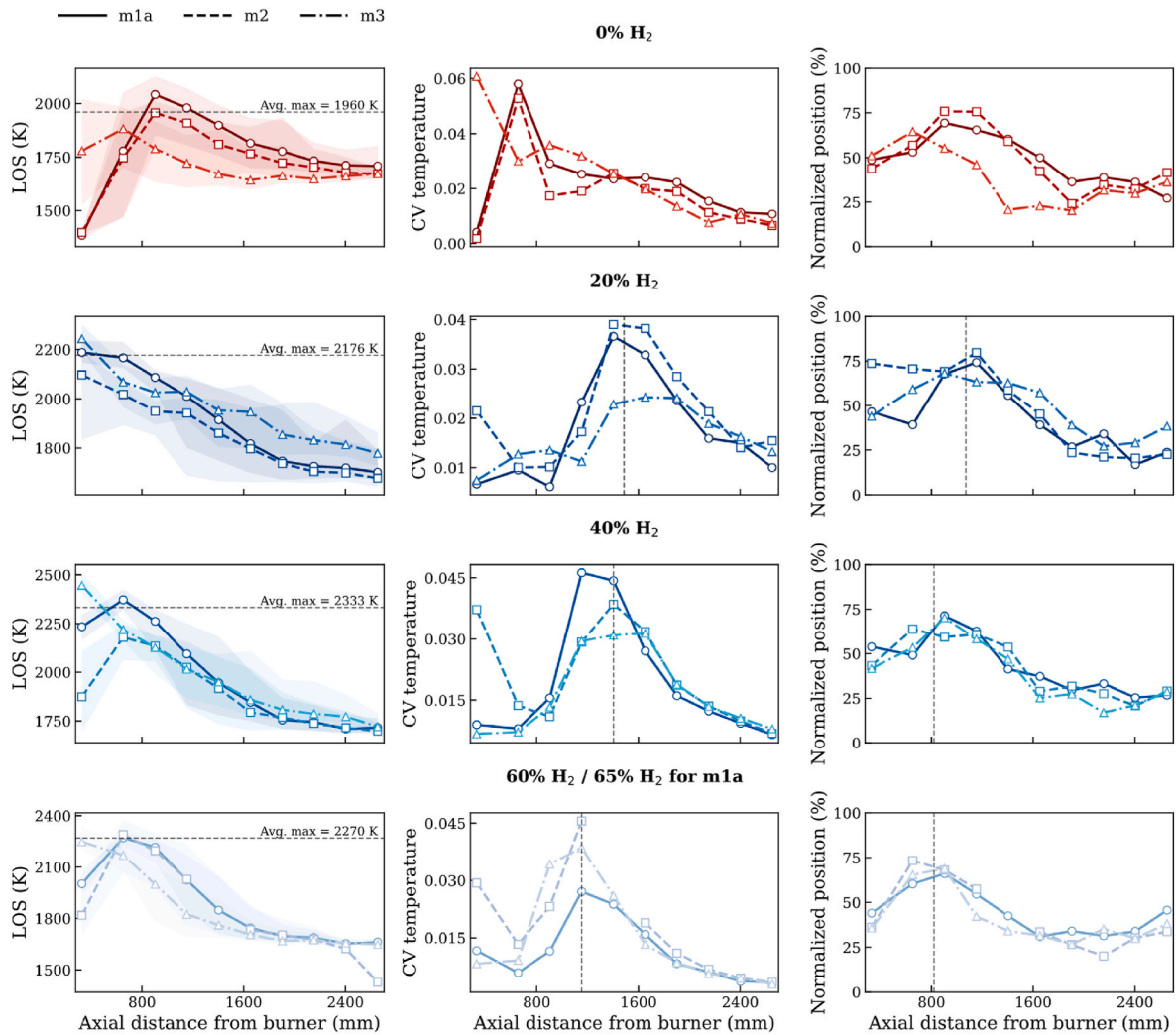


Fig. 7. LOS radiative-temperature indicators for m1a, m2 and m3 at 0%, 20%, 40% and 60–65% H_2 .

associated with larger-scale plume deformation, while m5 appears to exhibit finer-scale and more locally intense mixing at the plume boundary.

Overall, the visualisation indicates that the near-burner coal plume is sensitive to hydrogen fraction, hydrogen velocity, and injection direction. Increasing hydrogen velocity with higher hydrogen fraction tends to reduce plume coherence and increase dispersion, while higher hydrogen velocity at the same hydrogen fraction can shift the interaction zone downstream and produce a more penetrating plume. Inward and outward hydrogen injection generate different mixing structures, suggesting that hydrogen placement relative to the coal jet is an important control parameter for coal ignition, flame stability, and NO_x formation.

