

A review of hydrogen micromix combustion technologies for gas turbine applications

Gaurav Singh ^{*}, B. Deneys J. Schreiner, Xiaoxiao Sun, Vishal Sethi

Centre for Propulsion and Thermal Power Engineering, Cranfield University, MK43 0AL, UK

ARTICLE INFO

Handling Editor: Ramazan Solmaz

Keywords:

Hydrogen
Micromix combustion
NO_x formation
Injector
Flashback

ABSTRACT

Hydrogen micromix combustion is a promising technology for gas turbines, introducing rapid, miniaturized air-fuel mixing, significantly reducing combustion zone length and nitrogen oxides (NO_x) emissions. This review evaluates the state-of-the-art hydrogen micromix combustion technologies, focusing on injector performance, flashback characteristics, and NO_x reduction strategies. Injector designs are categorized based on premixing and flame stabilization techniques. While stationary gas turbines approach Technology Readiness Level (TRL) 9, aviation applications remain below TRL 4. This review identifies key design principles and predictive modelling challenges and presents a development roadmap for advancing hydrogen micromix combustion technology for aviation from TRL 4 to TRL 9 by 2040.

Abbreviation

AGP	Air guiding panel	LES	Large eddy simulations
AM	Additive manufacturing	LPBF	Laser powder bed fusion
AQF	Attached quadruple flame	LTO	Landing and take-Off Cycle
BJT	Binder jet technology	MT	Multitube
BR	Blockage ratio	NO _x	Nitrogen oxides
CC	Complex chemistry	RANS	Reynolds averaged Navier stokes
CFD	Computational fluid dynamics	RKE	Realizable k-epsilon
CVP	Contra-rotating vortex pairs	RQL	Rich burn quick quench lean
DLN	Dry low NO _x	SKE	Standard k-epsilon
DMLM	Direct metal laser melting	TET	Turbine entry temperature
DMLS	Direct metal laser sintering	TFM	Thickened flame model
EBU	Eddy break-up	TRL	Technology readiness level
ED	Energy density	UHC	Unburned hydrocarbons
EDC	Eddy dissipation concept	Symbols	
EDM	Electric discharge machining	Φ	Equivalence ratio
EEINO _x	Energy based NO _x emission index	τ	Residence time
FGM	Flamelet generated manifold	J	Momentum flux ratio
I-V	Inter Vortex	Le	Lewis number
JICF	Jet in cross flow	Sc	Schmidt number
LH ₂	Liquid hydrogen	S _f	Fuel induced swirl number
LDI	Lean direct injection	S _n	Vane induces swirl number

1. Introduction

The shift toward decarbonization in power generation and transportation sector necessitates alternative fuels. Green hydrogen (H₂) emerges as a promising fuel for gas turbine applications. However, the transition to H₂ as a fuel for gas turbines requires a paradigm shift in combustor technology when compared to kerosene [1]. The advantages offered by H₂ as fuel are significant: zero carbon emissions (CO, CO₂, and unburned hydrocarbon), wide flammability limits, and high flame speed. Further, low soot or particulates content can be expected as the only source will be from lubrication oil. Nonetheless, the open technical challenges in fundamental research, design methods, safety, and operability are nontrivial thus requiring a sustained effort over long time-scales [2].

Leading stationary gas turbine manufacturers such as Siemens Energy 3,4 and Mitsubishi Hitachi Power Systems (MHPS) have long been implementing natural gas - H₂ blends and are now progressing toward pure H₂-fueled gas turbines [5]. Companies such as Siemens Energy, MHPS, General Electric (GE), and Kawasaki Heavy Industries Ltd (KHI) [6] have demonstrated or plan to demonstrate up to 100% H₂ compatibility. These demonstrations have shown that the Dry Low NO_x (DLN) combustion technology used in these engines can safely operate on H₂, bringing the technology close to Technology Readiness Level (TRL) 9. Amongst these, the combustion systems employed by KHI, MHPS and GE are DLN micromix combustion technology. Micromix combustion

^{*} Corresponding author.

E-mail address: gaurav.singh@cranfield.ac.uk (G. Singh).

<https://doi.org/10.1016/j.ijhydene.2025.04.007>

Received 14 February 2025; Received in revised form 31 March 2025; Accepted 1 April 2025

Available online 14 April 2025

0360-3199/© 2025 The Authors. Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

technology involves the use of multiple small-scale flames to achieve rapid fuel-air mixing and short flame lengths, thus significantly reducing NO_x emissions, while mitigating auto-ignition and flashback associated with premixing.

In contrast the aviation industry, which faces similar pressures to decarbonize, lags and can potentially learn and adopt strategies from the stationary gas turbine community. The utilization of H_2 in aero gas turbine combustion systems dates back to the mid-20th century, with a modified Martin B-57B twin-engine aircraft by NASA [7] and Tu-155 [8] turbofan aircraft designed to run on liquid hydrogen (LH_2). Both studies concluded that H_2 has superior combustion characteristics and the only deterrents to its widespread application were low density, limited availability, and the complexities associated with its handling. Despite such promising benefits and historical successes, the H_2 combustion technology in the aviation sector is still below TRL 4 and needs accelerated development. Additional requirements such as altitude relight, higher OPR and more stringent safety requirements than in power industry require further research. However, knowledge from the power industry can be utilized to advance the micromix combustion technology for aero engine.

The use of H_2 as a fuel not only directly addresses the urgent need for decarbonization but also offers a unique advantage: water vapor is the only combustion by-product. Unlike conventional kerosene fuel cycles, where reducing fuel burn is a primary concern due to its direct relation to carbon emissions. H_2 cycles may permit exploration of engine cycles with lower Turbine Entry Temperatures (TETs) and Overall Pressure Ratios (OPRs), potentially greatly reducing NO_x emissions, while only slightly increasing mission water vapor production. Lower TETs may also enhance the durability of hot-end components, thus allowing for the use of less exotic materials. This may further potentially reduce manufacturing costs and extend the lifecycle of these components. However, the increase in water vapor from H_2 combustion can significantly raise the likelihood of contrail formation. Nevertheless, contrails may largely be eliminated by appropriate aircraft mission management. Contrails, contrail avoidance measures, and their implications for H_2 -fueled aircraft are elaborated in the ENABLE H_2 report from Rolt et al. [9].

