

Hydrogen staging effects on flame stability and emissions in a fuel-flexible combustor

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ABSTRACT

This study investigates the impact of fuel split between Jet-A1 and H₂ in a novel low-swirl combustor designed for low NO_x emissions and flashback resistance. The combustor combines airblast atomization for Jet-A1 with H₂ injection in a jet-in-crossflow configuration. Full and staged-injection strategies were examined experimentally at atmospheric pressure and elevated air inlet temperatures. The flame remained predominantly lifted up to 100% H₂ in full injection. Fuel staging enhances stability, extending the pure-H₂ lean blowout limit by a factor of 2.0 at 673 K and 1.6 at 473 K (air inlet temperature) compared with full-injection operation. NO_x emissions remain below 15 ppm, with full injection advantageous at full-load and staged injection at part-load. CO emissions decrease substantially even with a modest 15% H₂. Non-reactive simulations complement the experiments, providing insight into flow and mixing fields for both injection strategies. These findings demonstrate that full and staged injection jointly enable low NO_x emission and improved stability limits.

1. Introduction

Hydrogen (H₂) is increasingly considered a strong candidate for future aviation fuels due to its high specific energy and potential to enable carbon-free flight [1,2]. However, the adoption of H₂ in aviation faces major hurdles, including extensive aircraft modifications to accommodate H₂ and its larger required aircraft tank sizes, as well as the high costs of revamping ground infrastructure [3]. As a result, large-scale deployment of H₂ in aviation is unlikely in the near future [4,5]. To facilitate the transition to cleaner aviation fuels while avoiding flight range limitations from restricted H₂ fuel storage capacity, fuel-flexible combustors offer a promising intermediate solution. Fuel-flexible systems capable of operating on carbon-based fuels, pure H₂, or their mixtures, have gained considerable attention in both experimental [6–11] and numerical studies [12–14].

Despite this potential, the stark differences in combustion properties between H₂ and conventional fuels pose major challenges when used within the same combustor design. In conventional systems, a common strategy to reduce NO_x emissions is to promote a high degree of premixing between fuel and oxidizer, thereby maintaining a uniform temperature distribution [15]. The length of the premixing section is typically limited by the relatively short auto-ignition delay

time of liquid fuels under aero-engine conditions. The much higher flame speed of H₂ compared to Jet-A1 increases the risk of flashback and thermoacoustic instabilities [16]. To mitigate these risks, partially premixed injection strategies are commonly employed [17], in which H₂ is introduced as far downstream as possible before the combustion chamber to allow sufficient mixing while minimizing flashback risk. One prominent implementation of this approach is micromixing via jet-in-crossflow injection, which generates multiple miniaturized fuel jets that enhance fuel-air mixing, promote micro flames, and reduce NO_x emissions [18,19]. This configuration also provides the operational flexibility required to enable different staging, dilution, and dual-fuel approaches in advanced gas turbines [19].

Swirl-stabilized combustion remains the most effective approach for anchoring H₂ flame in the combustor away from solid components [20]. High-swirl flames anchor near the burner exit within the inner recirculation zone but are prone to flashback [21]. A higher lift-off height can be achieved with a low-swirl flame, allowing greater premixing upstream of the reaction zone and reducing the risk of flashback [22, 23]. Flashback resistance can be further enhanced by introducing a non-swirling axial airflow along the centerline of swirl generators, which reduces the velocity deficit at the core and shifts the stagnation

Abbreviations: LBO, Lean blowout; LOH, Lift-off height; ORZ, Outer recirculation zone.

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point downstream, effectively creating a plug-flow-like behavior at the burner outlet [24,25]. More recently, Link et al. [26] employed a non-rotating axial air jet in CH_4/H_2 fuel blends, successfully reducing the flashback risk associated with high H_2 content.

Extensive research has investigated the performance of fuel-flexible aero-engine combustors operating with aviation fuels blended with H_2 [7–9,27–29]. These studies have shown that H_2 addition substantially influences flame stabilization, combustion efficiency, and pollutant emissions. In particular, hydrogen enrichment modifies the flame structure, resulting in reduced flame length and lift-off height and changes in the overall flame topology [7,9,29]. Furthermore, H_2 addition to Jet-A1 spray flames can significantly alter exhaust emissions, with even modest hydrogen enrichment reducing CO emissions by up to 30%–50% [7,28].

Our previous work established the dual-fuel combustor architecture investigated in the present study. In Singh et al. [10], we introduced a low-swirl combustor utilizing airblast atomization for Jet-A1 with radial H_2 jet-in-crossflow injection and demonstrated flashback-resistant operation across the investigated fuel-flexibility range from pure Jet-A1 to pure H_2 under atmospheric conditions. This fuel-flexible combustor was subsequently evaluated with SAF (Sustainable Aviation Fuel)/Jet-A1 blends under engine-relevant operating conditions, demonstrating that H_2 addition can enhance flame stability while reducing pollutant emissions [30]. In both studies, however, the combustor was optimized for H_2 fuel splits up to 30% under full-load operation. For higher H_2 fuel splits, we reported a substantial rise in NO_x emissions, up to 30 ppm, together with flame anchoring close to the burner exit. These observations highlight the need for injection strategies that can simultaneously improve flame stability and reduce pollutant emissions up to 100% H_2 operation while maintaining robust operation across both full-load and part-load conditions.

While much of the existing work has focused on full-load operation, extending these findings to off-design conditions remains essential, as part-load operation introduces additional stabilization challenges. In particular, reduced turbulence intensity and weakened recirculation zones can challenge flame anchoring. This increases the likelihood of intermittent extinction and re-ignition events that compromise both efficiency and operational stability [31,32]. H_2 fuel staging has proven to be an effective strategy for stabilizing combustion under such off-design conditions [33]. Jaeschke et al. [34] demonstrated that fuel staging significantly affects the velocity and equivalence ratio distributions near the burner outlet, which can influence the flashback propensity of H_2 -enriched flames. Similarly, Liu et al. [35] report a significant extension of the lean blowout limit through the implementation of a fuel staging strategy in a novel multi-nozzle array combustor, highlighting its potential to enhance operational flexibility and stability.

However, the physical implementation and operating concept of staging considered in these studies differ from the present dual-fuel architecture. Conventional staged combustors commonly employ physically separated combustion zones and/or dedicated pilot/main fuel circuits. In contrast, the present architecture uses radial H_2 jet-in-crossflow injectors integrated within the burner nozzle, located at the inner and outer sides of the prefilmer conventionally used for liquid fuel atomization, promoting a high degree of premixing for both fuels. Staging of the H_2 injection then modifies the spatial distribution of H_2 addition without introducing a separate pilot flame or changing the central liquid-fuel injection system or overall combustor geometry. This allows the H_2 injection strategy to be optimized independently for full-load and part-load operation, while avoiding the additional fuel circuits and control complexity typically required by pilot-based staging strategies. To the best of the authors' knowledge, a systematic comparison of full and staged radial H_2 jet-in-crossflow injection in an integrated low-swirl dual-fuel combustor spanning the complete fuel-flexibility range (0%–100% H_2) has not yet been reported. In particular, no study has systematically identified the most suitable injection strategy for

representative full-load and part-load aero-engine operating conditions based on combustor stability and pollutant emissions.

Building on this validated architecture [10,30] and addressing the gap identified above, the present study systematically examines how the H_2 injection strategy, full versus staged, within an unchanged nozzle and combustor geometry, governs flame stability and pollutant emissions. Specifically, the present study: (i) directly compares full and staged radial H_2 jet-in-crossflow injection under identical operating conditions; (ii) evaluates both strategies across the complete fuel-flexibility range from 0%–100% H_2 ; (iii) examines the influence of the injection strategy on flame morphology, lift-off height (LOH), lean blowout (LBO) limits, and pollutant emissions under representative full-load and part-load operating conditions; and (iv) uses complementary non-reactive numerical simulations to identify the flow and mixing fields responsible for the observed differences between the two injection strategies.

2. Experimental details

2.1. Experimental setup and operating conditions

The experiments have been conducted in a fuel-flexible combustor shown in Fig. 1(a). This combustor is designed to target low-emission operation with Jet-A1 and H_2 fuels. The setup consists of three main sections: plenum, combustion chamber, and exhaust section. Air supplied by the compressor is preheated to temperatures of up to 673 K before entering the plenum chamber, where a flow straightener is installed to reduce transverse velocity fluctuations. The 460 mm long combustion chamber has a square cross-section of $100 \times 100 \text{ mm}^2$ and serves as the test section for the Jet-A1/ H_2 flame investigated in this study. Downstream, the combustion products are discharged through an exhaust section open to the ambient environment.