3.3. Apparent LOS temperature and flame characterisation

The LOS series are described by the mean and min–max range, the coefficient of variation (CV), and the normalised position of the mean within the min–max interval. The data are organised as follows: the main low-velocity families (m1a, m2 and m3) are presented first (Fig. 7), followed by the effect of hydrogen velocity (m1a versus m1b; Fig. 8) and finally the comparison between inward and outward hydrogen injection (Fig. 9).

The LOS and CV patterns are visually distinct between pure coal flames (shown in shades of red) and co-firing cases (shown in shades of blue). In pure coal, the peak temperatures are in P3 and, with the exception of mixing configuration m3 that has the peak temperature in P2, ignition has not occurred at the first measurement location. At 20% H_2 , the peak is located at P1. At 40% H_2 , the peaks are mostly located at P2, except for m3, which remains earlier at P1. Finally, at 60% H_2 , a similar trend to that at 40% H_2 is observed.

The dotted value in Fig. 7 is the average of the maximum measured LOS temperature across configurations at each hydrogen fraction. Because the true axial maximum may lie between ports and because particle loading affects the signal, it is used only as a comparative indicator. It increases from approximately 1980 K for pure coal to 2258 K at 40% H_2 and remains similar at 60% H_2 . This trend may indicate a significantly higher gas-temperature background experienced by the particles, although it cannot by itself quantify the increase in local hydrogen-flame gas temperature.

Concerning the CV, the sharp peak in pure coal cases marks the ignition location, as described in a previous study [14], whereas the broader features seen in co-firing correspond to the flame tail. Notably, the flame tail of pure coal is not discernible from the CV signal. This behaviour may be explained by two, not mutually exclusive, possibilities: (1) the pure coal flame is less stable throughout both the flame body and flame tail, producing relatively high CV values over the full measured length and making a distinct flame-tail peak less apparent than in the co-firing cases; and (2) the CV peak associated with the flame tail may occur downstream of the last measurement port, since the visible coal flame is substantially longer under pure coal operation. The averaged distance at which the CV peak corresponding to the flame tail is measured in co-firing shows a clear shift closer to the burner with

increasing hydrogen fraction, consistent with previous findings [14]. Similarly, the maximum of the normalised position, which indicates the densest part of the flame, moves progressively toward the burner as the hydrogen fraction increases.

m1a vs m2 — Relative to m1a, m2 gives a lower LOS temperature beyond P2 under pure-coal operation and through much of the co-firing series. This may be attributed to the hydrogen injection ports being purged with N_2 during non-hydrogen operation and to the greater distance from the primary air stream. Together, they could reduce local oxygen availability and, in turn, slightly lower the temperature. This reduction in LOS temperature near the burner appears consistent across co-firing cases. The normalised position of the average remains similar between cases, indicating no substantial difference in flame density. Regarding the CV, the m2 configuration yields the highest values at the first measurement location P0 for all co-firing cases. This may result from both the consumption of local O_2 by hydrogen and the entrainment of coal particles by the hydrogen jet momentum, leading to a less stable ignition zone and a slight downstream delay of ignition. This interpretation is supported at hydrogen fractions of 40% and 60%. At 20% H_2 , however, ignition occurs substantially earlier than in m1a, suggesting that additional mechanisms become more influential. At this lower hydrogen fraction, the closer interaction between the hydrogen and coal jets may promote more rapid ignition. The particularly high coefficient of variation observed at P0 for m2 may also reflect lower local oxygen and different velocity fields, as well as turbulence generated by the close proximity of the hydrogen and coal streams.

m1a vs. m3 — The m3 configuration, characterised by its strong mixing, consistently produces higher LOS temperatures at the first port and exhibits a temperature profile that decreases monotonically downstream, except in the pure coal case where the peak occurs at Port 1. It yields the highest temperature at Port 0 across all cases, a direct consequence of the enhanced mixing. For pure coal, the normalised position indicates a less dense flame beyond Port 2, consistent with earlier ignition and improved mixing.