H_2 has a very high energy density by mass 120 MJ/kg, approximately three times that of kerosene. It has a high laminar flame speed and wide flammability limits due to its high reaction rates (7 times that of kerosene) and high preferential diffusion coefficient [10]. Additionally, the low ignition energy of H_2 improves its ignitability compared to kerosene. Low pressure combustion tests have demonstrated that H_2 can maintain stable combustion at pressure as low as 0.01 bar at an equivalence ratio (Φ), compared to 0.043 bar for kerosene [7]. This indicates that H_2 could offer better performance in altitude relights conditions, owing to its broad flammability limits and low-pressure flame stability.

The physical properties of H_2 facilitate the development of compact and novel combustion systems for aero engines while maintaining key performance and operability criteria such as altitude relight, low pressure loss, and required outlet temperature profiles [11]. The properties of LH_2 also enable innovative thermal management systems such as cooled cooling air, facilitating reduction of cooling air demand and allowing for more thermally efficient engine configurations. Moreover, the transition to H_2 fuels might potentially reshape the economics of the aviation industry [12]. The transition to green H_2 promotes resilience against diminishing fossil fuel reserves and market volatility, ensuring the long-term sustainability of the aviation industry [13].

The study by Cecere et al. [14] provides a review of various H_2 combustion technologies for gas turbine applications, such as Rich burn-Quick mix-Lean burn (RQL), axially staged combustion, Lean Direct Injection (LDI), and micromix. However, it does not comprehensively address the variety of micromix injector technologies, their underlying design principles, or developmental progress. Similarly, Funke et al. [15] presented an in-depth analysis of micromix combustion technology but limited their study to a specific design developed at

Aachen University.

Therefore, this paper provides a comprehensive review of H_2 micromix combustion technology, detailing the state-of-the-art in both stationary and aero gas turbine applications. It specifically addresses various micromix combustor concepts currently under research and development at different institutions, encompassing both experimental investigations and numerical simulations. Particular attention is given to their underlying design principles, development stages, utilized design tools, and operational performance. The review further evaluates the effectiveness of numerical methods in capturing H_2 -air mixing processes, flame characteristics, and combustion dynamics, aiming to align industrial understanding with state-of-the-art developments. Subsequently, a roadmap tailored specifically for the aero engine sector is presented, outlining strategic directions and recommendations to facilitate targeted research and expedite the maturation and implementation of H_2 micromix combustion technology in aviation gas turbines.

2. NO_x formation

In gas turbine combustion, NO_x (NO and NO_2) is produced from atmospheric nitrogen at elevated temperatures and pressures. Three primary pathways contribute to NO_x formation in H_2 -air combustion: the N_2O mechanism, the NNH mechanism, and the thermal NO mechanism. Capurso et al. [16] comprehensively studied these mechanisms for swirl-stabilized H_2 -air combustion.

Thermal Nitric Oxide defined by Zeldovich mechanism primarily forms at elevated temperatures. The rate-limiting step of this mechanism ($\text{N}_2 + \text{O} \leftrightarrow \text{NO} + \text{N}$) exhibits a strong temperature dependence owing to its high activation energy [16]. As a result, thermal NO generation becomes particularly pronounced at temperatures above 1800 K [17].

The N_2O pathway in NO_x formation becomes prevalent at high pressures due to the involvement of a third body, M ($\text{N}_2 + \text{O} + \text{M} \leftrightarrow \text{N}_2\text{O} + \text{M}$). These three-body reactions typically have low activation energy, making the formation of N_2O less sensitive to combustion temperatures. Hence, the N_2O route is promoted at lower temperature as compared to thermal NO_x pathway, lean condition and at high pressure [16].

The NNH pathway, first proposed by Bozzelli and Dean [18], is recognized as a crucial route for NO_x formation in H_2 -air flames, particularly at flame fronts where relatively high concentrations of H and O radicals are present [19]. Experimental investigation by Harrington et al. [20] highlighted the NNH pathway's prominence at low pressures, reduced temperatures, and in fuel-rich combustion environments. Capurso et al. [16] further explained the connection between the NNH and N_2O pathways, highlighting that NNH reacts with O radicals to produce N_2O , which subsequently yields NO through interactions with O and H radicals in the post-flame region.

The NNH route is notably relevant in systems operating within intermediate temperature ranges (1300–1800 K) and short residence times (τ) [21]. Konnov et al. [22] provided insight into the temperature and residence time dependency of these mechanisms indicating that, at 1500 K, NO_x formation is predominantly influenced by the NNH pathway across all Φ and τ , with minimal contribution from thermal NO . At elevated temperatures of 1800 K, the significance of thermal NO escalates, particularly in stoichiometric and rich mixtures beyond 2 ms, signifying a transition in the prevailing NO production process. This trend is accentuated at 2100 K, where thermal NO predominates from as early as 1 ms post-ignition, diminishing the influence of the NNH pathway to negligible.

The above findings and Lefebvre's insights [17] collectively highlight that NO_x production is intricately linked to the duration that the NO_x precursors remain in the combustion zone, the reaction rates determined by fuel type and combustion operating conditions, and the fuel-oxidizer mixing quality. Therefore, in DLN combustion systems, effectively managing these three elements is crucial for controlling NO_x formation. In this context, the H_2 micromix combustion principle stands out as a promising technique. This combustion method is specifically

designed to capitalize on the unique properties of H₂, facilitating rapid combustion in a lean homogeneous mixture, while addressing the challenges of autoignition and flashback.

