



Fuel-flexibility study of Jet-A1 and H₂ in a low-swirl multi-burner combustor

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ABSTRACT

Transitioning toward carbon-neutral aviation necessitates innovative strategies. Hydrogen (H₂) is a promising alternative fuel due to its clean combustion characteristics. However, its low volumetric energy density, limited availability, and the need for extensive infrastructure and aircraft redesign constraints limit full adoption. Fuel-flexible burner technologies that enable blending of H₂ with Jet-A1 (or Sustainable Aviation Fuel) present a practical alternative. This study experimentally investigates the impact of H₂ addition in selected burners featuring lifted Jet-A1 spray flames in a multi-burner array developed as part of the European project FFLECS (Novel Fuel-Flexible ultra-Low Emissions Combustion systems for Sustainable aviation). The low-swirl combustor consists of five flames, with fuel-flexible operation implemented in either the central burner (burner 3) or adjacent burners (burners 2 and 4), representing every second or third burner in an annular combustor. High-speed OH* chemiluminescence imaging was employed to analyze flame shape and interactions, and an exhaust gas analyzer system was used to measure pollutant emissions. The flame shape and lift-off height were examined at elevated air inlet temperatures, with the H₂ blending varied up to 100% in the fuel-flexible burner(s). Moreover, H₂ addition in the selected burner(s) improves the lean blowout limit and reduces NO_x and CO emissions in both the fuel-flexible and neighboring Jet-A1 burners. Thus, the integration of fuel-flexible nozzles in selected burners provides novel insights into neighboring flame interactions and supports the development of future ultra-low-emission aero-engines.

Novelty and significance statement: This study investigates the fuel flexibility in a low-swirl multi-burner combustor using Jet-A1 and H₂, combining fuel-flexible burners suitable for up to 100% H₂ operation with Jet-A1 burners in the same combustion chamber. The fuel-flexible burners utilize airblast atomization for Jet-A1 and H₂ jet-in-crossflow injection, enabling stable operation up to 100% H₂ without flashback or thermoacoustic instabilities. To the best of the authors' knowledge, no prior experimental studies have systematically investigated selective burner-level H₂ addition in multi-burner combustors (e.g., every second or every third burner), motivated by constraints of limited onboard H₂ availability. Key findings include: (i) H₂-rich flames have only a minor effect on flame shape but a strong influence on the emissions, (ii) strategic H₂ placement extends lean blowout limits compared to uniform Jet-A1 operation. These results provide novel insights into interactions between neighboring flames in multi-burner systems and demonstrate that targeted H₂ addition can enhance stability and reduce emissions.

1. Introduction

Hydrogen-fueled gas turbines offer a promising route toward achieving cleaner and more sustainable energy systems [1–3], drawing interest for their potential to achieve zero carbon emissions [4]. However, the low volumetric energy density of H₂ necessitates relatively large storage tanks in aircraft. Combined with potential aircraft redesigns depending on flight range, as well as challenges in large-scale production, storage, and safe handling [5], these factors remain major obstacles. Consequently, widespread adoption of H₂ is unlikely before the end of this decade [6–8].

While fully H₂-powered aero-engines will require considerable time to realize, near-term strategies such as limited H₂ injection into conventional fuels or sustainable aviation fuels (SAF) present an attractive approach. This strategy can support retrofit-based combustor development for future low-emission aero-engines with Jet-A1, SAF, and H₂ fuels [9,10]. Fuel-flexible systems capable of operating on both H₂ and aviation fuels can enhance flame stability, reduce local pollutant emissions near airports, and lower overall CO₂ emissions across flights without restricting flight range. Nevertheless, the distinct physical and chemical properties of H₂-rich fuel mixtures, including higher reactivity

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Table 1
Operating conditions of each burner at relative air pressure drop ($\Delta p/P$) of 3% under two topological configurations.

Configuration	T_{air} (K)	$\dot{m}_{\text{Jet-A1}}$ (g/s)		$\dot{m}_{\text{H}_2}$ (g/s)	$\dot{m}_{\text{air}}$ (g/s)	P (kW)	U_b (m/s)
		Burner 3	Other burners	Burner 3			
A	473	0–0.86	0.86	0–0.31	25.3	37.1	75.8
	673	0–0.72	0.72	0–0.26	21.2	31.1	90.5
B	473	0–0.86	0.86	0–0.31	25.3	37.1	75.8
	673	0–0.72	0.72	0–0.26	21.2	31.1	90.5

and flame speed [11], prevent the direct application of conventional combustor designs for low NO_x and stable combustion.

Extensive experimental research has explored the effects of H_2 addition on combustion characteristics in single-burner configurations. Early studies demonstrated that H_2 addition extends flame stability and improves lean blowout (LBO) limits due to higher flame speed and a broader flammability range of H_2 compared to conventional aviation fuel [12–17]. H_2 addition has also been reported to shorten the flame length and alter the flame topology [13,15,17,18]. Furthermore, H_2 addition has been shown to significantly reduce pollutant emissions, particularly CO, by enhancing oxidation rates under lean operating conditions [13,15,17,19]. Consistent with these observations, our recent single-burner study demonstrated the feasibility of operating SAF/Jet-A1 blend with H_2 addition, achieving comparable improvements in flame stability and emission characteristics under aero-engine-relevant conditions [20]. Collectively, these findings provide an important foundation for understanding fuel-flexible combustion behavior in simplified combustion systems.