Effect of hydrogen velocity on coal-particle flame behaviour

The influence of hydrogen velocity on coal combustion is investigated in Fig. 8 by comparing the reference configuration m1a with the high-velocity configuration m1b.

m1a vs m1b — In the baseline configuration, hydrogen is already injected at relatively high theoretical velocities, reaching 100 m/s and 200 m/s for 20% and 40% H_2 , respectively. Increasing the theoretical velocity to 1000 m/s and 2000 m/s in version b is expected to modify turbulence and mixing significantly. The LOS temperature is consistently lower at high hydrogen velocity for both 20% and 40% H_2 , with reductions on the order of 200 K. The flame tail does not appear strongly affected at 40% H_2 , but at 20% H_2 it shifts upstream. This trend is also weakly visible in the normalised position, which indicates an earlier dense flame zone compared with the lower-velocity case. Although hydrogen velocity affects coal combustion, these changes are smaller than the differences observed between families at the same hydrogen velocity.

Effect of inward versus outward injection - The outward and inward hydrogen injection configurations give broadly similar LOS

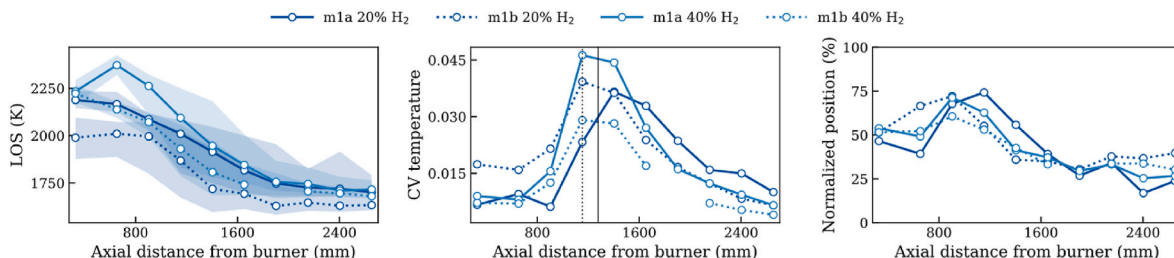


Fig. 8. Effect of hydrogen velocity (m1a vs m1b) on LOS radiative-temperature indicators at 20% and 40% H_2 .

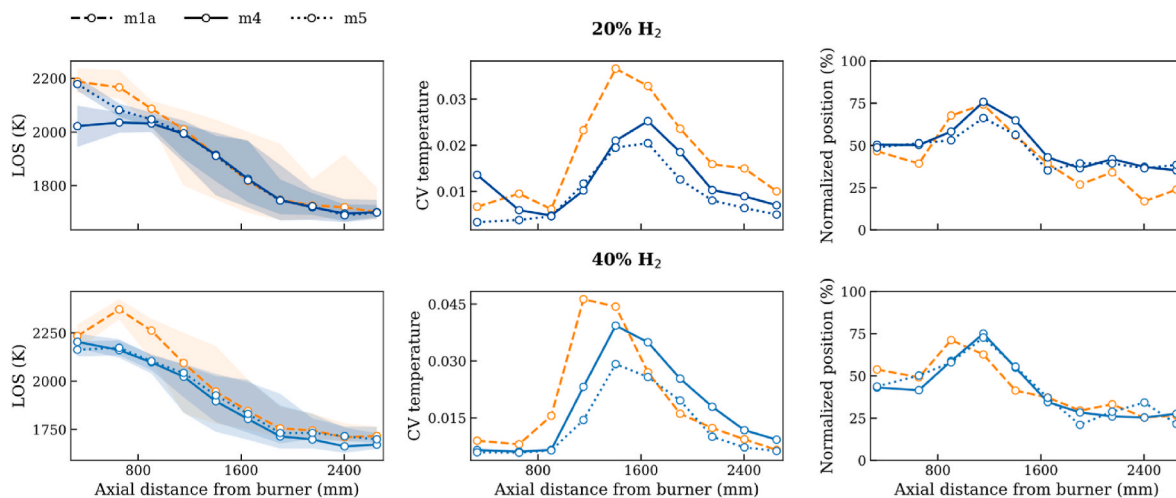


Fig. 9. LOS radiative-temperature indicators for outward and inward hydrogen injection at 20% and 40% H_2 .

temperature profiles. Only m5 shows notably higher LOS temperature at P0 and P1 for 20% H_2 . In this region, the CV is higher for m4, indicating a more unstable or spatially delayed ignition zone. At 40% H_2 , the CV and normalised-position profiles are similar, with the main observable difference being a lower CV for m5. This suggests a more homogeneous LOS temperature series, plausibly caused by stronger local mixing.