3. Micromix combustion systems

The H₂ micro-mixing concept has been identified as a promising design for DLN H₂ combustion system. It significantly improves the homogeneity of the fuel-air mix, ensuring that the mixture remains consistently lean across operating conditions. As described by Dahl et al. [23] “micromix is an attempt to minimize the scale of mixing and to maximize the mixing intensity”. H₂ micromix combustion aims to reduce the scale of mixing, ideally to the molecular level, limited only by manufacturing feasibility and costs. While perfect molecular-level mixing remains a theoretical goal, practical micromix systems deploy numerous small flames, compared to the fewer but larger flames in traditional combustors. The intensification of mixing is restricted by the allowed pressure losses in gas turbines. Hence, efficient flow geometries that enhance H₂ and air mixing are crucial in minimizing the formation of hot spots and temperature gradients, which are typically associated with higher NO_x production.

Typically, combustion systems are divided into diffusion and premix categories. However, for the structural clarity within this paper, H₂ micromix combustion systems have been categorized by flame stabilization methods: bluff body-stabilized, LDI, swirl-stabilized, and co-flow.

3.1. Bluff body stabilized

The principles underlying bluff body stabilized micromix flames deviate significantly from those governing conventional burners. Further, new parameters are introduced that dictate the shape, size, anchoring, and stabilization behaviour. One specific geometry type (Fig. 1), originally defined as “two-dimensional” micro-mix burner, is used to elaborate on these [23].

Aerodynamic Flame Stabilization: Aerodynamic flame stabilization is crucial for the efficient operation of micromix combustion systems. As

illustrated in Fig. 1-i, two distinct recirculation zones, referred to as the inner and outer vortices, form downstream of bluff bodies. The air guiding panel (AGP) and the H₂ supply segment act as bluff bodies, with their induced blockage defining the size, shape, and intensity of these recirculation zones [26]. These recirculation zones, in turn, significantly influence key aspects of the micromix combustion system:

- **Formation of an Inter-Vortex (I-V) Shear Layer:** A steep velocity gradient is established between the two recirculation zones, resulting in the formation of an I-V shear layers. These layers are instrumental in inducing flow instabilities that transition into turbulence. The turbulence within these layers significantly improves the mixing of fuel and oxidizer. This improved mixing facilitates the propagation of an optimal flame front within the layers, which is crucial for efficient and complete combustion.
- **Combustion Energy for Flame Sustenance:** The hot exhaust gases recirculating within the outer vortex provide the necessary activation energy to the air and fuel mixture in the I-V shear layers, promoting continuous ignition. This is key to maintaining flame stability.
- **Flame Containment:** The spatial arrangement of the recirculation vortices serves the critical function confining the extents of the micro-flames. This confinement prevents the micro-flames from coalescing into a larger, unified flame front.

Jets-in-Crossflow: Upon injection (Fig. 1-ii), the H₂ jet undergoes significant bending due to the momentum difference between the jet and the freestream air. This initiates a series of aerodynamic events such as the formation of vortical structures and the development of mixing shear layers that culminate in the creation of counter-rotating vortex pairs (CVP). The CVP play a significant role in augmenting the entrainment of surrounding air into the H₂ jet, thereby further enhancing the mixing of H₂ with the air [27].

This interaction, known as Jet-In-Crossflow (JICF), is defined by the Momentum Flux Ratio (J) between the H₂ fuel jet and the air crossflow and can be expressed as Eq. (1):

$$J = \frac{\rho_j V_j^2}{\rho_{CF} V_{CF}^2} \quad (1)$$

Where ρ_j and V_j are the density and velocity of the H₂ jet in kg/m³ and m/s respectively. ρ_{CF} is the density of air crossflow and V_{CF} is the velocity of air crossflow at air gate exit in the same units.

J is a fundamental parameter in understanding and predicting the behaviour of H₂ jets in a micromix environment. It influences the degree of jet bending, the strength and orientation of the vortical structures, and the effectiveness of the mixing process. Flame anchoring, essential for low NO_x emissions, is determined by the recirculation vortices resulting from an appropriate choice of the burner geometry i.e., blockage and by the momentum flux of the JICF.

Jet Trajectory and Penetration: The characterization of H₂'s mean jet trajectory (characterized by y in Fig. 1-ii) is essential in the context of JICF within the micromix flame. This trajectory determines the penetration of the H₂ jet in the crossflow, a critical factor for optimal flame positioning. Ideal mixing is obtained by placing the H₂ plume in the turbulent shear layer and thus proper penetration ensures this occurs. It is imperative to avoid H₂ entrainment into both the inner and outer recirculation zones as this can significantly increase the residence time of hot combustion products, consequently elevating NO_x emissions.

For analytical modelling of jet trajectory, correlations based on experimental studies are employed such as the one proposed by Pratte and Baines [28] shown in Eq. (2).

$$\frac{y}{rd} = A \left(\frac{x}{rd} \right)^B \quad (2)$$

On the left of this equation, y is the vertical position of the jet

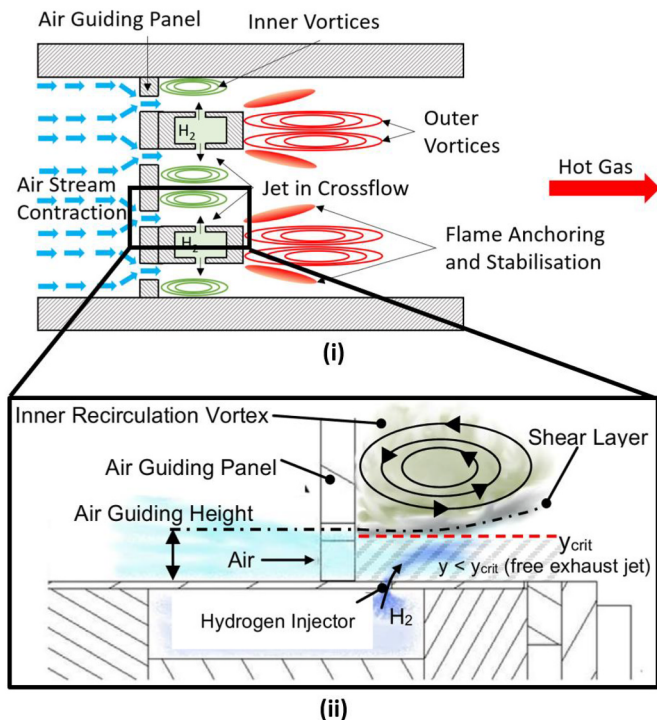


Fig. 1. Micro-mix burner design showing (i) aerodynamic flame stabilization [24] (ii) H₂ injection depth definition [25].

trajectory i.e., injection depth, r is the effective velocity ratio ($\sqrt{J}$), and d is the diameter of the jet. On the right, x is the streamwise distance from the jet nozzle measured in the direction of the crossflow, A is an empirical constant that scales the magnitude of the trajectory influenced by various parameters, including the J and B is another empirical constant influencing the rate at which the trajectory grows with distance depending on the specific flow configuration and fluid properties. B is in the range (0, 1), thus describing the trajectory as a radical function.