Despite extensive research on single-burner configurations, a critical gap remains in understanding multi-burner interactions, where neighboring flames can influence stability and emissions. Addressing this gap is essential for advancing H_2 integration in practical aero-engine combustors, which typically feature multiple closely spaced nozzles [21]. Interactions between adjacent flames can significantly alter the local and global flow fields, impacting key combustor performance characteristics such as flame shape, stability limits, lean blowout behavior, and pollutant emissions in carbon-based fuel systems [22–26]. However, the behavior of H_2 /aviation fuel blend flames in multi-burner configurations remains less understood. Systematic dual-fuel experiments under engine-relevant conditions are therefore critical for developing next-generation low-emission combustors and enabling practical H_2 adoption in aero-engines under limited onboard H_2 availability.

This study investigates the effect of non-uniform H_2 fuel distribution on a multi-burner combustor operating at atmospheric pressure and elevated air temperatures. The low-swirl combustor comprises five Jet-A1 flames arranged linearly, with fuel flexibility implemented in the central burner (burner 3) or adjacent burners (burner 2 and 4), capable of operating from pure Jet-A1 to pure H_2 . The outermost burners operate on pure Jet-A1 and serve as periodic boundary conditions for the flame array. The resulting flame shape, lift-off height, and exhaust emissions are analyzed as H_2 content increases from 0%–100%, with particular emphasis on the interaction between the fuel-flexible and neighboring Jet-A1 burners.

2. Experimental setup and measurements

2.1. Multi-burner facility

Experiments were conducted on a multi-burner combustor in which fuel flexibility was implemented in selected burner(s) to investigate the combustion characteristics of H_2 and Jet-A1. Fig. 1(a) shows the multi-burner facility, with fuel flexibility implemented only in the central burner, operated on pure H_2 while the remaining burners are fueled with Jet-A1. The rig comprises a five-burner array operating at

atmospheric pressure and represents a simplified conventional annular combustor. Previous studies have reported experiments on this facility for Jet-A1-only operation [23,25]. The setup includes five separate air supply plenums, a combined combustion chamber with optical access, and an exhaust. Compressed air is preheated up to 673 K and fed into the plenums. Each burner has a cross-sectional area of $100 \times 100 \text{ mm}^2$ and a height of 460 mm from the burner exit. The chamber is enclosed with quartz glass on all sides for optical access, while the exhaust is open to the ambient.

The fuel-flexible nozzle employed in this study has been previously described for a single-burner setup in [15] (Fig. 1(b)). The main features of the nozzle are: two main air supplies separated by a prefilmer lip, with only one supply imparting swirl. Additionally, a small non-swirled airflow enters near the nozzle axis in the axial direction to prevent flame flashback and enhance operational safety. The nozzle has an effective area of 380 mm^2 , enabling dual-fuel operation across the selected burners. Jet-A1 and H_2 are supplied via a water-cooled fuel lance to maintain room temperature and prevent coking of Jet-A1. Jet-A1 is injected axially through a hollow cone atomizer (flow number 0.74, bore diameter 0.35 mm, inner half-angle 60°) using a two-step airblast atomization, forming a liquid film on the prefilmer that is then atomized at the prefilmer tip by high air velocities. H_2 is injected through 12 holes of 0.35 mm diameter at the outer prefilmer on an annular ring into the air crossflow. These H_2 injectors are mounted perpendicular to the airflow and inclined at 55° relative to the burner axis. The burner exhibits a relatively low overall swirl number around 0.1 (no inner recirculation zone targeted). Such a low swirl number promotes a lifted flame with improved flashback resistance and low- NO_x potential, relevant for modern gas turbine applications. The non-reacting flow structure and mixing dynamics in a single-sector burner were characterized using Reynolds-Averaged Navier–Stokes (RANS) simulations in our previous work [15], offering further details for interested readers.

A top-view schematic illustrating the burner arrangement and numbering (1–5) is shown in Fig. 1(c). To systematically investigate the influence of spatial fuel heterogeneity on flame stability and emissions, the five-burner linear array was operated under two distinct configurations. The topological arrangements are: Configuration A – central burner (burner 3) fueled with a Jet-A1/ H_2 blend and adjacent burners (burners 2 and 4) on pure Jet-A1; Configuration B – central burner on pure Jet-A1 and adjacent burners supplied with the Jet-A1/ H_2 blend. To ensure experimental consistency and minimize boundary effects in both cases, the outermost burners (burners 1 and 5) were maintained at constant Jet-A1 flow across all operating conditions. This arrangement mimics annular combustor operation in which every second or third burner is fuel-flexible.