Fig. 1(b) illustrates a detailed representation of the burner examined in this study. The dual-fuel nozzle, previously characterized for Jet-A1/ H_2 operation in [10], features 12 H_2 injectors. In the present study, two configurations are employed: (i) a nozzle with 24 H_2 injectors on the outer side and 8 H_2 injectors on the inner side of the prefilmer (Fig. 1c), and (ii) the previously characterized nozzle with 12 H_2 injectors on the outer side of the prefilmer only (Fig. 1d). The nozzle comprises two main air streams (primary and secondary vanes) which are separated by a prefilmer lip. An additional non-swirling air stream is supplied through the tertiary vanes to avoid flashback in the vicinity of the nozzle centerline. Swirl is introduced exclusively through the secondary vanes, which comprise eight tangentially angled vanes with trailing edges oriented at 45° relative to the nozzle axis, corresponding to a swirl number of 0.76. In contrast, the primary and tertiary vane stages feature zero trailing-edge angle and comprise eight and twelve straight vanes, respectively, ensuring zero swirl generation. The burner exhibits an overall swirl number of approximately 0.1, evaluated following [36] by accounting for the combined axial and angular momentum fluxes from all three vane passages and normalizing by the nozzle radius.

Fuels (Jet-A1 and H_2) are delivered to the burner through a water-cooled fuel lance, which maintains approximately ambient fuel temperature and thereby mitigates the risk of Jet-A1 coking (Fig. 1b). The liquid fuel is injected through a centrally mounted pressure atomizer, characterized by a nominal spray cone angle of 60° , an orifice diameter of 0.35 mm, and a flow number of 0.74. Atomization is achieved through a two-stage airblast process. In the first stage, the pressure-swirl atomizer generates a hollow-cone spray that impinges on the prefilmer, where it develops into a thin liquid film. In the later stage, this film is disintegrated into fine droplets by shear stresses in the mixing layer formed between the co-flowing air streams at the prefilmer exit. In the full-injection configuration, H_2 is supplied through 24 circumferentially distributed injectors (0.35 mm) on the outer prefilmer and 8 injectors (0.4 mm) on the inner prefilmer. To investigate staged-injection, this configuration was applied with only 50% of the outer

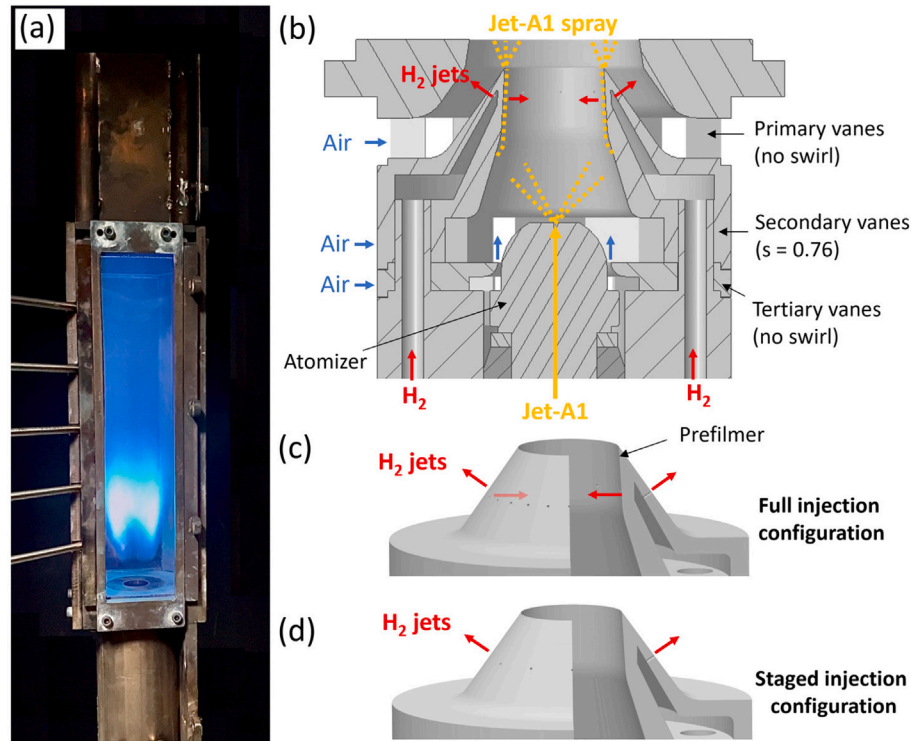


Fig. 1. (a) Experimental fuel-flexible combustion facility at KIT, Germany. Schematics of (b) the fuel nozzle cross-section, (c) full-injection configuration (24 outer and 8 inner H_2 injectors), and (d) staged-injection configuration (12 outer H_2 injectors).

Table 1

Experimental conditions for full- and staged-injection cases at relative air pressure drop of $\Delta p/P = 3\%$.

OC #	T_{air} (K)	$\dot{m}_{Jet-A1}$ (g/s)	$\dot{m}_{H_2}$ (g/s)	$\dot{m}_{air}$ (g/s)	ϕ (-)	P (kW)	P_{sp} (MJ/kg _{air})	U_b (m/s)
1	473	0–0.86	0–0.31	25.3	0.5–0.42	37.1	1.46	75.8
	473	0–0.69	0–0.25	25.3	0.4–0.33	29.7	1.17	75.8
2	573	0–0.78	0–0.28	23.0	0.5–0.42	33.8	1.46	83.5
	573	0–0.63	0–0.22	23.0	0.4–0.33	26.9	1.17	83.5
3	673	0–0.72	0–0.26	21.2	0.5–0.42	31.1	1.46	90.5
	673	0–0.58	0–0.20	21.2	0.4–0.33	24.9	1.17	90.5

injection holes active, arranged alternately around the circumference, with no injection from the inner prefilmer. This arrangement redistributes the H_2 fuel flow among fewer active injectors within the outer prefilmer, increasing the jet-in-cross flow momentum flux ratio (J) and, accordingly, the radial H_2 penetration, while preserving the combustor geometry and overall injection concept. Here, J is defined as the ratio between the hydrogen jet and free-stream air momentum fluxes: $J = \rho_{H_2} u_{H_2}^2 / \rho_{air} u_{air}^2$, where ρ and u denote the density and velocity of the respective flows. Experiments with full H_2 injection active were performed from 15% to 100% H_2 to avoid potential coking in the H_2 injectors on the inner side of the prefilmer, whereas for staged-injection, experiments were conducted from pure Jet-A1 (0% H_2) to 100% H_2 .

Jet-A1 flow rate ($\dot{m}_{Jet-A1}$) was determined using Coriolis-based measurement instrumentation, with a stated uncertainty of 0.1% (Krohne OPTIMASS 3400c). H_2 mass flow rate ($\dot{m}_{H_2}$) was regulated via a thermal mass flow controller, providing an accuracy of 0.1% (Bronkhorst EL-Flow). Air flow rate ($\dot{m}_{air}$) measurements were carried out using a thermal flow meter, having uncertainty of 0.5% (Bronkhorst In-Flow).

The H_2 fuel split is defined at fixed thermal power (P) and $\dot{m}_{air}$ as: $\%H_2 = \dot{m}_{H_2} LHV_{H_2} / (\dot{m}_{H_2} LHV_{H_2} + \dot{m}_{Jet-A1} LHV_{Jet-A1})$ [27]. Here, $LHV_{Jet-A1} = 43.1$ MJ/kg and $LHV_{H_2} = 119.97$ MJ/kg denote the lower

heating values of Jet-A1 and H_2 , respectively. The global equivalence ratio for fuel-flexible operation is expressed as: $\phi = [\dot{m}_{Jet-A1} / \dot{m}_{air} \cdot (1 + \alpha)] / F^{\circ}_{Blend}$, where $\alpha = \dot{m}_{H_2} / \dot{m}_{Jet-A1}$. The fuel–air ratio of the blended fuel under stoichiometric conditions is defined by: $F^{\circ}_{Blend} = (1 + \alpha) / (1 / F^{\circ}_{Jet-A1} + \alpha / F^{\circ}_{H_2})$, with $F^{\circ}_{Jet-A1} = 0.068$ and $F^{\circ}_{H_2} = 0.029$ [7]. Table 1 summarizes the complete set of experimental conditions, including the fuel and air mass flow rates ($\dot{m}_{Jet-A1}$, $\dot{m}_{H_2}$, $\dot{m}_{air}$), air preheating temperature (T_{air}), and corresponding thermal power (P) and specific thermal power (P_{sp}).

2.2. Measurement techniques

High-speed OH^* chemiluminescence imaging was used to characterize the combustion process. The imaging system comprised a CMOS camera (Vision Research Phantom v1212) integrated with an intensified relay optics unit (LaVision HS-IRO). Optical access was provided through a UV lens (Cercor, focal length 100 mm, f/2.8), combined with bandpass filtering targeted at the OH^* emission band (Chroma, transmission >80% over 300–340 nm with 10 nm FWHM). A total of 5000 instantaneous frames were recorded at a sampling frequency of 1 kHz, with a spatial resolution of 1280×800 pixels. The intensifier settings were optimized to accommodate variations in emission intensity across operating conditions, with the gain set to 58% and the gate time fixed at 30 μ s. Based on a field of view of 260 mm $\times$ 160 mm, the resulting spatial resolution was approximately 203.1 μ m per pixel in the horizontal direction and 200 μ m per pixel in the vertical direction.