3.4. In-flame O_2 concentration

The in-flame O_2 maps were acquired at 510 kW. The outlet NO_x emissions, expressed in mg/MJ, are very similar to those measured at 580 kW. Although the global air-to-fuel ratio was maintained, it is acknowledged that changes in load may affect mixing, flame position, heat loss and residence time. The maps are therefore presented only as qualitative evidence of the local oxidising environment sampled under a related, but not identical, operating condition.

Fig. 10 interpolates between discrete sampling positions for visual clarity; the coloured fields should not be read as high-resolution

measurements between the points. The near-burner sampling is particularly uncertain because the probe disturbs the flow and the temperature field, consequently, the first measurement location is already downstream of the apparent coal-ignition position.

Within these limitations, the measured O_2 concentration in the coal-plume region decreases as the hydrogen fraction increases. This trend is consistent with upstream hydrogen oxidation consuming part of the available oxygen that may contribute to the downstream shift in apparent ignition at higher hydrogen fractions.

3.5. Summary of outlet NO_x trends and their correlation with burner parameters

m1a - Reference configuration. The reference case serves as the baseline against which all subsequent mixing strategies are evaluated.

m1b - Increasing the hydrogen jet velocity relative to the reference case m1a leads to a clear increase in outlet NO_x within the tested range. This effect was measured only at 20–40% hydrogen substitution in the present study, but it is consistent with previous observations in the HICK unit [13,15], where higher H_2 injection velocity at 30% H_2 increased NO_x . The m1b configuration appears to reduce the benefit of hydrogen-assisted coal ignition by lowering the inferred coal-particle heating effect, particularly at 40% H_2 , as seen by the significant decrease of the LOS temperature at both 20% and 40% H_2 . This may then promote higher fuel NO_x formation. For thermal NO_x , two competing effects are likely. At low hydrogen fraction, reduced heat transfer from the hydrogen flame to the coal particles may increase the hydrogen-flame temperature and promote thermal NO_x formation, while the higher hydrogen velocity may shorten the high-temperature residence time [20] and partially limit thermal NO_x formation. However, at high hydrogen fraction, thermal NO_x is expected to become increasingly important, reducing the significance of the fuel NO_x . In this case, the residence-time effect in the hydrogen flame may become more relevant. Under such conditions, elevated hydrogen velocity could potentially reduce the overall NO_x level.

m2 - Reduced oxygen availability between fuel streams. Restricting the oxygen supply in the region between the hydrogen and coal jets, combined with a closer spatial interaction between the two fuels, yields a modest but consistent reduction in outlet NO_x during co-firing. Notably, in the pure coal baseline, increasing the primary air flow separation distance does not measurably alter NO_x .

m3 - Swirl-enhanced mixing. The introduction of swirl produces the strongest fuel-air mixing among the tested configurations. At low hydrogen fractions (0–20% H_2), this enhanced mixing correlates with lower NO_x , consistent with shorter apparent ignition distance and more

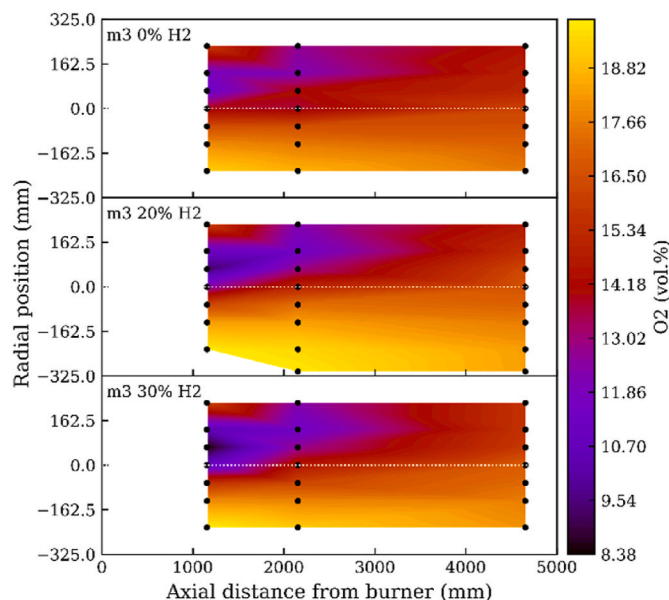


Fig. 10. Sampled in-flame O_2 at 510 kW for m3 at 0%, 20% and 30% H_2 ; colours are linearly interpolated between measurement points. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

rapid devolatilisation. At higher hydrogen fractions, however, this benefit diminishes and appears to reverse: intensified mixing likely accelerates hydrogen combustion and increases peak temperatures, thereby promoting thermal NO_x formation through the Zeldovich mechanism. The m3 configuration is therefore favourable for low NO_x at modest hydrogen substitution, but the trend appears to invert at higher hydrogen fractions.