2.2. Operating conditions and fuel splits

The mass flow rate of Jet-A1 was measured using Coriolis mass flow meters ($\pm 0.1\%$ accuracy), H_2 using a thermal mass flow controller ($\pm 0.1\%$ accuracy), and total airflow using a thermal flow meter ($\pm 0.5\%$ full-scale accuracy). Experiments were conducted at atmospheric pressure with preheated air temperatures (T_{air}) of 473 K and 673 K. The five burners were ignited using individual pilot flames, which were

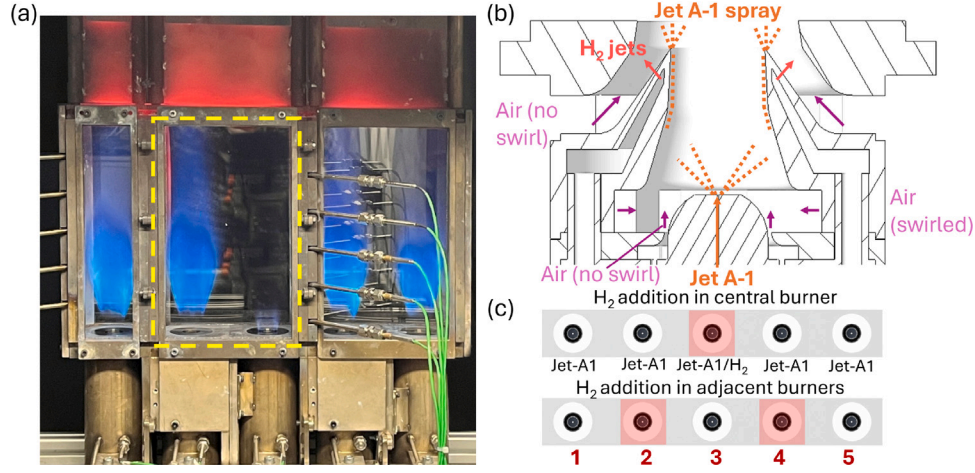


Fig. 1. (a) Multi-burner combustor with the central burner on 100% H₂ and neighboring burners on Jet-A1, (b) fuel-flexible nozzle schematic, and (c) top-view schematic of combustor with burner numbers.

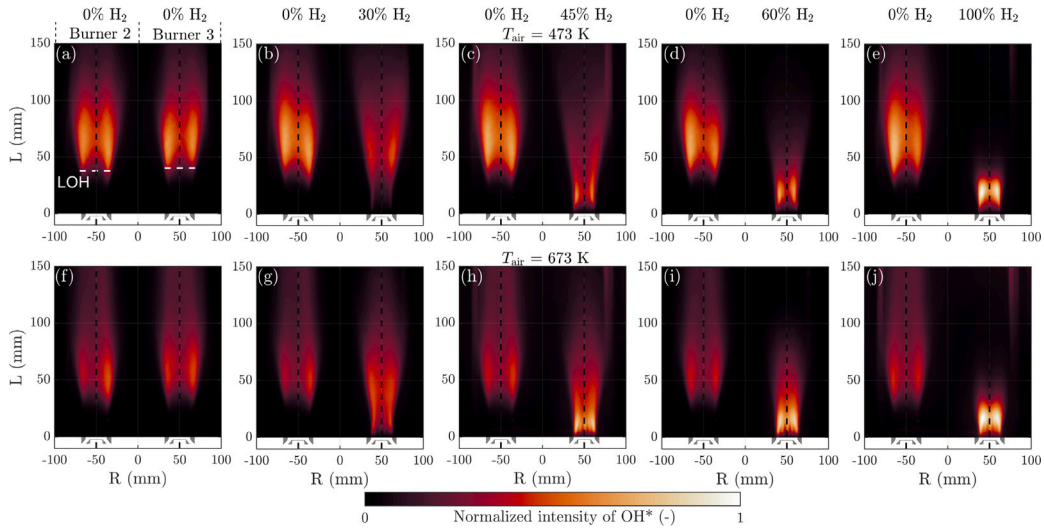


Fig. 2. Normalized time-averaged OH* chemiluminescence images for different Jet-A1/H₂ fuel splits (burner 3) at (a–e) $T_{\text{air}} = 473 \text{ K}$ and (f–j) $T_{\text{air}} = 673 \text{ K}$. Operating conditions for configuration A are listed in Table 1.

withdrawn immediately after successful flame stabilization. The total air mass flow rate ($\dot{m}_{\text{air}}$) was kept constant to maintain a fixed thermal power (P) per burner. Fuel mass flow rates are denoted as $\dot{m}_{\text{Jet-A1}}$ and $\dot{m}_{\text{H}_2}$. The H₂ fraction in the fuel-flexible burner(s) was systematically varied from 0 to 100%, defined as the ratio of H₂ thermal power to the total thermal power of Jet-A1 and H₂ [13]. All other operating parameters were held constant to isolate the effects of fuel splits. A detailed summary of the experimental conditions is provided in Table 1, where the relative air pressure drop ($\Delta p/P$) is kept constant across varying T_{air} to maintain comparable airblast atomization and spray conditions, leading to approximately invariant Weber-number scaling across all cases.

2.3. Measurement techniques

Side-view OH* chemiluminescence images of flames from burners 2 and 3 (indicated by the yellow dashed box in Fig. 1(a)) are captured. A high-speed camera (Phantom V1212) coupled with a high-speed intensifier (LaVision HS-IRO) is used for imaging. A 100 mm f/2.8 UV lens (Cerco) with OH* filter (Chroma, $T > 80\%$ over 300–340 nm, FWHM 10 nm) is employed. Images are recorded at 1 kHz for 5 s at 1280×800 pixels. Given a field of view of $356 \text{ mm} \times 224 \text{ mm}$, the

image acquisition system provides a spatial resolution of $278 \text{ } \mu\text{m}/\text{pixel}$ horizontally and $280 \text{ } \mu\text{m}/\text{pixel}$ vertically.