The lift-off height (LOH) is defined as the distance between the fuel nozzle exit and the horizontal line upstream of which 5% of the total OH^* chemiluminescence intensity is detected. The LOH is extracted directly from the raw line-of-sight OH^* chemiluminescence images. This relatively low threshold was chosen to minimize the impact of different OH^* intensities from the Jet-A1 and H_2 -rich flame, enabling a consistent LOH definition across the full fuel-flexibility range. The mean LOH and its standard deviation are computed from 2000 images,

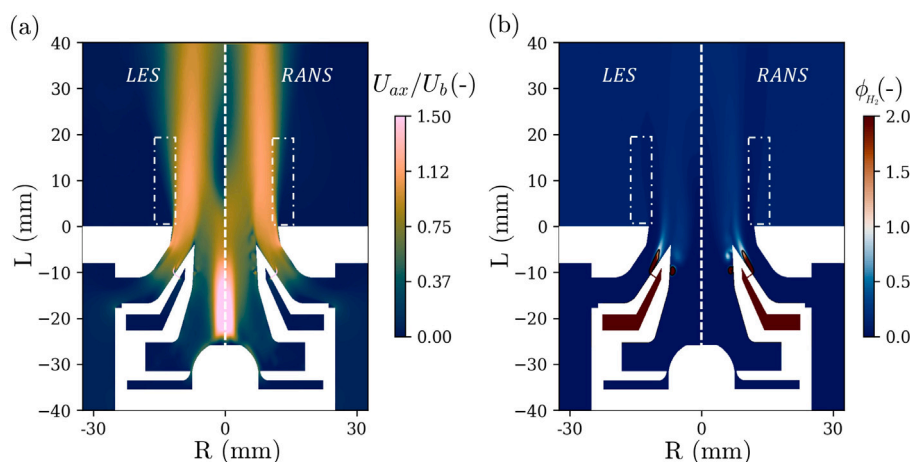


Fig. 2. Comparison of LES and RANS contours of (a) normalized axial velocity (U_{ax}/U_b) and (b) H_2 equivalence ratio (ϕ_{H_2}) with the $\phi_{H_2} = 1$ iso-line superimposed in black, for the 30% H_2 case under the full-injection configuration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for which the statistics were found to be converged at each operating condition, and are reported in Fig. 8(b,d) as a function of H_2 fuel split.

For exhaust gas measurements, a water-cooled sampling probe was positioned 440 mm above the combustor nozzle exit. The collected exhaust gas was transported through a heated line to prevent condensation, then passed through a dehydrator before entering the analysis modules. An Advanced Optima exhaust gas analysis system was used to measure O_2 using ABB Magnos 206 as well as CO and CO_2 using ABB Uras 26. O_2 was operated on its 0–25 vol.% range (detection limit: 0.05 vol.% and repeatability: ± 0.05 vol.%). CO was operated on its 0–600 ppm range (detection limit: 2.4 ppm and repeatability: ± 3 ppm). NO_x emissions (NO and NO_2) were quantified using an Eco Physics CLD 700 EL chemiluminescence analyzer. NO_x was operated in the 0–100 ppm (detection limit: 0.1 ppm and repeatability: ± 0.5 ppm). The expanded uncertainty in Figs. 8 and 9 was obtained by combining, in quadrature, the standard error of the steady-state readings with a relative systematic uncertainty accounting for the analyzer and the O_2 normalization, multiplied by a coverage factor of 2 (approximately 95% confidence).

The lean blowout (LBO) limit was determined by progressively reducing ϕ at each H_2 fuel split until flame extinction. The pressure drop across the burner ($\Delta p/P$) was maintained at 3% throughout the experiments, corresponding to a constant bulk airflow rate (Table 1). The $\dot{m}_{H_2}$ was held constant while $\dot{m}_{jet-A1}$, and hence ϕ , was reduced manually in increments of $\Delta \dot{m}_{jet-A1} = 0.05$ g/s, with a steady-state dwell time of approximately 30 s at each step. Flame extinction was identified using two independent criteria: (i) loss of the UV flame-detector (Flamონიტек KLC 10/230, BST Solutions) signal and (ii) a combustor temperature below 773 K. Either criterion triggered automatic shutoff of both fuel supplies, and the $\dot{m}_{jet-A1}$ immediately prior to extinction was recorded as the LBO condition.

3. Results and discussion

The analysis begins with numerically simulated flow and mixing fields, highlighting the role of H_2 injection in flame stabilization through its influence on flow topology and mixing. This is followed by an examination of experimentally obtained flame shapes and morphologies under varying air inlet temperatures (T_{air}), specific thermal powers (P_{sp}), and H_2 injection configurations. Later, the study quantifies the extension of LBO limits with H_2 staging and evaluates the effect of H_2 addition on NO_x and CO emissions for both injection strategies.

3.1. Flow field analysis

The flow structure and mixing behavior in the non-reacting cases are examined using both Large Eddy Simulation (LES) and Reynolds-Averaged Navier–Stokes (RANS) methods. An initial LES is performed for the full-injection configuration at operating condition OC 3 (Table 1), with the H_2 mass flow rate $\dot{m}_{H_2}$ set to 30% of its maximum value (0.26 g/s) for the nominal specific thermal power ($P_{sp} = 1.46$ MJ/kg_{air}). This condition is selected as the reference case for validating the RANS approach against LES, as the experiments exhibited the most pronounced differences in flame morphology and stabilization between the full- and staged-injection configurations at this operating point. The analysis focuses exclusively on H_2 –air mixing, while spray effects are neglected. RANS simulations are subsequently used to examine the influence of the injection strategy across the investigated operating conditions. The simulations are performed using the pressure-based solver in ANSYS Fluent 23R2. In the LES framework, subgrid-scale stresses are modeled using the dynamic Smagorinsky–Lilly approach [37]. A mixture-averaged diffusion formulation is employed to properly resolve the rapid transport characteristics of H_2 during the mixing process. The complete numerical setup, including mesh resolution, near-wall treatment, boundary conditions, and statistical convergence of the LES, is given in Section S1 of the Supplementary Material. A quantitative comparison of LES and RANS predictions of H_2 jet penetration and mixing at multiple axial locations is provided in Section S2 of the Supplementary Material. Because the RANS results increasingly diverge from the LES as the flow progresses toward the combustion chamber, the downstream mixing metrics are used only for qualitative comparison between configurations rather than as absolute quantitative predictions.

Given the significant computational cost associated with LES for the current configuration, a corresponding RANS simulation using the $k-\omega$ SST model is subsequently conducted at the same operating condition. The objective is to identify an optimal modeling strategy capable of reproducing the LES-predicted velocity and mixing fields with acceptable accuracy, thereby enabling a computationally efficient yet reliable investigation of a broader range of operating conditions.

The best agreement with LES results is achieved by setting both the turbulent Schmidt and turbulent Prandtl numbers to 0.3. These values are consistent with previous jet-in-crossflow RANS studies, where reduced Schmidt and Prandtl numbers were shown to improve jet penetration predictions over the standard range of 0.7–0.9 [38,39]. As this calibration reflects the underlying jet-in-crossflow mixing physics rather than a case-specific fit, the same values are retained across the

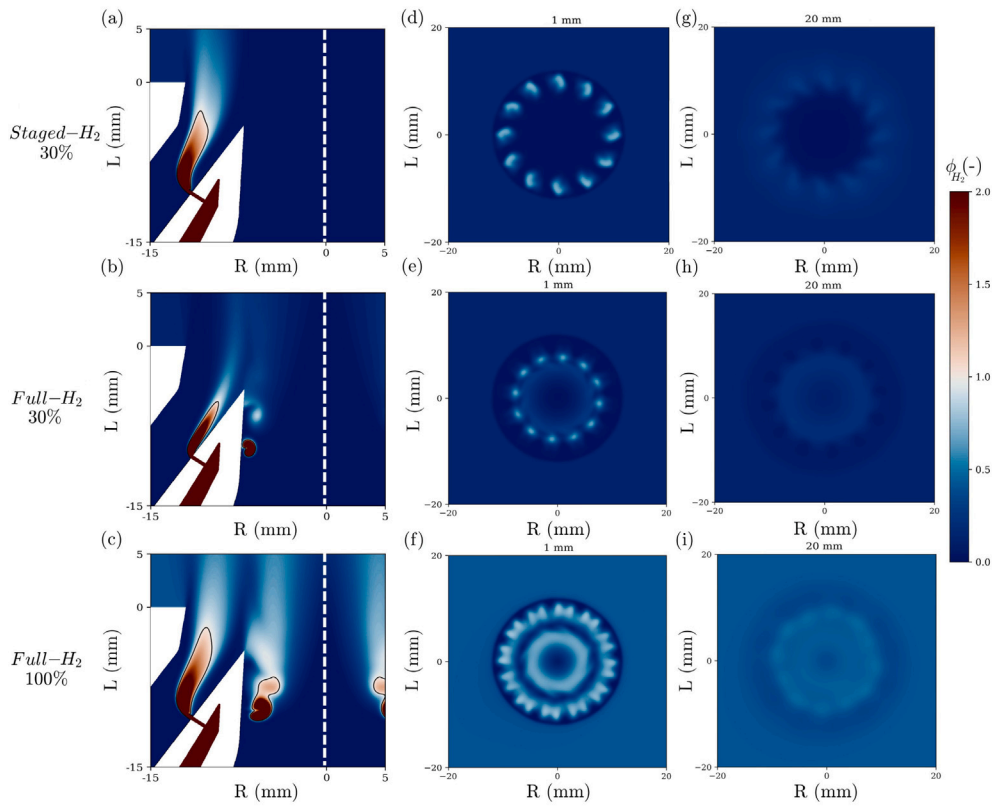


Fig. 3. RANS H_2 equivalence ratio (ϕ_{H_2}) distributions for the staged-injection configuration at 30% of the maximum $\dot{m}_{H_2}$ (top row), and for the full-injection configuration at 30% and 100% (middle and bottom rows, respectively). (a–c) The first column shows jet penetration within the burner on the mid-plane, and (d–f) and (g–i) present the ϕ_{H_2} distributions on cross-sections located at 1 mm and 20 mm in the combustor, respectively. The black iso-line ($\phi_{H_2} = 1$) is superimposed in all cases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

full RANS parametric study. Based on this calibrated setup, two additional RANS simulations are performed: one for the full-injection configuration operating at 100% H_2 and another for the staged-injection configuration at 30% H_2 . The former is used to evaluate the influence of increased H_2 content, whereas the latter enables a direct comparison between full and staged-injection strategies at identical operating conditions.