m4 - Outward hydrogen injection. The outward-directed hydrogen injection is the main exception to the low- H_2 NO_x reduction trend: NO_x at 20% hydrogen substitution is substantially higher than at 40%. This behaviour can be interpreted as a dual penalty at low substitution. First, the hydrogen flame is not sufficiently coupled to the coal particles to enhance devolatilisation, which limits the potential reduction in fuel NO_x formation. Second, the weaker cooling of the hydrogen reaction zone by coal particles may allow higher local flame temperatures to develop. A possible additional factor is the injection direction: the hydrogen jet points toward the hot secondary air. This hotter background may increase the base level of thermal NO_x formation. At 40% substitution, the fuel NO_x contribution decreases with the coal fraction, while thermal NO_x likely becomes increasingly important, giving NO_x levels closer to the reference case. Interestingly, at a 40% hydrogen fraction, the hydrogen injection strategy appears to have little influence on NO_x emissions, except in the high velocity m1b case.

m5 - Inward hydrogen injection. Directing the hydrogen jets inward toward the coal stream produces only a marginal NO_x reduction at 20% and 40% H_2 . Outlet NO_x is also slightly higher than for m2, despite the nominally closer fuel interaction. This suggests that inward injection provides limited additional benefit compared with straight hydrogen injection under the present conditions.

4. Conclusion

This pilot-scale study investigated how hydrogen-energy fraction and burner-mixing configuration affect combustion behaviour and NO_x emissions during hydrogen-coal co-firing under conditions representative of rotary-kiln iron-ore pellet induration. Five burner families, comprising six configurations, were compared by varying fuel placement, hydrogen-injection direction, primary-air swirl and hydrogen-jet momentum.

The results show a non-monotonic NO_x response to increasing hydrogen-energy fraction across the burner configurations. Compared with pure-coal operation for m1a, m2 and m3, 20% hydrogen substitution reduces outlet NO_x by 15–24%, whereas at 40% substitution the change ranges from a 5% reduction to a 31% increase, and at 60% substitution outlet NO_x increases by 42–97%. Low hydrogen substitution is generally accompanied by apparent coal ignition closer to the burner, increased coal-particle heating and a shorter coal flame compared with pure coal. However, the response depends on burner configuration. Primary-air swirl improves ignition and reduces NO_x at low hydrogen fractions but becomes less favourable as the hydrogen-energy fraction increases. Outward hydrogen injection produces particularly high NO_x emissions at low substitution, while inward injection shows little effect. Increasing hydrogen-jet momentum increases NO_x at both 20% and 40% substitution.

The measurements do not directly resolve individual chemical pathways; however, based on the present understanding and the consistency among the experimental observations, the results are interpreted mainly in terms of the changing balance between fuel NO_x and thermal NO_x formation as the hydrogen fraction increases. At low hydrogen substitution, the coal-particle heating rate is higher, and earlier devolatilisation may promote the release of fuel-bound nitrogen under locally oxygen-lean conditions, thereby reducing its conversion to NO_x . At higher substitution, the reduction in coal-nitrogen input and its conversion to NO_x is outweighed by conditions that favour thermal NO_x formation. From a retrofit perspective, the NO_x results favour straight hydrogen injection at lower velocity, as neither inward nor outward

injection provided a clear and consistent advantage, while increasing the velocity consistently increased NO_x within the tested substitution range.

CRedit authorship contribution statement

Samuel Colin: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christian Fredriksson:** Writing – review & editing, Validation, Supervision, Resources, Methodology. **Fredrik Normann:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fredrik Normann reports financial support was provided by Swedish Energy Agency. Fredrik Normann reports financial support, administrative support, and travel were provided by Luossavaara-Kiirunavaara AB. Fredrik Normann reports financial support was provided by European Union. Samuel Colin reports a relationship with Luossavaara-Kiirunavaara AB that includes: employment. Christian Fredriksson reports a relationship with Luossavaara-Kiirunavaara AB that includes: employment. Fredrik Normann reports a relationship with Luossavaara-Kiirunavaara AB that includes: employment. Fredrik Normann reports a relationship with Chalmers University of Technology that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2026.157982>.

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