NO_x and CO emissions were measured by sampling exhaust gases for 40 s at 1 Hz once the operating conditions stabilized. A temperature-controlled probe positioned 435 mm downstream of the burner exit acquired measurements above burners 2 and 3. Gas samples are passed through a dehydrator to individual analyzers under controlled pressure. Concentrations of O₂ (ABB Magnox 206), CO, and CO₂ (ABB Uras 26) are measured, while NO_x (NO + NO₂) is determined using an Eco Physics CLD 700 EL.

3. Results and discussion

Flame morphology based on OH* chemiluminescence, flame lift-off height (LOH), lean blowout (LBO) limits, and pollutant emissions are systematically evaluated for H₂ fuel splits ranging from 0 to 100% in the multi-burner combustor under configurations A and B. For reference, LOH, LBO limits, and emission characteristics obtained from the single-sector combustor in our previous study [15] are included to enable direct comparison with the multi-burner combustor.

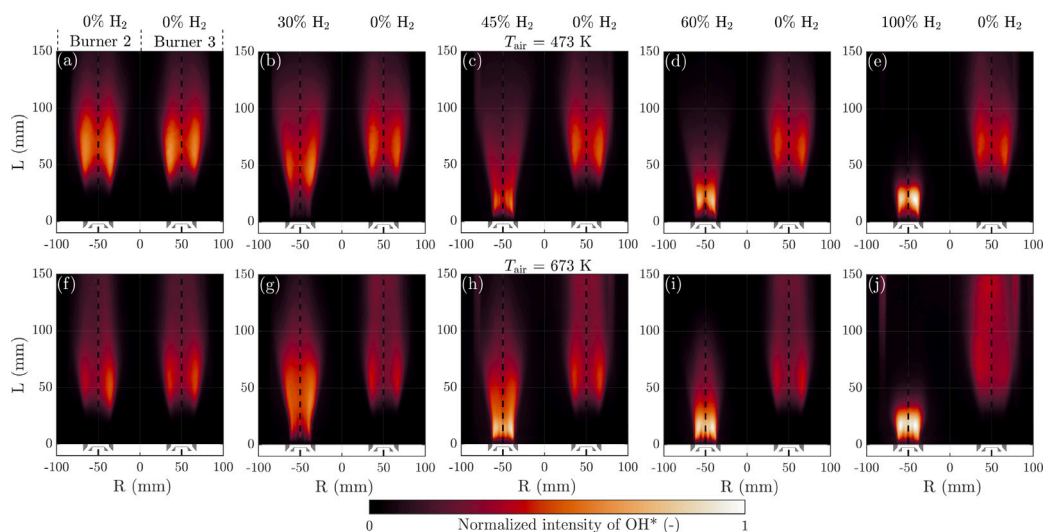


Fig. 3. Normalized time-averaged OH* chemiluminescence images for different Jet-A1/H₂ fuel splits (burner 2) at (a–e) $T_{\text{air}} = 473$ K and (f–j) $T_{\text{air}} = 673$ K. Operating conditions for configuration B are listed in Table 1.

3.1. Flame shape and morphology

In this section, time-averaged OH* chemiluminescence images for configurations A (Jet-A1 in burner 2 and Jet-A1/H₂ blends in burner 3) and B (Jet-A1 in burner 3 and Jet-A1/H₂ blends in burner 2) are shown up to 100% H₂. For each fuel split, the images are normalized by the maximum OH* intensity obtained during 100% H₂ operation at the corresponding T_{air} to enable consistent comparison across all operating conditions. Systematic variation of the H₂ fuel split at constant P is particularly relevant for aero-engine applications, where performance and emissions must be optimized for Landing and Take-Off (LTO) cycle conditions [13,27].

Fig. 2 presents normalized time-averaged OH* chemiluminescence images illustrating the flame structures for configuration A. The experiments were performed at air inlet temperatures of $T_{\text{air}} = 473$ K and 673 K, with thermal powers of $P = 37.1$ kW and 31.1 kW per burner, respectively, and a fixed relative pressure drop ($\Delta p/P$) of 3% across all nozzles (see Table 1). In both T_{air} cases, the specific thermal power is 1.46 MJ/kg_{air}, corresponding to an equivalence ratio of approximately 0.5 for Jet-A1 combustion, representative of maximum-thrust conditions in aero-engines.

At $T_{\text{air}} = 473$ K, pure Jet-A1 operation produces broadly distributed, high-luminosity reaction zones located far downstream of the fuel nozzle, with both flames (burner 2 and 3) exhibiting nearly identical spatial characteristics (Fig. 2(a)). It is evident that the flame is lifted, enabling a certain degree of pre-evaporation and premixing of Jet-A1 fuel with air. For up to 15% H₂ (not shown), the flame topology at burners 2 and 3 remains similar to the pure Jet-A1 case, due to limited radial H₂ jet penetration in the fuel-flexible burner. As the H₂ content further increases (in burner 3), the flame becomes more compact and shifts upstream toward the burner due to the higher flame speed and reactivity of H₂-rich fuel, as depicted in Fig. 2(b–e). For instance, at 30% H₂, the Jet-A1/H₂ flame notably shifts towards the burner exit with an increase in radial H₂ jet penetration (Fig. 2(b)). In contrast, the adjacent Jet-A1 flame (burner 2) remains largely unaffected up to 45% H₂, with noticeable changes beyond this fuel split.