Fig. 2(a) presents the normalized axial velocity field (U_{ax}/U_b) and Fig. 2(b) shows the H_2 equivalence ratio distribution (ϕ_{H_2}) within the burner and combustion chamber, as predicted by both LES and RANS simulations. Inspection of the U_{ax}/U_b contours, where U_{ax} is the axial velocity and U_b is the bulk flow velocity, in Fig. 2(a) indicates that the RANS simulation successfully accounts for the dominant flow-field characteristics inside the burner. In particular, it reasonably captures the flow behavior associated with the non-swirled primary vanes (see Fig. 1b), which, together with the outer prefilmer holes, establish a jet-in-crossflow configuration. Upon exiting these passages and entering the combustion chamber, both simulations exhibit a homogeneous high-velocity flow originating from the described outer channel at the burner exit, which gradually decelerates within the combustor.

The primary discrepancy between the LES and RANS results arises in the swirled flow region, which governs the axial position of the small inner recirculation zone forming between the two high-velocity jets. In the RANS simulation, this recirculation zone is shifted slightly downstream, indicating a modest overprediction of its axial extent. However, this difference does not significantly influence the predicted mixing fields, as illustrated in Fig. 2(b) by the equivalence ratio (ϕ_{H_2}) distribution. For the present operating condition, where $\dot{m}_{H_2}$ corresponds to 30% of the maximum value (0.26 g/s), both the outer and inner H_2 jets remain confined along the prefilmer walls. As a result of the limited radial H_2 jet penetration, no fuel reaches the outer

burner wall region near the exit, as highlighted by the white dotted box in Fig. 2(b). More specifically, the RANS simulation reproduces the LES-predicted jet penetration within the burner on the mid-plane, with reasonable accuracy, as indicated by the extension of the black $\phi_{H_2} = 1$ iso-line. In contrast, within the inner side of the prefilmer, the mixing field predicted by RANS appears less homogeneous, likely due to the higher coherence of the turbulent jet structures observed in Fig. 2(a). Overall, RANS captures the jet penetration and global mixing topology predicted by LES, while underestimating the degree of turbulent homogenization in the downstream region. Additionally, a comparison of the predicted axial velocity profiles with PIV measurements under isothermal conditions is provided in Section S2 of the Supplementary Material (Fig. S4). Therefore, RANS is adopted for the subsequent analysis of the effects of $\dot{m}_{H_2}$ and H_2 injection configuration, with emphasis on relative jet penetration and global mixing trends rather than local turbulence quantities.

Fig. 3 shows the H_2 equivalence ratio (ϕ_{H_2}) distribution for the three aforementioned operating conditions. The first column in Fig. 3(a–c) illustrates the jet penetration for the staged-injection configuration at 30% of the maximum $\dot{m}_{H_2}$ (OPC, top row), and for the full-injection configuration at 30% and 100% (OPB and OPA, middle and bottom rows, respectively). For all three cases, no combustible mixture is observed to impinge on the outer injector wall. The corresponding wall-standoff distances, defined in Section S2 of the Supplementary Material, as the distance from the wall to the location where ϕ_{H_2} reaches the lower flammability limit, are 2.57 mm for OPB, 0.43 mm for OPA, and 0.50 mm for OPC (Table S2 of the Supplementary Material). For OPB, where LES is available, the metric yields 2.32 mm from LES versus 2.57 mm from RANS, an 11% difference. No LES counterpart is available for OPA and OPC, for which the predicted margin is below 1 mm. Consistent with this prediction, no flame flashback was

observed during the experiments, as monitored by OH* chemiluminescence imaging throughout the experimental campaign. A dedicated flashback assessment was not performed in the present study. However, in our previous work on the same combustor, employing a staged-injection configuration with 12 H₂ injectors, no evidence of flashback was observed for pure H₂ operation up to $\phi = 0.7$ and relative air pressure drops as low as 1% [10].

As discussed previously, the jet penetration in the staged-injection configuration is optimized up to 30% of the maximum $\dot{m}_{H_2}$, whereas in the full-injection configuration it extends to 100%. In both the staged-injection configuration (30%) (Fig. 3a) and the full-injection configuration (100%) (Fig. 3c), the outer jets exhibit similarly strong radial H₂ jet penetration toward the outer wall of the nozzle. In contrast, in the full-injection configuration (30%) (Fig. 3b), the H₂ jets remain more confined and appear pinched against the prefilmer.

The second column (Fig. 3d–f) shows cross-sections located 1 mm downstream of the burner exit. In the staged-injection configuration (Fig. 3d), the reduced number of injection holes results in a higher degree of unmixedness, characterized by twelve distinct high- ϕ regions separated by ultra-lean zones. This behavior contrasts markedly with the full-configuration cases (Fig. 3e,f), where the mixture is already more homogeneous. In particular, on the inner side of the prefilmer, the combined effects of swirl and the jet-in-crossflow arrangement promote rapid mixing. On the outer side of the prefilmer, increasing $\dot{m}_{H_2}$ enhances both the radial penetration of the H₂ jets and the tangential spreading of the mixture. This trend is attributed to the strengthening of counter-rotating vortex pairs induced by the higher jet-to-crossflow momentum ratio, with the characteristic kidney-shaped structures clearly visible in contours (Fig. 3f).

Finally, the cross-section at 20 mm downstream of the combustion chamber (Fig. 3g–i) indicates that a degree of unmixedness remains in the staged-injection configuration (Fig. 3g). In this case, the mixture remains ultra-lean near the inner radii, as no fuel is injected into the swirled flow. Consequently, no flammable mixture is present in this region, and flame stabilization can occur only at larger radial positions. In contrast, for the full-injection configuration at 30% H₂ (Fig. 3h), mixture homogeneity is achieved closer to the burner axis, with only minor residual ϕ_{H_2} non-uniformities at larger radii. For the full-injection configuration at 100% H₂ (Fig. 3i), mixing is further enhanced compared to cases shown in Fig. 3(g) and (h). The resulting mixing field exhibits two dominant ϕ_{H_2} levels: a leaner region near the inner radii, associated with the swirled jet-in-crossflow, and a comparatively richer region at the outer radii, corresponding to the non-swirled jet-in-crossflow.

3.2. Flame shape and morphology in fuel-flexible combustor

This section examines the flame structure under reacting conditions in the fuel-flexible combustor for both injection configurations. The morphological evolution of the time-averaged OH* chemiluminescence images, spatially reconstructed using inverse Abel transformation, is analyzed for fuel blends ranging from 0 to 100% H₂. The OH* fields are normalized by their respective maximum value to enable direct comparison between cases. Varying the H₂ fuel split at constant $\mathcal{P}$ is relevant in practical aero-engine operation to optimize pollutant emissions, particularly during high-demand phases such as take-off, as well as during low-load conditions such as idle and taxiing [40,41]. To capture these operating extremes, two specific thermal power levels are considered in this study: $\mathcal{P}_{sp,1} = 1.46 \text{ MJ/kg}_{air}$ and $\mathcal{P}_{sp,2} = 1.17 \text{ MJ/kg}_{air}$, representative of high- and low-load operation in the experimental combustor.

3.2.1. Influence of air inlet temperature

Fig. 4 illustrates the time-averaged inverse Abel transformed OH* chemiluminescence images for different H₂ fuel splits at $\mathcal{P}_{sp,1}$ in full-injection configuration (see Table 1). The columns correspond to increasing H₂ blends, and the rows represent air inlet temperatures of $T_{air} = 673 \text{ K}$ and 473 K , respectively. Although the relative pressure drop ($\Delta p/P = 3\%$) across the burner remains nearly constant with variations in T_{air} , increasing the T_{air} leads to a higher bulk velocity U_b . However, this effect is partially offset by the corresponding increase in laminar flame speed at elevated T_{air} .

In the case of Jet-A1 operation (0% H₂), a strongly luminous reaction zone is observed over a wide region and is positioned relatively far downstream from the burner exit plane for both air inlet temperatures of $T_{air} = 673 \text{ K}$ and 473 K (Fig. 4a,f). The flames remain lifted in both cases, promoting enhanced pre-evaporation and mixing of Jet-A1 with the incoming airflow. However, for elevated T_{air} , the reaction zone becomes more compact, with a slightly reduced LOH compared to the lower T_{air} case. This behavior is not solely driven by the increased laminar flame speed but is also potentially related to the stronger outer recirculation zone (ORZ) at higher T_{air} , which arises from a reduced expansion ratio between fresh and burned gases, in agreement with observations reported for lean lifted spray flames by Shamma et al. [22].