Steinberg et al. [29] conducted experimental investigations to determine the values of coefficients A and B for heated H_2 jets in heated crossflow air. Their findings revealed that the Pratte and Baines correlation, originally derived for non-reacting flow with $r > 1$, still predicts the jet trajectories in reacting cases with $r \approx 1$. Values of $1.2 < A < 1.3$ and $0.42 < B < 0.43$ were reported. You et al. [30] correlated the simulated mean jet trajectory to the one calculated using Eq. (2) and constants ($A = 1.25$ and $B = 0.425$) and reported a good agreement.

Funke et al. [31], have correlated the injection depth of the H_2 (y) into the air cross flow using Eq. (3).

$$y \propto rd \quad (3)$$

Eq. (3) implies that a higher r results in greater penetration of the H_2 stream into the air stream. A critical injection depth (y_{crit}) can be defined as the maximum penetration height for the H_2 plume to remain in the I-V, ensuring ideal mixing as shown in Fig. 1-ii. Ayed et al. [32] introduce a constant α to Eq. (4) that is a function of the air gate height and boundary layer growth, with those authors recommending $3 < \alpha < 4$.

$$y_{crit} = \alpha rd \quad (4)$$

3.1.1. Aachen University and Kawasaki Heavy Industries

Design Principles and Key Features: Aachen University (AU), in collaboration with KHI and B&B-AGEMA GmbH, has been developing a H_2 micromix combustion system tailored for industrial-grade heavy-duty gas turbines and has been reviewed in isolation in Ref. [15]. Their design aims to address the challenges of flashback and auto-ignition inherent in premixing processes while facilitating a lean-homogenous mixture of H_2 and air. To this end, a JICF diffusion flame, stabilized by a bluff body, is employed. The burner's architecture integrates direct H_2 injection into an air crossflow within the combustion chamber, with flame stabilization being achieved downstream of the injection point, utilizing H_2 feed as a bluff body. To aid discussion of the AU work, additional terms referring to Fig. 2 are essential for reviewing their technological progression including:

- Energy Density (ED) measures the required energy per unit area per bar to fulfil the cycle conditions as shown in Eq. (5), thereby ensuring the system's operational efficacy within the prescribed design constraints.

$$ED = \frac{2 * m_{H2per\ injector} * LHV}{A_{ref} * P_3} \quad (5)$$

- Blockage Ratio (BR) defines the fraction of the cross-sectional area blocked by a bluff body, such as an AGP, Eq. (6) or an H_2 segment, Eq. (7) which in turn affects the downstream flow dynamics and the overall efficiency of the micromix flames.

$$BR_{AGP} = \frac{d_{AGP}}{D_{AGP}} \quad (6)$$

$$BR_{H2} = \frac{d_{H2seg}}{D_{H2seg}} \quad (7)$$

The evolution of micromix research at AU includes identifying critical geometric design features and operating conditions with their impact on the flow and combustion dynamics. In 2011 Funke et al. [34] investigated various geometric modifications including the H_2 injection

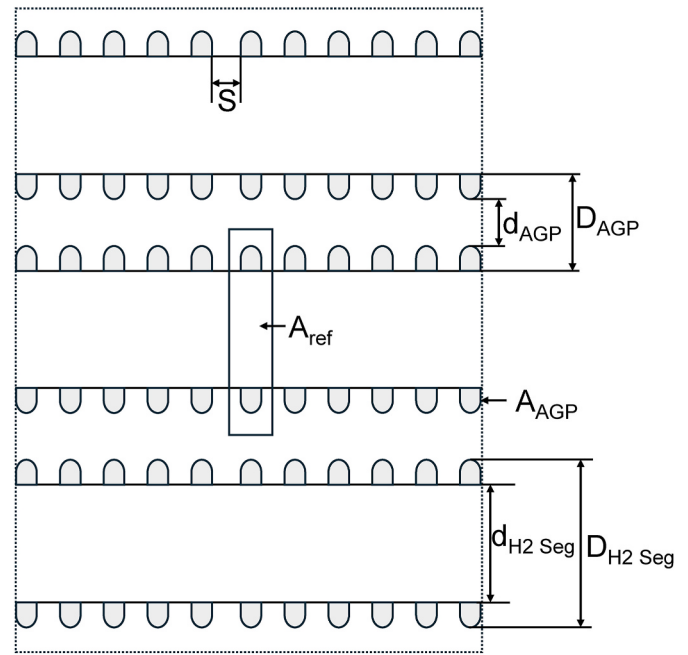


Fig. 2. AU definition of Micromix blockage ratio (BR), energy density (ED) and injector distance (s) adapted from [33].

diameter and the dimensions of the AGP. The research revealed the influence of the BR on induced recirculation zones and their correlation with NO_x generation. Reducing the size of recirculation zones shifts the flame, thus increasing flame interactions and consequently elevating the NO_x emissions.

In 2012 [31], the research transitioned towards analysing the impact of the J on NO_x emissions, conducted through alterations in the AGP air gates while the H_2 injection diameter remained unchanged. This identified critical thresholds for J that are design dependent, which significantly impact flame anchoring and emission characteristics. Surpassing these thresholds leads to an exponential rise in NO_x emissions, attributable to the merging of flames that become detached from its anchoring point. Additionally, the study concluded that the NO_x formation is marginally associated with pressure drop and the ED at the injector.