At 45% H₂, enhanced radial H₂ jet penetration increases fuel concentration near the outer recirculation zone, stabilizing the Jet-A1/H₂ flame closer to the burner exit (Fig. 2(c)). The remaining Jet-A1 fuel (in burner 3) sustains a relatively long and broad reaction zone. As the H₂ content increases to 60%, the Jet-A1/H₂ flame shows a highly luminous reaction zone anchored in the outer recirculation region near the burner exit, while the overall flame becomes more compact as

the Jet-A1 fraction decreases (Fig. 2(d)). Simultaneously, the adjacent Jet-A1 flame (burner 2) exhibits slightly reduced intensity on the side facing the Jet-A1/H₂ flame. This behavior is likely driven by turbulent mixing between neighboring flames, whereby burnt gases from the H₂-rich flame interact with the adjacent Jet-A1 flame, while fresh reactants are simultaneously entrained toward the H₂-rich flame. During a pure H₂ operation, the flame (burner 3) is highly compact and remains close to the exit, yet remains distinctly detached (Fig. 2(e)). Correspondingly, the adjacent Jet-A1 flame experiences further intensity reduction on the side facing the H₂ flame, highlighting the modest influence of the fuel-flexible burner.

At elevated T_{air} , the relative pressure drop is kept constant, leading to an increase in bulk velocity (U_b). The effect of this increased U_b on the lift-off height is counterbalanced by the concurrent rise in laminar flame speed. Simultaneously, higher T_{air} enhances Jet-A1 pre-evaporation and premixing, promoting a more homogeneous mixture. The normalized time-averaged OH* chemiluminescence images at $T_{\text{air}} = 673$ K (Fig. 2(f)–(j)), obtained at the same specific thermal power as in Fig. 2(a–e). Fig. 2(a) reveals a distinctly more compact reaction zone positioned closer to the burner exit during pure Jet-A1 operation. This upstream shift is consistent with the strengthening of the outer recirculation zone at elevated T_{air} , associated with a reduced density expansion ratio between fresh and burnt gases.

With increasing H₂ content, the relocation of the reaction zone in the Jet-A1/H₂ flame (burner 3) toward the burner becomes more pronounced than at 473 K (Fig. 2(g)–(j) versus Fig. 2(b)–(e)). In contrast, the Jet-A1 flame (burner 2) remains consistent for all the fuel splits up to 100% H₂. For instance, at 30% H₂, the high-luminosity reaction zone in burner 3 moves closer to the burner exit (Fig. 2(g)). At 45% and 60% H₂, the reaction zone in burner 3 becomes more compact and remains near the burner exit, while the OH* intensity increases (Fig. 2(h), (i)) compared with lower T_{air} cases (Fig. 2(c), (d)). At 100% H₂ operation, the fuel-flexible burner exhibits a strongly luminous, highly compact reaction zone (Fig. 2(j)). Although fuel splits above 30% may locally deteriorate premixing and generate conditions closer to stoichiometric at larger radii, the overall flame anchoring location remains largely unchanged. This robustness reflects the burner design, which sustains a uniform, high-velocity exit flow, further reinforced by the axial momentum imparted by the angled H₂ injection.

Fig. 3 presents normalized time-averaged OH* chemiluminescence images illustrating flame shapes for configuration B at $T_{\text{air}} = 473$ and 673 K, with operating conditions summarized in Table 1. In Fig. 3(a, f), pure Jet-A1 flames at both T_{air} are essentially identical to those

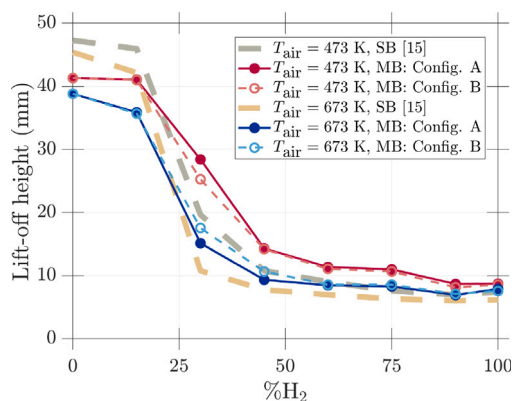


Fig. 4. Effect of H_2 addition on lift-off height in multi-burner (configurations A and B) and single-burner at different T_{air} . SB: Single burner and MB: Multi-burner array.

observed in configuration A (Fig. 2(a), (f)). At $T_{air} = 473$ K, for H_2 fuel splits between 30% and 100% (Fig. 3(b)–(e)), the Jet-A1/ H_2 flame (burner 2) exhibits OH^* intensities comparable to configuration A (Fig. 2(b)–(e)). In contrast, the centered Jet-A1 flame (burner 3) shows lower OH^* intensity than the corresponding Jet-A1 flame in configuration A. Moreover, beyond 60% H_2 , additional differences emerge: in configuration A (Fig. 2(d)–(e)), the neighboring Jet-A1 flame (burner 2) experienced slight intensity reduction on the side adjacent to the Jet-A1/ H_2 flame, whereas in configuration B (Fig. 3(d)–(e)), the central Jet-A1 flame (burner 3) exhibits reduced intensity on both sides due to interactions with surrounding H_2 -rich flames (burners 2 and 4). Burnt gases from the H_2 -rich flames entrain toward the central Jet-A1 flame from both sides. Simultaneously, fresh reactants from the adjacent Jet-A1 flames are drawn toward the H_2 -rich flames, modifying local flow and heat release distribution.