At a 30% H₂ fuel split (Fig. 4b,g), the flame at low T_{air} closely resembles the structure observed for pure Jet-A1, as the H₂ jets exhibit insufficient penetration to significantly influence the flame. However, at elevated T_{air} , the flame exhibits a distinct structure. In the lower region of the flame (up to approximately 75 mm in axial distance), the behavior remains similar to that of a pure Jet-A1 flame. This can be attributed to the limited radial penetration of the H₂ jets, which restricts the amount of H₂ reaching the ORZ where flame stabilization occurs. In contrast, the upper region exhibits a noticeably higher OH* intensity, indicating that a larger fraction of H₂ participates in combustion near the combustor centerline under these conditions. Furthermore, the higher flame speed of H₂ in this region promotes more intense heat release, leading to a shortened flame length and increased flame intensity. This behavior is consistent with the numerical results shown in Figs. 2(b) and 3(b), which depict the H₂ equivalence ratio distributions. In these simulations, both the inner and outer H₂ jets remain confined along the prefilmer walls, preventing locally rich mixtures from reaching the outer burner walls in the exit region highlighted by the white dotted box in Fig. 2(b). Increasing the H₂ content to 60% (Fig. 4c,h) further compacts the flame, with the reaction zone shifting closer to the burner exit. This behavior results from increased radial H₂ jet penetration, which brings more fuel into the ORZ, combined with the higher flame speed. Elevated T_{air} further amplifies these effects, producing shorter and more compact flames compared to the 30% H₂ case. At a 90% H₂ fuel split (Fig. 4d,i), the flame further contracts and moves closer to the burner exit, with additional low-intensity combustion streaks persisting slightly downstream. Elevated T_{air} reinforces this effect, reflecting faster H₂ oxidation and improved flame stabilization.

During pure H₂ operation (Fig. 4e,j), the flame exhibits an extended reaction zone away from the burner, with additional intense combustion streaks near the exit due to localized H₂ presence. This behavior is consistent with the numerical predictions shown in Fig. 3(c), where the increased H₂ mass flow enhances both the radial penetration of the jets along the prefilmer and the tangential spreading of the mixture in the swirling region. These flow features indicate increased H₂ availability within the ORZ and provide a plausible interpretation of the observed flame stabilization and sustained combustion over a broader spatial extent. At lower T_{air} , the reaction zone intensity closer to the burner is comparatively higher, likely due to reduced premixing and locally higher fuel concentrations associated with the penetrating H₂ jets. In contrast, at elevated T_{air} , enhanced mixing shifts the dominant reaction zone farther downstream, so that most of the reaction zone intensity remains located away from the burner exit.

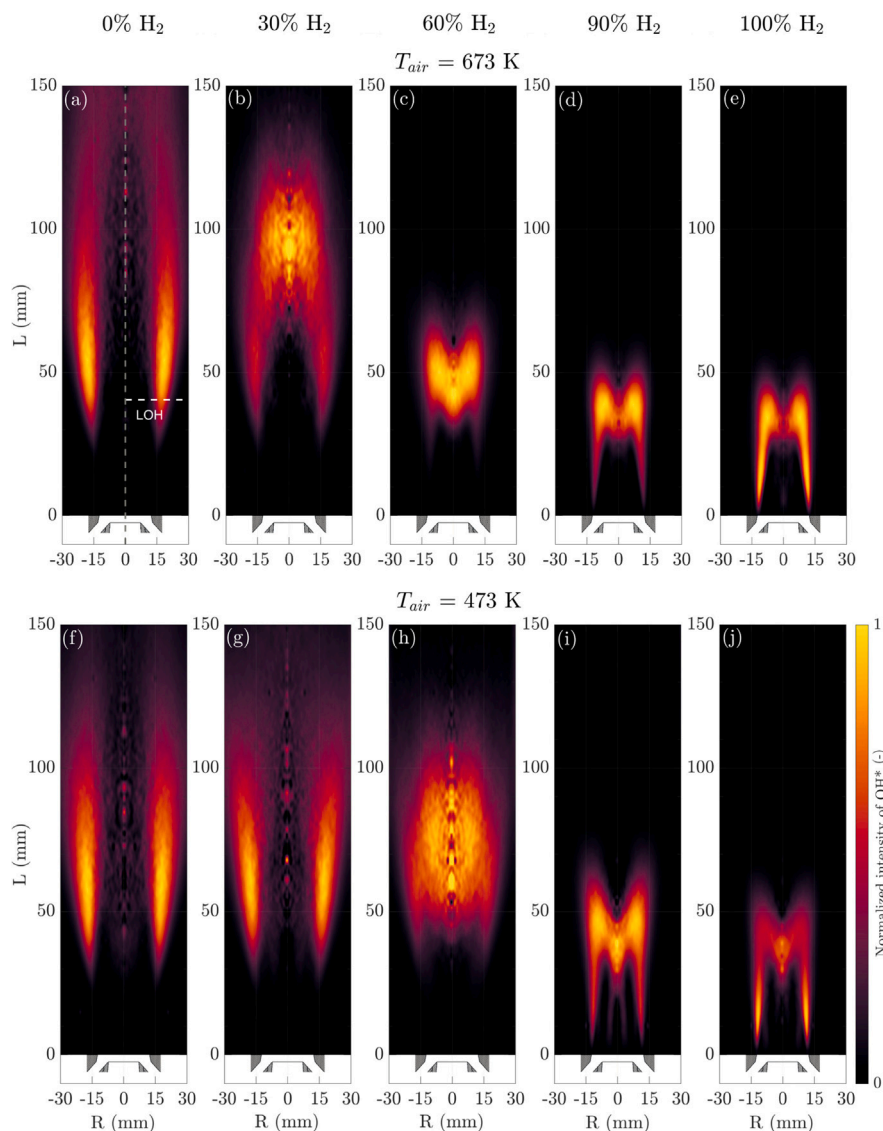


Fig. 4. Time-averaged inverse Abel transformed OH^* images across various fuel splits at a specific thermal power ($P_{sp,1}$) of 1.46 MJ/kg_{air} and air inlet temperature of (a–e) $T_{air} = 673$ K and (f–j) $T_{air} = 473$ K for the full-injection configuration.

3.2.2. Influence of specific thermal power

Next, the flame behavior in the full-injection configuration under off-design conditions is discussed. Fig. 5 presents time-averaged, inverse Abel-transformed OH^* fields for various H_2 fuel splits at $T_{air} = 473$ K and $P_{sp,2}$, corresponding to conditions near LBO (Table 1, OC1). The reaction zone spans a relatively wide area and is located far downstream of the burner exit. H_2 addition up to 30% has only a minor effect on the overall flame shape, although the reactive zone extends slightly downstream, indicating a modest enhancement of the flame stabilization. At 60% H_2 , the flame develops a two-zone structure. The lower region of the flame exhibits similarities to the pure Jet-A1 case, albeit with reduced OH^* intensity due to the lower contribution of Jet-A1. In contrast, the upper region exhibits significantly higher OH^* intensity than in the 30% H_2 case, indicating that a greater portion of H_2 is consumed near the combustor centerline. Moreover, at $P_{sp,2}$, the flame stabilizes at a position further downstream of the burner exit compared to $P_{sp,1}$ case (see Fig. 4h), primarily due to the limited radial penetration of the H_2 jets. Further increasing the H_2 fuel splits up to 90% results in a more compact flame, with the reaction zone concentrated closer to the burner exit. At 100% H_2 fuel split, no stable flame could be sustained, as the mixture reached the stability limit.

This is attributed to insufficient radial penetration of the H_2 jets, which limits effective anchoring in the ORZ, combined with the absence of Jet-A1. Interestingly, at elevated $T_{air} = 673$ K (not shown for brevity), the flame morphology remain largely similar to that observed at $T_{air} = 473$ K and stays stable up to 100% H_2 operation, owing to the higher laminar flame speed, which facilitated sustained combustion.

To overcome the inability to sustain a stable flame under part-load conditions at $T_{air} = 473$ K, H_2 fuel staging seems a viable solution, as it promotes enhanced H_2 jet penetration at the same mass flow rates.

3.2.3. Effect of H_2 staging on flame stabilization

H_2 staging strategy is introduced here to enhance jet penetration and improve flame stabilization under part-load conditions. In this approach, the number of outer H_2 injectors is reduced from 24 to 12, and the inner injectors are deactivated. By optimizing the local fuel–air distribution, H_2 fuel staging not only promotes flame stabilization near the LBO limit but also allows better control over combustion characteristics, thereby broadening the stable operating range of the combustor while potentially lowering emissions near the stability limits.