Subsequent studies in 2013 [35] and 2014 [36] concentrated on injector design and operational parameters to reduce NO_x at increased energy densities by optimizing J , injection depth (y), and recirculation zone areas. In 2015 [33], the research further advanced into aerodynamic flame stabilization in scaled-up designs, where the BR_{AGP} and BR_{H2} were increased, while maintaining the normalized injection depth (y/d) and J from previous designs. This research demonstrated a reduction in NO_x formation attributed to the increased BR, which facilitated a higher influx of relatively cooler air into the recirculation zones.

Ayed et al.'s studies conducted in 2016 [32] and 2017 [24], utilized Computational Fluid Dynamics (CFD) to refine geometric configurations to optimize for reduced nitrogen oxide emissions. In a design space exploration, they investigated a variety of geometric modifications, including the reduction of air gate thickness and the introduction of novel stepped-burner head geometries, alongside enhancements in mixing distance and air gate panel elevation. This collection of studies underscores the iterative and integrated nature of micromix injector design and optimization, showcasing the detailed interrelation among various design aspects. In a collaborative effort with Fraunhofer IPT, AU employed additive manufacturing (AM), specifically the Laser Powder Bed Fusion (LPBF), to fabricate the complex micromix combustion chamber [37].

Experimental and Numerical Approaches: A comprehensive numerical

and experimental campaign was undertaken to develop and refine the DLN micromix combustion design. Initial numerical studies employed 3D CFD Reynolds-Averaged Navier-Stokes (RANS) simulations, utilizing a realizable $k - \epsilon$ (RKE) turbulence model. For the combustion of H_2 and air, a one-step Hybrid Eddy Break-Up (EBU) model was implemented. This model integrates the reaction rate driven by turbulent mixing with the chemical kinetic reaction rate derived from the Arrhenius equation. The former is determined by the EBU combustion model and assumes that the reactants combust immediately upon mixing. The latter accounts for the chemical timescale necessary for the combustion of fully mixed reactants. The hybrid EBU methodology involves calculating both the turbulent mixing-driven and chemical kinetic reaction rates, selecting the lower of the two as the rate-limiting step [33]. This approach was chosen to decrease the computational resources and time needed for simplified single injector analyses. The formation of thermal NO was evaluated using the extended Zeldovich mechanism available as postprocessing field function in STAR-CCM + [38]. Comparative analysis between experimental NO_x measurements and simulation results showed qualitative trend agreement. However, the simulated NO_x levels were slightly lower than the experimental data [36], which was anticipated since the simulations only accounted for thermal NO_x , excluding other NO_x formation pathways such as NNH and N_2O . Ayed et al. conducted a study utilizing the Eddy Dissipation Concept (EDC) to model H_2 micromix combustion. Their reasoning was based on the EDC's capability to couple the effects of turbulent mixing and chemical kinetics, making it suitable for H_2 micromix modelling. The results of their model demonstrated good agreement with experimental data at lower power conditions. However, as the equivalence ratio increased so did discrepancies between the model and the experimental data [39]. This indicates that while EDC is effective in certain conditions, its accuracy may diminish under higher equivalence ratios.

Subsequent work [40] compared the hybrid EBU model with the Complex Chemistry (CC) model, and the Flamelet Generated Manifold (FGM) model with NO calculations based on the extended Zeldovich mechanism as postprocessing field function against experimental measurements (Fig. 3-i). Both CC and FGM used modified H_2 combustion mechanism by Li et al. [41]. The CC model provided the most accurate NO emissions predictions, while the FGM model, despite using the same reaction mechanism as the CC model, significantly underpredicted emission trends by capturing the large increase in NO_x for $\Phi > 0.5$, illustrating its potential value in scenarios where computational efficiency and accuracy must be balanced such as in preliminary design stages.

To further verify NO_x emission prediction accuracy the hybrid-EBU model with the thermal NO equations as postprocessing was compared with a CC model incorporating NO reactions (41) (Fig. 3-ii).

The modified reaction scheme by Li et al. [41] was used for H_2 combustion and NO reactions were incorporated into Goswami et al. [43]. Simulations also included a conjugate heat transfer model to evaluate the impact of heat transfer through the geometry on the reaction zone temperature and NO_x emissions. Results showed that the CC model with integrated NO mechanism closely matched experimental data but increased computational costs tenfold. It should be noted that the burner designs assessed in these studies represent generational advancements relative to one another. Consequently, the design progression should be interpreted and analysed independently. Each generation corresponds to a distinct iteration of the burner design, showcasing the evolutionary progress across different versions.

NO_x Emissions Performance: Kawasaki Heavy Industries has developed a prototype DLN 100 % H_2 micromix combustor for the 1.7 MW class M1A-17 gas turbine based on the design advancements from Aachen University. Notably, measured NO_x emissions remained under 35 ppm at 16 % O₂ across all operational loads with a 0.55 mm H_2 injection hole size. This was facilitated by fuel staging: from idle to 30 % load only the inner H_2 rings were fueled while beyond 30 % load all rings were operational (43).