At elevated T_{air} (Fig. 3(g)–(j)), the OH^* intensities of the blended Jet-A1/ H_2 flame (burner 2) and the central Jet-A1 flame (burner 3) closely resemble those observed in configuration A (Fig. 2(g)–(j)). However, beyond 60% H_2 , the central Jet-A1 flame (burner 3) loses its well-defined, compact reaction zone. While the overall flame appears larger, the characteristic lateral “wings” of a lifted spray flame are absent. This behavior arises from the combined interactions with neighboring H_2 -rich flames (burners 2 and 4). The concentrated heat release at larger radii near the burner exit of the H_2 -rich flames enhances the entrainment of burned gases into the central Jet-A1 flame. This localized heat release increases the local flow rate, promoting stronger mixing and a more homogeneous equivalence ratio within the central flame. Simultaneously, the entrainment of hot gases from the H_2 -rich flames accelerates droplet evaporation in the central Jet-A1 flame, contributing to a more uniform fuel–air distribution. Moreover, the flow field of the central Jet-A1 burner may be influenced by the strong flow expansion near the exit of the H_2 -rich burners, which can reduce the size of the outer recirculation zone. Collectively, these interactions produce a broader, less structured flame anchored near the burner axis. These observations highlight the strong influence of neighboring H_2 -rich flames on the behavior of Jet-A1 flames under engine-relevant conditions in multi-burner combustors.

3.2. Influence of H_2 on flame lift-off height (LOH)

LOH is a critical parameter for assessing flame stability, as it reflects the extent of fuel–air mixing prior to flame stabilization and serves as an important indicator of pollutant emissions. LOH is defined as the axial distance between the burner exit plane and the base of the flame, determined from time-averaged OH^* chemiluminescence images. Fig. 4 illustrates the variation of LOH in the fuel-flexible burner, namely

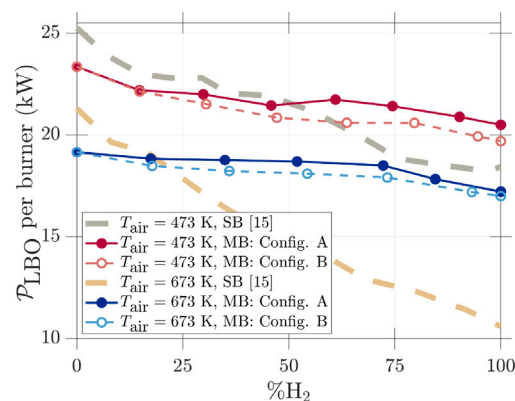


Fig. 5. Improvement in LBO limits with increasing H_2 splits in multi-burner (configurations A and B) and single-burner combustors at different T_{air} .

burner 3 in configuration A and burner 2 in configuration B, for both the multi-burner and single-sector combustors as a function of H_2 fuel splits at two T_{air} . In the multi-burner combustor, LOH decreases progressively with increasing H_2 content in both configurations, but is less pronounced than in the single burner. For the pure Jet-A1 case (0% H_2), LOH in a multi-burner setup is lower compared to a single-sector burner, likely due to a change in flow fields and interaction of flames that promote earlier flame stabilization. Up to 15% H_2 , the lift-off is decreases slightly at $T_{air} = 673$ K due to increased flame speed and limited radial jet penetration, whereas it remains nearly unchanged at $T_{air} = 473$ K. At 30% H_2 , the flame at 473 K and 673 K shifts closer to the burner exit but remains higher than in the single-burner case, likely related to the flame stabilization at the outer recirculation zone (Fig. 2(b), (g) in configuration A and Fig. 3(b), (g) in configuration B). A slight variation in the LOH is observed between configurations A and B at this fuel split, arising from interactions between neighboring Jet-A1/ H_2 and Jet-A1 flames under different topologies. This alters the local mixing and flow field, thereby slightly shifting the flame stabilization location. At higher H_2 blends, local fuel-rich conditions near the burner periphery lead to a decrease in LOH for both configurations A and B of multi-burner as well as for single-sector combustors. Overall, a modest but consistent difference in LOH is observed between single- and multi-burner configurations up to 30% H_2 , beyond which the difference becomes negligible at higher H_2 fuel splits. In contrast, the LOH of the neighboring pure Jet-A1 flames in both multi-burner configurations (A and B) remains largely unchanged across all fuel splits, exerting minimal influence on LOH from the fuel-flexible flame(s).

3.3. Influence of H_2 on lean blowout (LBO) limits

LBO represents a critical stability limit at low thermal-power operation, where reduced heat release and slower reaction rates can compromise flame anchoring. The ability of a flame to resist local extinction depends on both reaction rate and flow strain, and therefore, the fuel composition directly affects the LBO limit, making it a key design parameter in lean combustion systems. LBO is typically defined as the maximum air-to-fuel ratio or minimum thermal power at which the flame can be sustained before complete extinction, representing the minimum fuel flow required for stable operation under given conditions.