Fig. 6 shows the time-averaged inverse Abel-transformed OH^* fields for different H_2 fuel splits at $T_{air} = 473$ K and $P_{sp,2}$ in the staged-injection configuration. Up to 30% H_2 , the flame closely resembles pure

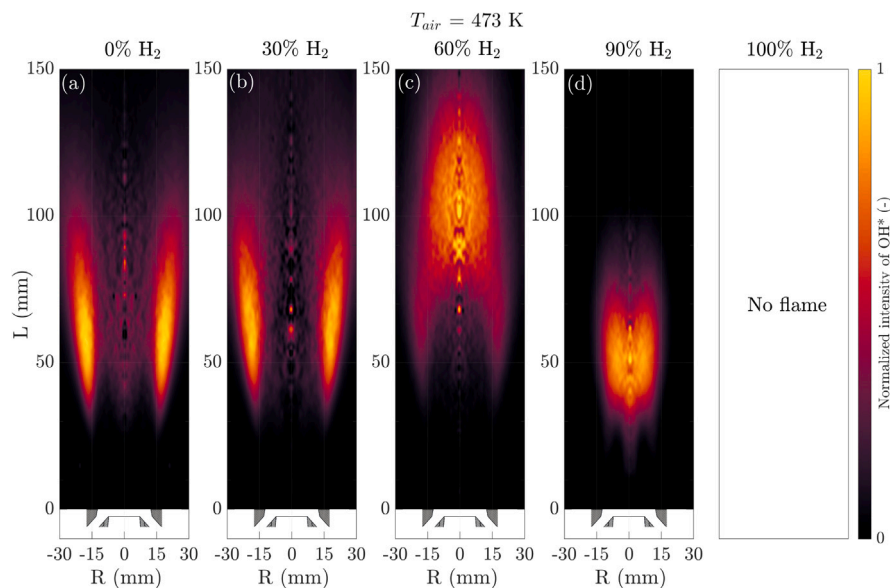


Fig. 5. Time-averaged inverse Abel transformed OH* images across various fuel splits at a specific thermal power ($P_{sp,2}$) of 1.17 MJ/kg_{air} and an air inlet temperature of $T_{air} = 473$ K for the full-injection configuration.

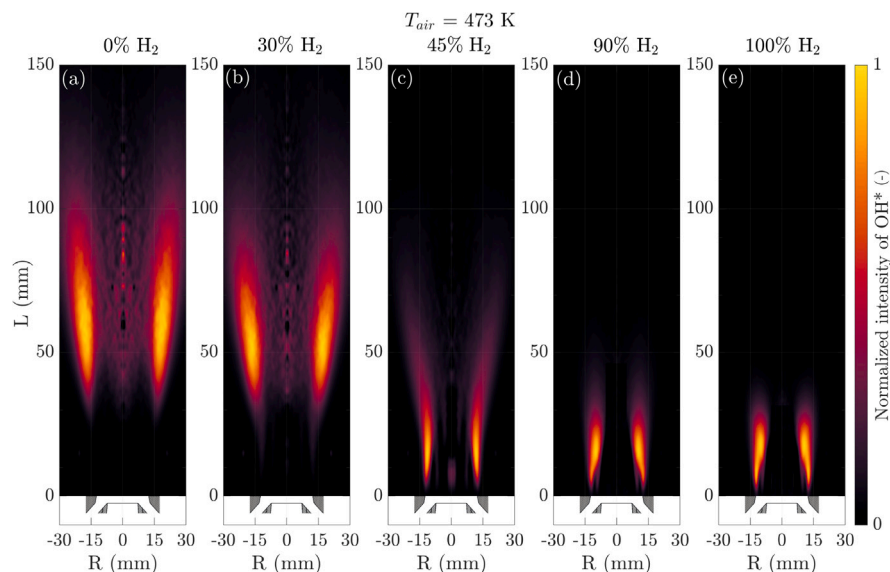


Fig. 6. Time-averaged inverse Abel transformed OH* images across various fuel splits at a specific thermal power ($P_{sp,2}$) of 1.17 MJ/kg_{air} and an air inlet temperature of $T_{air} = 473$ K for the staged-injection configuration.

Jet-A1 due to limited H₂ jet penetration, although the flame becomes slightly more compact and shifts slightly toward the burner exit. This observation agrees well with the numerical simulations for the staged-injection configuration in Fig. 3(a), which show that the local mixture develops toward the external wall of the fuel nozzle. Above 30% H₂, the flame morphology deviates noticeably from that observed in the full-injection configuration as shown in Fig. 5(c–d). At 45% H₂, the flame shifts closer to the burner exit, enhancing flame anchoring with the support of the ORZ. For fuel splits between 45% and 100% H₂, the flame anchoring position near the burner plane stays essentially constant, whereas the overall flame length gradually reduces with decreasing proportion of Jet-A1 (Fig. 6c–e). At 100% H₂, the staged-injection system produces a compact but slightly detached reaction zone closer to the burner plane (Fig. 6e), whereas no stable flame was obtained in the full-injection configuration under the same conditions.

The non-reacting simulations show that, at the same $\dot{m}_{H_2}$, staged injection yields greater radial H₂ jet penetration and a fuel distribution extending further toward the ORZ (Fig. 3a,b). This difference in the simulated fuel distribution is qualitatively consistent with the observed differences in flame position and stability. However, the simulations exclude heat release and spray effects, so they show cold-flow mixing trends only and do not identify the flame stabilization mechanism.

3.3. Improved lean blowout limits

The influence of H₂ addition on the lean blowout (LBO) characteristics is examined for both injection configurations. Low thermal power increases the risk of LBO due to reduced heat release and slower reaction rates. Under leaner conditions, increased local strain can promote partial extinction, leading to flame instability and eventual blowout. The LBO limit represents the minimum fuel flow required to sustain

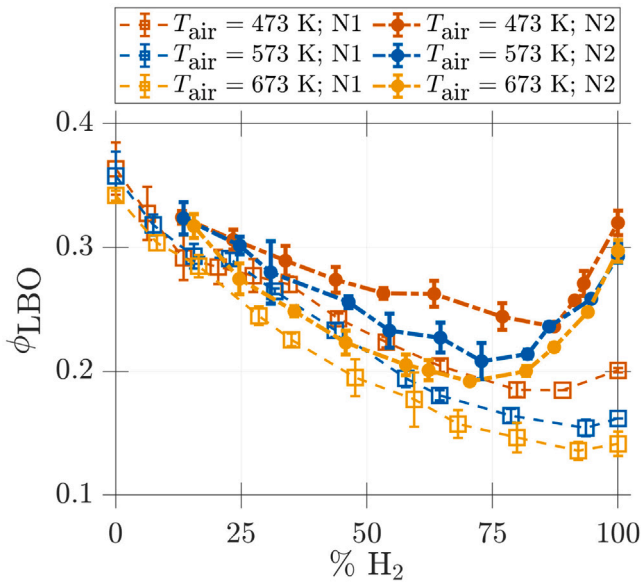


Fig. 7. Comparison of lean blowout limits for distinct T_{air} and H_2 injection configurations (N1: 12 outer injectors; N2: 24 outer and 8 inner injectors) across various fuel splits. Error bars indicate the standard deviation of the measured ϕ_{LBO} , calculated from three independent experimental repetitions. The corresponding operating conditions are summarized in Table 1.

stable combustion, corresponding to the minimum global equivalence ratio (ϕ) at which a self-sustaining flame can be maintained.

Fig. 7 summarizes the LBO limits of the fuel-flexible combustor for various H_2 fuel splits, three air inlet temperatures (T_{air}), and two H_2 injection configurations (staged and full-injection configurations, referred to as N1 and N2). The standard deviation of the LBO equivalence ratio (ϕ_{LBO}), obtained from three repeated measurements at each operating condition, is represented by the error bars. In the full-injection configuration, ϕ_{LBO} initially decreases with increasing H_2 content and rises again at higher blends. For instance, at $T_{\text{air}} = 473$ K, ϕ_{LBO} drops from 0.33 (15% H_2) to 0.31 (100% H_2). This trend becomes more pronounced for intermediate H_2 blends as T_{air} increases, while the extremes of low and high blends show only minimal changes: ϕ_{LBO} decreases from 0.33 to 0.30 at $T_{\text{air}} = 573$ K and from 0.31 to 0.29 at $T_{\text{air}} = 673$ K. In contrast, for the staged-injection configuration, ϕ_{LBO} decreases substantially with increasing H_2 content, dropping from 0.37 (0% H_2) to 0.20 (100% H_2) at 473 K, and further reducing to 0.16 and 0.14 at 573 K and 673 K, respectively. A distinct variation in LBO limits is evident with changing T_{air} . Up to 30% H_2 , LBO limits remain similar across different air inlet temperatures, as H_2 jet penetration is limited and combustion is primarily governed by Jet-A1. Between 30%–70% H_2 , ϕ_{LBO} decreases with increasing H_2 contents for both injector configurations, reflecting the higher reaction rate and flame speed of H_2 -rich flames.