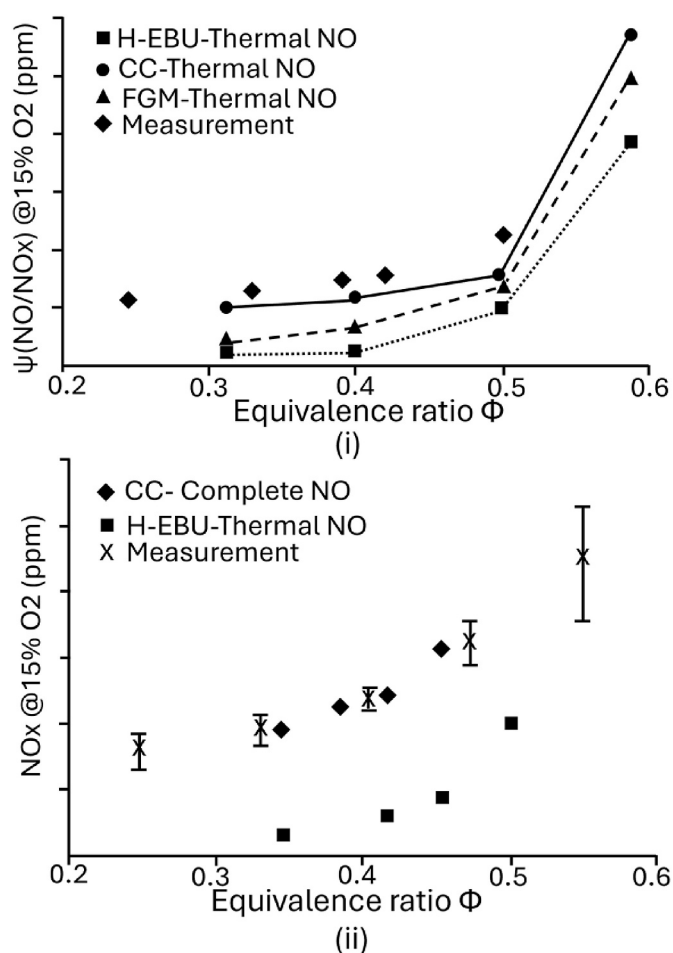


Fig. 3. Experimental NO_x measurement vs calculated using (i) Hybrid-EBU, CC and FGM with thermal NO adapted from Ref. [40] (ii) Hybrid-EBU and CC with NO integrated adapted from [42].

3.1.2. Cranfield University

Design Principles and Key Features: Cranfield University's (CU) development of a H_2 micromix combustion system for aero engine applications employs a JICF diffusion flame stabilized by a bluff body, like AU as detailed in Section 3.1.1. The micromix geometry investigated by CU has a H_2 injection orifice 0.3 mm with a semi-circular airgate with aspect ratio of 0.5. The geometry is designed for low J operation ($0.5 \leq J \leq 0.6$) and has pressure loss of $< 3\%$ [44].

Experimental and Numerical Approaches: The research comprises both numerical and experimental investigations. Numerically, significant efforts have been dedicated to understanding the predictive capabilities of state-of-the-art numerical tools and models in capturing H_2 's preferential diffusion in air. Lopez et al. [45] conducted thermodynamic modeling to explore the flame regime of H_2 micromix flames and verify the applicability of flamelet models in CFD combustion simulations. They concluded that H_2 micromix flames reside in the transition flamelet regime, suggesting that flamelet models such as FGM can effectively model H_2 micromix combustion in JICF configurations. Additionally, they refined the FGM combustion model for H_2 micromix systems by calibrating it against Large Eddy Simulation (LES) results. Their study indicated that conventional assumptions for hydrocarbon fuels, such as unity Lewis (Le) and Schmidt (Sc) numbers, are inadequate for modeling H_2 micromix flames. Instead, they recommended using values such as $Sc \approx 0.2$, and $Le \approx 0.3$, due to H_2 's distinct thermal diffusivity and molecular transport properties, which significantly impact flame structure and stability.

Concurrently, Zghal et al. [46] evaluated the performance of the

FGM model against the more computationally demanding CC model under high-pressure conditions (15 bar) using both RANS and LES. Their assessment revealed that the choice of turbulence-chemistry interaction model, particularly when coupling the CC model with the EDC or the Thickened Flame Model (TFM) in LES, significantly affects predictions, especially concerning flame length. The FGM model, when applied with RANS, tended to predict shorter flame lengths and lower flame temperatures compared to the CC-EDC model.

Sun et al. [47] and Agarwal et al. [48] conducted a comprehensive design space exploration for the H₂ micromix combustion system. Numerically, it was established that the mixing of H₂ and air, alongside the flame interaction, critically influences flame temperatures, thereby impacting NO_x formation, as shown in Fig. 4.

In an effort to improve the predictive capability of RANS turbulence-chemistry models, Sun et al. [49] conducted an numerical analysis to assess the sensitivity of species diffusion models in the turbulent combustion of a H₂/air jet in crossflow. This study investigated RANS and LES using FGM with kinetic rate closure and CC with both EDC and laminar flame concept (LFC) closure. The research focused on different molecular diffusion coefficient models, including mixture-averaged, multi-component, and multi-component with thermal diffusion, as well as on non-dimensional diffusion parameters, specifically the *Le* and *Sc* numbers. The findings highlighted the significant sensitivity of flame characteristics, such as flame length and temperature, to variations in molecular and turbulent diffusivities (*Le* and *Sc* numbers), while the molecular diffusion coefficient showed negligible sensitivity. LES results demonstrated better physical alignment, underscoring the predominance of turbulent mixing over molecular diffusion in determining flame structure. This highlights the importance of accurate turbulence modelling in predicting H₂ combustion behavior. Singh et al. [50] used LES-calibrated RANS FGM models to derive a reduced order EINO_x prediction model shown in Eq. (8).

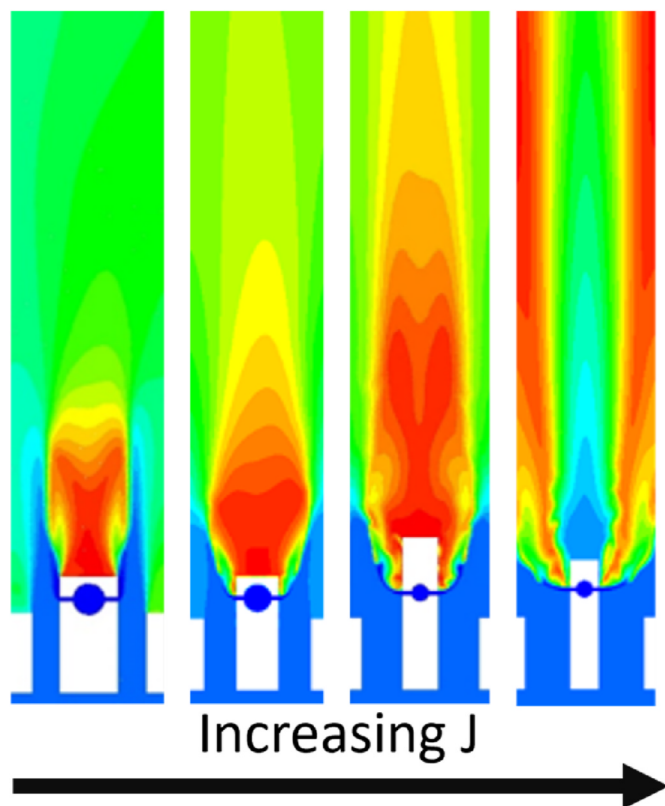


Fig. 4. NO_x and Flame interactions in micromix flame dependency on J, adapted from [44].