In our study, LBO experiments were conducted on the multi-burner combustor to evaluate the effect of H_2 addition in the fuel-flexible burner(s) on overall flame stability. To ensure controlled blowout in the central region, the outermost burners (1 and 5) were operated 10% richer. This compensates for higher wall heat losses and the

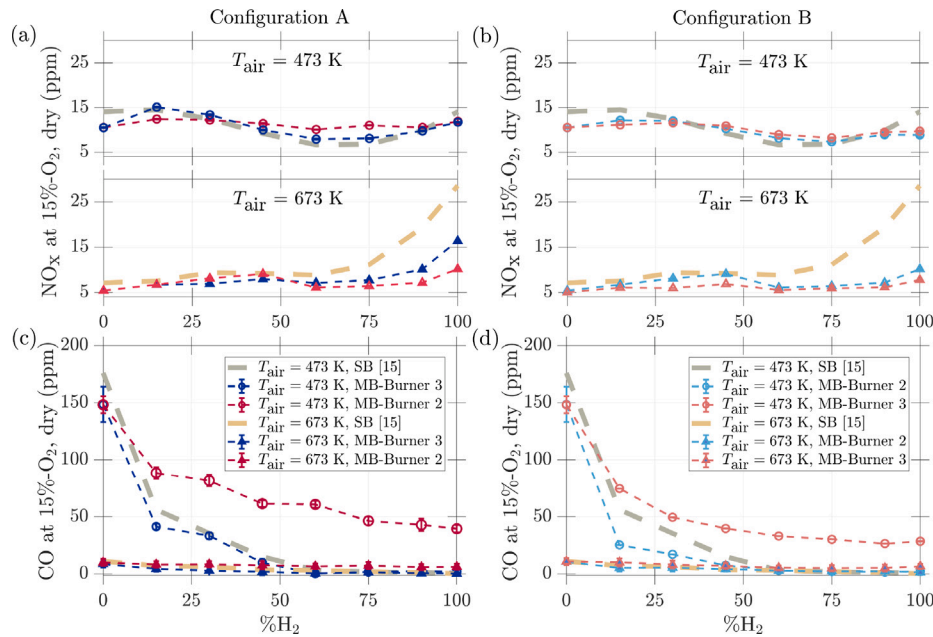


Fig. 6. Effect of H_2 addition on NO_x and CO emissions in multi-burner (configurations A and B) and single-burner combustors at different T_{air} . Error bars indicate the maximum measurement range during sampling time.

absence of adjacent stabilizing flames, ensuring that the pure Jet-A1 flames in the inner burners (2–4) extinguish first. This approach provides a consistent boundary condition and isolates the influence of fuel flexibility on the inner flames. Fig. 5 depicts the thermal power at LBO (P_{LBO}) for different H_2 splits at two T_{air} for configurations A and B. At $T_{air} = 473$ K, P_{LBO} decreases from 23.4 kW (pure Jet-A1) to 20.5 kW (100% H_2) in configuration A, and from 23.4 kW to 19.5 kW in configuration B. In contrast, at elevated $T_{air} = 673$ K, the reduction in P_{LBO} is less pronounced, dropping from 19.2 kW to 17.2 kW for both configurations. LBO improvement in configuration B is more pronounced at low T_{air} , as the central Jet-A1 flame is slower and less reactive, making the influence of adjacent H_2 -rich flames more effective in enhancing flame anchoring. At high T_{air} , the Jet-A1 flame is already more stable, so the marginal benefit from neighboring H_2 -rich flames is reduced. By comparison, the single-burner combustor exhibits substantially improved LBO limits for both T_{air} compared to the multi-burner combustor, where neighboring Jet-A1 burners extinguish earlier and determine the LBO limits. This suggests that extending fuel flexibility to each burner in a multi-burner arrangement could further enhance overall combustor stability.

3.4. Influence of H_2 on pollutant emissions

Pollutant emissions (NO_x and CO) represent a key consideration in aero-engine development. NO_x and CO concentrations, normalized to 15% O_2 , are reported in Fig. 6 for varying H_2 content in the fuel-flexible and adjacent Jet-A1 burners. The dry exhaust gas measurements from burners 2 and 3 in both multi-burner configurations are presented alongside single-burner results for direct comparison.

3.4.1. Improvement in NO_x emissions

Fig. 6(a, b) illustrates the influence of H_2 addition on NO_x emissions at both T_{air} in both the multi-burner (configurations A and B) and single-burner combustors. At $T_{air} = 473$ K, both configurations (A and B) show that burners 2 and 3 exhibit approximately 30% lower NO_x emissions than the single burner during pure Jet-A1 operation. This reduction is driven by neighboring flame interaction, which promotes earlier flame anchoring and likely induces recirculation of hotter exhaust gases within the outer recirculation zone. This enhances mixing

and promotes pre-evaporation of the reactants, as also supported by the reduced LOH under these conditions (see Fig. 4). In contrast, at $T_{air} = 673$ K, the NO_x reduction is less pronounced, consistent with improved pre-evaporation already occurring at elevated inlet temperatures.