Interestingly, at higher H_2 fuel splits up to 100%, a pronounced difference emerges between the full and staged-injection configurations. In the staged-injection configuration, ϕ_{LBO} continues to decrease markedly, whereas in the full-injection case, ϕ_{LBO} significantly increases between 75% and 100% H_2 . This contrasting behavior is not explained by H_2 jet momentum alone, since the jet momentum flux ratio (J) increases continuously with increasing H_2 fraction. For staged injection, the increasing J is accompanied by enhanced radial H_2 penetration (see Section S3 and Fig. S5 of the Supplementary Material), providing a plausible explanation for the continued improvement in flame stability. In contrast, the full-injection configuration shows a non-monotonic LBO response, with ϕ_{LBO} improving up to approximately 70%–75% H_2 before increasing again toward pure H_2 . We hypothesize

that this behavior may result from competing contributions of the two fuels: residual Jet-A1 spray may contribute to flame stabilization through droplet evaporation and heat release in the ORZ, complementing the fast chemistry and wide flammability range of H_2 . As the H_2 split increases further, this potential spray-supported contribution decreases, while the radial H_2 penetration in the full-injection configuration may not increase sufficiently to compensate. This interpretation is consistent with the observed LBO trend, although the underlying mechanism cannot be established from the present measurements. Dedicated spray diagnostics would be required to verify the relative contributions of spray evaporation and H_2 penetration and are therefore recommended for future work.

Overall, increasing T_{air} has a minimal effect on LBO for Jet-A1 or low H_2 blends but strongly influences flames with high H_2 content. Moreover, staged injection consistently provides improved flame stability at high H_2 fuel splits, resulting in lower ϕ_{LBO} and an extended stable operating range of the fuel-flexible combustor.

3.4. Pollutant emissions

NO_x and CO emissions constitute key performance constraints in the design of gas turbine combustors. Figs. 8 and 9 present the dry exhaust emissions (NO_x and CO) of the fuel-flexible combustor across a range of H_2 fuel splits and H_2 injection configurations. Both NO_x and CO concentrations are reported in ppm and normalized to 15% O_2 . Uncertainties associated with the gas analyzers and the O_2 measurement used for normalization were combined in quadrature into a systematic uncertainty, expressed as a relative fraction of the measured value. This was combined in quadrature with the statistical uncertainty, taken as the standard error of the mean of the steady-state measurements (standard deviation divided by the square root of the number of samples) at each operating condition, and multiplied by a coverage factor of 2 (approximately 95% confidence) to obtain the expanded uncertainty shown as error bars in Figs. 8 and 9. For a representative low-concentration condition of approximately 5 ppm NO_x (at 15% O_2), the calculated expanded uncertainty is around ± 1.2 ppm.

3.4.1. Effect of H_2 addition on NO_x emissions and lift-off heights

Fig. 8 illustrates the influence of H_2 addition on NO_x emissions and the corresponding LOH at two different P_{sp} for full and staged-injection configurations.

At the nominal specific power ($P_{\text{sp},1}$) shown in Fig. 8(a), NO_x emissions remain around 14 ppm during pure Jet-A1 operation. The corresponding LOH is also highest (Fig. 8b), promoting enhanced premixing prior to combustion. LOH error bars represent the standard deviation over the corresponding image ensemble (Section 2.2). Compared to low T_{air} conditions, elevated T_{air} promotes faster pre-evaporation and improves mixing of Jet-A1 and air, resulting in improved mixture homogeneity and lower NO_x emissions. As the H_2 content increases, both NO_x emissions and LOH become more sensitive to T_{air} . As the H_2 content increases up to 60%, both full and staged-injection configurations (N1 and N2) show a gradual decrease in NO_x at lower T_{air} , whereas increasing T_{air} leads to higher NO_x due to elevated adiabatic flame temperatures. Correspondingly, the LOH remains higher for the full-injection case, where the flame remains largely lifted (Fig. 4b,g), but decreases significantly in the staged-injection configuration beyond 15% H_2 , as the flame position shifts toward the burner plane due to strong H_2 jet penetration.

From 75% H_2 up to 100% H_2 , the full-injection configuration exhibits a reduction in NO_x emissions, consistent with more uniform fuel distribution and enhanced premixing predicted numerically at 100% H_2 (Fig. 3c). In contrast, the staged-injection configuration shows a sharp increase in NO_x emissions across all T_{air} conditions, with the highest levels observed at elevated T_{air} . This increase is driven by the combined effects of higher adiabatic flame temperatures and insufficient fuel–air mixing. Correspondingly, the LOH gradually decreases

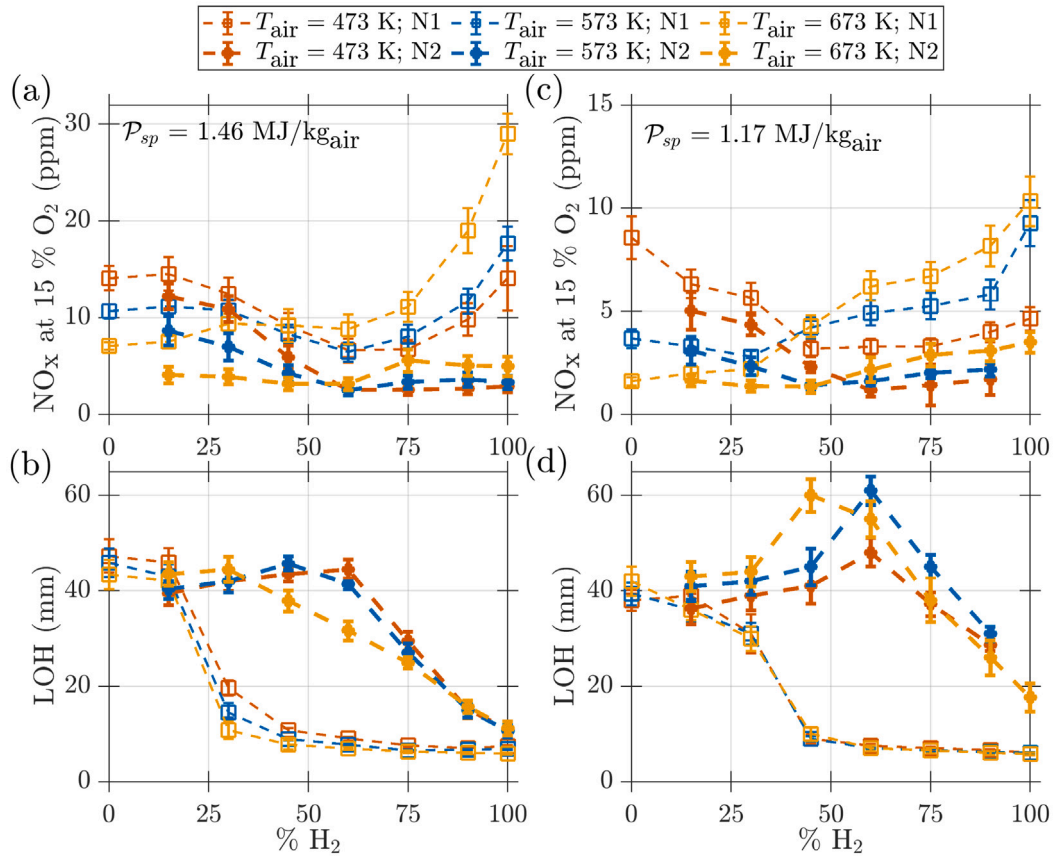


Fig. 8. Variation of NO_x emissions and corresponding flame lift-off height as a function of H_2 blends for different T_{air} and H_2 injection configurations (N1: 12 outer injectors; N2: 24 outer and 8 inner injectors) at (a, b) $P_{sp,1} = 1.46 \text{ MJ/kg}_{\text{air}}$ and (c, d) $P_{sp,2} = 1.17 \text{ MJ/kg}_{\text{air}}$. NO_x error bars represent the expanded uncertainty (coverage factor of 2), incorporating both statistical and systematic contributions, whereas LOH error bars represent the standard deviation across the image ensemble. The corresponding operating conditions are listed in Table 1.

in the full-injection configuration with increasing fuel split, whereas it remains low in the staged-injection configuration, likely due to jet impingement near the outer nozzle wall. Notably, at 100% operation, the LOH in the full-injection case is only slightly higher than in the staged configuration. However, the dominant reaction zone is located substantially farther downstream (see Fig. 4e,j), which promotes a higher degree of premixing.

For the lower specific power condition ($P_{sp,2}$) close to LBO limit (Fig. 8c), the NO_x emission trends are similar to those observed at nominal power (Fig. 8a), but at significantly lower emission levels. NO_x emissions remain below 5 ppm for the full-injection configuration and below 10 ppm for the staged-injection configuration. In Fig. 8(d), the LOH in the full-injection configuration steadily increases up to 60% H_2 before decreasing at higher fuel splits. In contrast, for the staged-injection configuration, LOH decreases progressively with increasing H_2 content, exhibiting a pronounced drop between 30% and 45% H_2 . Notably, under part-load conditions, LOH remains lifted up to 30% H_2 , whereas under full-load operation it remains lifted only up to 15% H_2 (Fig. 8a), owing to reduced radial penetration. No data are reported for pure H_2 in the full-injection configuration at low T_{air} due to the LBO limit, as discussed in Section 3.2. These observations demonstrate that while full-injection is effective under high-load conditions, staged-injection significantly enhances flame anchoring, extends LBO limits, and preserves low NO_x emissions under part-load operation, highlighting its critical role for fuel-flexibility and H_2 staging in combustor performance.