$$EINO_x = 0.0864 P_3^{0.4} \frac{T_3}{e^{191}} \Phi^{1.95} e^{-19(\omega - 0.006344)} \quad (8)$$

The units used in the correlation are kPa for P_3 , K for T_3 and ω is specific humidity [51].

In the final phase, various injector geometries were experimentally investigated under conditions up to 10 bar, $0.25 < \Phi < 0.5$, and $T_3 = 600$ K. Three injector configurations were defined at different J: low, medium, and high. The low and medium J injectors exhibited significantly lower NO_x emissions. Comparisons against the LES results suggest that in these configurations, flames are shorter and primarily confined within the inner recirculation zone, thereby minimizing flame-flame interactions. Conversely, the high J design resulted in longer flames that merged, potentially increasing NO_x formation.

Different AM techniques such as Direct Metal Laser Sintering (DMLS), Binder Jetting Technology (BJT) and micro-Electric Discharge Machining (micro-EDM) were explored, and it was found that the micro-EDM produced the most promising results in terms of hole ovality. Consequently, Giannouloudis et al. [52] adopted a hybrid approach whereby DMLS was used to fabricate the injector body followed by drilling of 0.3 mm H₂ injection holes using micro-EDM.

3.1.3. Incheon National University

Design Principles and Key Features: Incheon National University (INU) has developed a can-type diffusion micromix burner, consisting of an assembly of multiple can-type units. For each individual can, air flows through an annular space between inner and outer can cylinders with H₂ injected from the inner cylinder in a JICF configuration as illustrated in Fig. 5-(i). This approach aims to mitigate manufacturing challenges linked to micromix injectors, as detailed in Section 3.1.1 and 3.1.2, and to address the issue of increased pressure loss from blockage seen in previous designs. A prototype can, $\phi 60$ mm, featured 30 equispaced H₂ injection holes in one ring. The study explored various H₂ hole diameters varying the J, ranging from 0.6 mm to 1.2 mm, and recess lengths varying the degree of premixing from 5 mm to 25 mm. The design's recess length impacts the mixing of fuel and air, with flame stabilization occurring downstream of the inner cylinder which acts as a bluff body [30].

Experimental and Numerical Approaches: The research work integrated both numerical simulations and experimental investigations. The numerical models used in this study were validated against the experimental data, demonstrating a significant agreement in predicting NO_x emission trends. For the turbulence modelling, the k- ϵ model was employed, while EDC was utilized for combustion modelling. GRI-Mech 1.2 mechanism (22 species and 105 reactions) [53] was used for the chemical reactions involved in H₂ combustion. The authors commented that the geometry exhibited very low-pressure loss, and optimal micro-flame formation and stability were observed with larger momentum ratios. Flame stability was linked to the recess length, which governs the mixing time of fuel and air, highlighting the importance of balancing momentum ratio and mixing time for low NO_x emissions in H₂ micro-flames.

NO_x Emissions Performance: Experimental results indicated that $\phi 0.8$ mm holes and a recess length of 25 mm produced micro-scale flames (Fig. 5-ii) and achieved the lowest NO_x emissions, under 10 ppm at atmospheric pressure, $T_3 = 560$ K, and $\Phi = 0.4$ [30].

3.2. Lean Direct Injection

LDI is a combustion technology developed to reduce NO_x emissions in gas turbine combustors, particularly in aero engines. LDI is characterized by the “direct” injection of fuel into the combustion zone [54], eliminating the need for a separate premixing section. It operates under lean-burn conditions, where the fuel burns with an excess of air to minimize flame temperatures and thereby reduce NO_x formation. In the LDI design methodology [55], multiple small-diameter air and fuel