During pure H_2 operation, at $T_{air} = 473$ K, NO_x emissions in configuration A approach those of the single burner for both the fuel-flexible and adjacent Jet-A1 flames, whereas configuration B exhibits slightly lower values. At $T_{air} = 673$ K, the fuel-flexible burner shows further reductions in NO_x emissions of approximately 40% for configuration A and 57% for configuration B relative to the single burner. This is driven by entrainment of fresh gases from the central Jet-A1 flame toward the adjacent H_2 flames, which moderates peak temperatures and reduces NO_x emissions. In contrast, NO_x emissions in the neighboring Jet-A1 flame increase by approximately 35% for both configurations (A and B) under 100% H_2 operation in the fuel-flexible burner compared to pure Jet-A1 operation, further confirming neighboring flame interactions (see Figs. 2j and 3(j)).

Moreover, at both 473 K and 673 K, a clear minimum in NO_x emissions is observed at intermediate H_2 blends of approximately 60%–75%, with values around 8 ppm (15% O_2 , dry), which are significantly lower than those obtained during operation with pure Jet-A1 (0% H_2) and pure H_2 (100% H_2) operation. This indicates that a non-uniform H_2 fuel distribution strategy may be advantageous; for instance, alternating higher H_2 fuel splits such as 60% in every second or third nozzle while maintaining others on pure Jet-A1 could potentially reduce overall emissions more effectively than applying a uniform 30% H_2 split across all nozzles.

3.4.2. Improvement in CO emissions

As expected, CO emissions decrease markedly with increasing H_2 content in both the multi-burner (configurations A and B) and single-burner combustors (Fig. 6(c, d)). At $T_{air} = 473$ K, during pure Jet-A1 operation, CO emissions for both configurations A and B are 15% less compared to the single burner. Even a modest addition of 15% H_2 reduces CO emissions drastically for the fuel-flexible burner in both configurations A and B. In contrast, CO emissions in the single-burner case are slightly higher than those of the fuel-flexible burner in configuration A and significantly higher than in configuration B. The effect of H_2 addition in the fuel-flexible burner is also noticed in

the neighboring Jet-A1 flame for both configurations, where a higher reduction in CO emissions is observed in configuration B. Increasing H_2 in the fuel-flexible burner leads to a continuous decrease in CO emissions for both the fuel-flexible and neighboring Jet-A1 burners, with configuration B consistently exhibiting lower CO emissions levels than configuration A. In fuel-flexible burner(s), CO levels approach zero beyond approximately 45% H_2 in both configurations, whereas continuous reduction in CO levels is observed up to 100% H_2 in neighboring Jet-A1 burner(s). Here, CO emissions are reduced by approximately 70% in configuration A and 80% in configuration B compared to the pure Jet-A1 case. In contrast, the single-burner configuration maintains slightly higher CO emissions across all fuel splits. Such pronounced reduction in CO with H_2 addition is particularly relevant for low-thrust aero-engine operating conditions, such as idle/taxiing.

At elevated T_{air} , CO emissions are already low during pure Jet-A1 operation (≈ 10 ppm) and decrease further with increasing H_2 content, ultimately approaching zero for both configurations in multi-burner and single-sector combustors as the H_2 content increases. These results highlight the potential of strategic H_2 integration in multi-burner systems to achieve low-emission operation across a wide range of operating conditions.

4. Conclusion

This study demonstrates the fuel flexibility of a lab-scale multi-burner combustor operating on Jet-A1 and H_2 . Selective H_2 blending is implemented for the first time in two topological arrangements: configuration A with the central burner on Jet-A1/ H_2 blends and surrounding burners on Jet-A1, and configuration B with the central burner on Jet-A1 and adjacent burners on Jet-A1/ H_2 , while the outermost burners remained on Jet-A1. Increasing H_2 fuel splits at air inlet temperatures of 473 K and 673 K shifts the Jet-A1/ H_2 flame(s) closer to the burner exit and reduces their lift-off height, whereas the neighboring Jet-A1 flames remain largely unaffected. Modest variations in chemiluminescence intensity are observed in the Jet-A1 flames at high H_2 splits, reflecting pronounced neighboring flame interactions.

Dual-fuel operation in the fuel-flexible burner(s) significantly extends the overall lean blow-out (LBO) limits in both multi-burner configurations, although the improvement remains lower than in a single-sector combustor. NO_x emissions remain below 10 ppm for 45%–90% H_2 in the fuel-flexible burner(s), with reductions also observed in the neighboring Jet-A1 flames due to interactions with the adjacent Jet-A1/ H_2 flames. Furthermore, even a modest 15% H_2 addition significantly reduces CO emissions in both the fuel-flexible and the neighboring Jet-A1 burners at low air inlet temperatures. With 100% H_2 addition, CO emissions in the neighboring Jet-A1 flame(s) decrease further by factors of 3.7 and 5.2 in configurations A and B, respectively, highlighting the potential for low-emission operation under part-load conditions.

Overall, this study indicates that incorporating fuel-flexible nozzles, in every second burner or every third burner, improves flame stability, extends LBO limits, and substantially reduces pollutant emissions. The results reported highlight the potential of H_2 -blend strategies to achieve ultra-low emissions in future hybrid aero-engines.

CRediT authorship contribution statement

Samarjeet Singh: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Stefan R. Harth:** Writing – review & editing, Formal analysis, Conceptualization. **Dimosthenis Trimis:** Writing – review & editing, Supervision, Funding acquisition.

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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Data availability

The data and information that support the findings of this article are freely available at <https://doi.org/10.5281/zenodo.23062725>.

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