3.4.2. Effect of H_2 addition on CO emissions

As expected, CO emissions decrease with increasing H_2 content in the fuel split (Fig. 9). At nominal specific thermal power ($P_{sp,1}$),

pure Jet-A1 operation (0% H_2) produces the highest CO emissions, reaching 176 ppm at $T_{\text{air}} = 473 \text{ K}$, 17 ppm at 573 K, and 11 ppm at 673 K (Fig. 9a). Even a modest 15% H_2 addition substantially reduces CO emissions, decreasing to 45 ppm at 473 K for the full-injection configuration and to 56 ppm for the staged-injection configuration. At lower T_{air} , slightly lower CO levels are observed for the full-injection case compared to staged-injection, which is attributed to improved fuel-air mixing. This difference diminishes with increasing T_{air} , where both injection strategies exhibit similar trends. With further increases in H_2 content, CO emissions continue to decline up to 45% H_2 and approach near-zero values at very high H_2 blends for all T_{air} and both injection configurations.

At reduced specific thermal power ($P_{sp,2}$), corresponding to operation near the LBO limit, CO emissions are significantly higher (Fig. 9b), reaching 2400 ppm for pure Jet-A1 at 473 K, 250 ppm at 573 K, and 50.6 ppm at 673 K. The elevated CO at 473 K is attributed to incomplete CO oxidation at low preheat temperature, further promoted by the intermittent flame behavior near LBO. This interpretation is consistent with the exhaust-gas measurements (see Section S4 and Fig. S6 of the Supplementary Material): the highest-CO condition also exhibits the highest residual O_2 concentration (14.5–15.5 vol.% at $P_{sp,2}$ versus 12.5–13.5 vol.% at $P_{sp,1}$), indicating that the elevated CO is not associated with globally O_2 -deficient exhaust conditions. Reduced-power operation is generally associated with higher CO and lower NO_x [42], consistent with the opposing trends in Figs. 8 and 9. Although increasing the H_2 fuel split provides a viable approach to reducing CO at low-power conditions (e.g., at idle/taxi), the present fuel-flexible configuration was primarily developed to achieve low pollutant emissions while maintaining flashback-safe operation at high-power conditions.

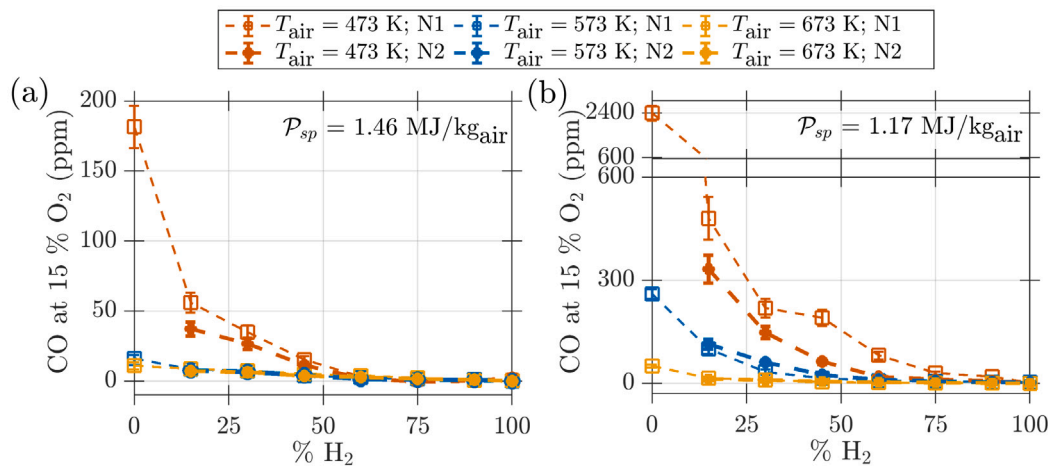


Fig. 9. Variation of CO emissions across various H_2 blends for different T_{air} and H_2 injection configurations (N1: 12 outer injectors; N2: 24 outer and 8 inner injectors) at (a) $P_{sp,1} = 1.46$ and (b) $P_{sp,2} = 1.17$ MJ/kg $_{air}$, with operating conditions given in Table 1. Error bars show the expanded uncertainty (coverage factor of 2), incorporating both statistical and systematic contributions.

Introducing 15% H_2 leads to a pronounced reduction, lowering CO emissions to 330, 122.4, and 17 ppm for the full-injection configuration and to 448, 49.4, and 15 ppm for the staged-injection configuration at 473, 573, and 673 K, respectively. Further increases in H_2 content continue to reduce CO emissions, although emission levels remain higher than those observed at nominal specific power operation due to the proximity to stability limits. Similar to the nominal power condition, the full-injection configuration under part-load condition exhibits slightly lower CO emissions than staged-injection at lower T_{air} , while this distinction becomes negligible at higher T_{air} . These results highlight the strong potential of H_2 addition to mitigate CO emissions during part-load operation, which is particularly relevant for air quality in the vicinity of airports.

4. Conclusion

This study investigated the effects of H_2 addition and injection strategy on flame structure, lean blowout (LBO), and pollutant emissions in a fuel-flexible low-swirl combustor combining an airblast atomizer for Jet-A1 with H_2 jet-in-crossflow injection. While this dual-fuel architecture was established in our previous work, the present study provides the first systematic comparison of full and staged-injection strategies across the complete fuel-flexibility range, from pure Jet-A1 to pure H_2 , under both full-load and part-load conditions. Full injection employed all 32 H_2 ports (24 outer, 8 inner), whereas staged injection employed only 12 outer ports, with the inner ports deactivated. Experiments were complemented by non-reactive simulations to characterize the associated flow and H_2 -air mixing behavior.

Distinct flame morphologies emerge with increasing H_2 fuel split and changing injection strategy. Full injection produces predominantly lifted flames, remaining detached from the burner exit even at 100% H_2 , whereas staged injection promotes flame stabilization closer to the burner exit, particularly at high H_2 contents. Non-reactive simulations at a 30% H_2 fuel split indicate that, at the same H_2 mass flow rate, staging results in greater radial penetration of the H_2 jets and a fuel distribution extending further toward the outer recirculation zone, consistent with the observed difference in flame location.

The two injection strategies exhibit markedly different LBO behavior. Staged injection progressively lowers ϕ_{LBO} with increasing H_2 content, whereas full injection exhibits a non-monotonic response, with ϕ_{LBO} decreasing up to approximately 70%–75% H_2 before increasing again toward pure H_2 . As a result, for pure H_2 , staging extends the LBO limit by a factor of 2.0 at 673 K and 1.6 at 473 K relative to full-injection operation at the same air inlet temperature. Compared

with pure Jet-A1, staged operation with pure H_2 exhibits LBO limits lower by factors of 2.4 at 673 K and 1.8 at 473 K. The continued increase in H_2 jet momentum ratio across the fuel-split range indicates that jet momentum alone does not determine the LBO response; the resulting fuel distribution and the contribution of the remaining Jet-A1 also influence flame stability. Thus, staged injection provides a clear stability advantage at high H_2 fuel splits, particularly under elevated air inlet temperature conditions.

Emissions depend strongly on operating conditions and injection strategy. At the higher specific thermal power, full injection maintains NO_x emissions below approximately 15 ppm across the complete investigated fuel range, whereas staged injection provides comparable NO_x levels up to approximately 75% H_2 , followed by a pronounced increase at higher fuel splits. At the lower specific thermal power investigated ($P_{sp,2} = 1.17$ MJ/kg $_{air}$), NO_x remains below approximately 5 ppm for full injection and 10 ppm for staged injection. In addition, an H_2 addition of approximately 15% substantially reduces CO emissions from around 175 to 50 ppm at nominal power and from around 2400 to 400 ppm at part-load, particularly benefiting low air inlet-temperature operation. Taken together, these results support a condition-dependent operating strategy: full injection is preferable for high-load operation where low NO_x emissions are prioritized, whereas staged injection should be employed at high H_2 fuel splits under leaner, lower-power conditions where an extended LBO margin is required.

The present numerical analysis is limited to non-reactive RANS/LES simulations of the cold-flow mixing field and therefore does not directly resolve the reacting flame-stabilization process or spray-flame interactions. Reacting simulations with fully resolved spray dynamics were not feasible across the complete experimental matrix. Future work should investigate transient switching between full and staged injection over a broader range of load conditions and employ dedicated reacting-flow and spray diagnostics to further quantify the mechanisms governing flame stabilization. Overall, the results demonstrate that H_2 injection strategy provides an effective additional degree of freedom for managing the trade-off between flame stability and emissions, enabling the stable operating envelope of a H_2 -Jet-A1 fuel-flexible combustor to be extended toward leaner and increasingly hydrogen-rich conditions. These findings are relevant to the design and operation of fuel-flexible gas-turbine combustors and provide guidance for the development of hydrogen-capable gas-turbine engines.

CRedit authorship contribution statement

Samarjeet Singh: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Nicola Scopolini: Writing – review & editing, Formal analysis. **Matteo Amerighi:** Writing – review & editing, Formal analysis. **Antonio Andreini:** Writing – review & editing, Supervision. **Stefan R. Harth:** Writing – review & editing, Formal analysis, Conceptualization. **Dimosthenis Trimis:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors 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 material related to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2026.157948>.

Data availability

The data and information that support the findings of this article are freely available at <https://doi.org/10.5281/zenodo.23037088>.

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