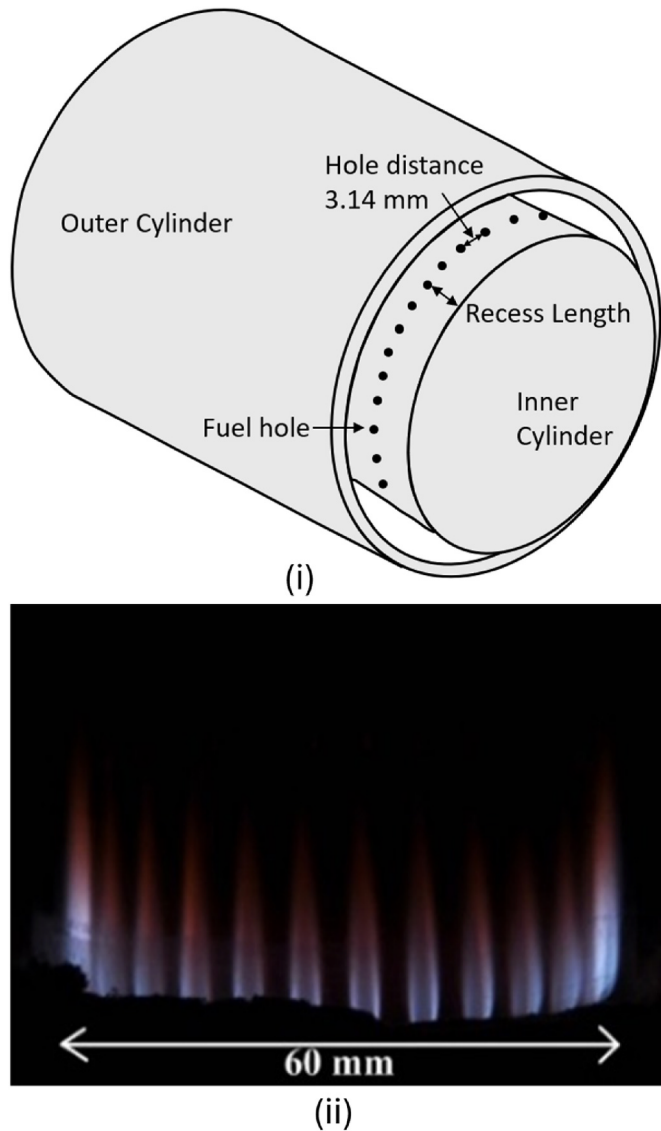


Fig. 5. (i) INU single can micromix burner (ii) flame visualization for 0.8 mm H₂ hole at recess length of 25 mm [30].

mixing nozzles are employed to enhance the mixing of fuel and air. This design reduces transport distance and increases mixing speed, promoting a more homogeneous fuel-air mixture, and preventing the formation of hot spots. This approach is particularly effective at medium to high power levels, as it aims to reduce peak flame temperatures through uniform mixing, a crucial factor in minimizing NO_x emissions [56]. To improve this mixing process while adhering to the LDI concept, NASA, GE, and others have developed a LDI H₂ micromix burner with JICF configuration. In these designs, H₂ is introduced in a JICF configuration with a short premixing zone located inside the air and fuel nozzle. This modification aims to maximize the mixing of air and fuel to enhance combustion efficiency and reduce NO_x emissions.

3.2.1. NASA Glenn Research Center

Design Principles and Key Features: NASA Glenn Research Center (GRC) developed LDI H₂ micromix burner incorporating a partially premixed approach. Different burner configurations with variations in air gate shape were manufactured and tested [10]. Among these, the N1 design (Fig. 6) incorporates two H₂ injection holes placed 180° apart in each cylindrical mixing tube, using a JICF arrangement. The primary function of this tube is to facilitate a short duration of premixing before

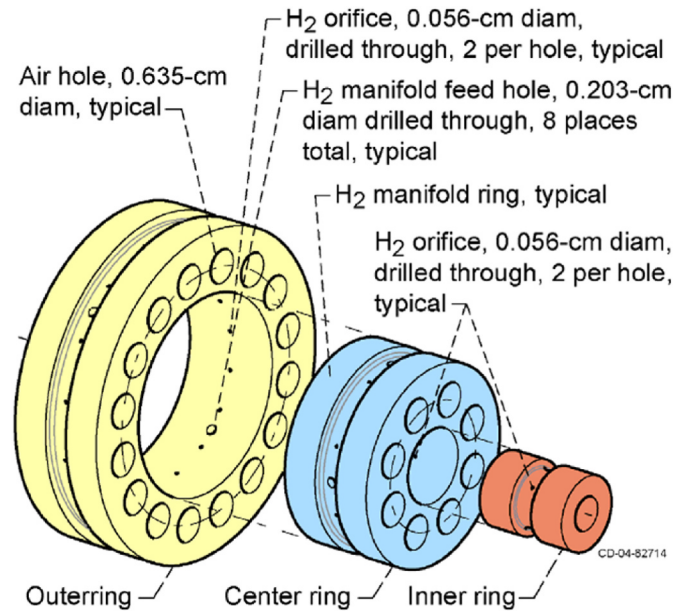


Fig. 6. NASA N1 LDI micromix burner in test piece assembly ([8]).

the fuel-oxidizer mixture enters the combustion zone. The mixing tubes have 0.635 cm, and the H₂ injection holes are 0.056 cm. NASA N1 burner was constructed from three separate ring segments seam-welded together to create a leak-proof structure for H₂ containment. The NASA N1 burner was fabricated in-house at NASA, while the other three injector designs were produced by prominent manufacturers in the rocket and aerospace sectors. While these were prototypes and subject to a limited test campaign, the performance benefits are notable in achieving reduced NO_x emissions compared to kerosene LDI burners. All tested LDI configurations succeeded in maintaining low NO_x levels without encountering any flashback or autoignition issues. The authors suggest that with additional modelling and optimization further improvements in performance is possible.

Marek et al. [10] also derived a correlation (Eq. (9)) with coefficients (Table 1) for predicting NO_x emissions for the tested configurations, employing a fixed geometry. This correlation was derived for a range of conditions, specifically combustor entry pressures ($0.7 \leq P_3 \leq 1$ MPa) temperatures ($588 \leq T_3 \leq 811$ K), and reference velocities ($30 \leq V_{ref} \leq 45$ m/s).

NO_x Performance and Emission Trends at $P_3 = 0.7$ MPa and $T_3 = 700$ K, NO_x emissions were maintained below 10 ppm (as measured) across all equivalence ratios ($0.1 < \Phi < 0.48$) for NASA N1 burner [10].

$$NO_{xppm} = A(143P_3)^a \Phi^b \tau^c e^{\frac{1.8T_3 - 460}{d}} \left(\frac{\Delta P}{P}\right)^e \quad (9)$$

The units used in the correlation are MPa for P_3 , ms for τ , and K for T_3 .

3.2.2. GE Energy

Design Principles and Key Features: GE Energy has developed a multitube (MT) micro-mixer employing a JICF configuration with a partially premixed setup (Fig. 7) [57]. In this design, air flows through several straight tubes of millimetre-scale diameter, arranged in parallel between a front and back plate. A fuel plenum encases these tubes, and flow conditioners are used to distribute the fuel evenly. The fuel is introduced

Table 1
Coefficients for NASA N1 H₂ micromix burner in 6.35 cm liner [10].

A	a	b	c	d	e	R ²
8.05 ⁻⁶	2.98	1.15	0.579	645	0.658	0.73

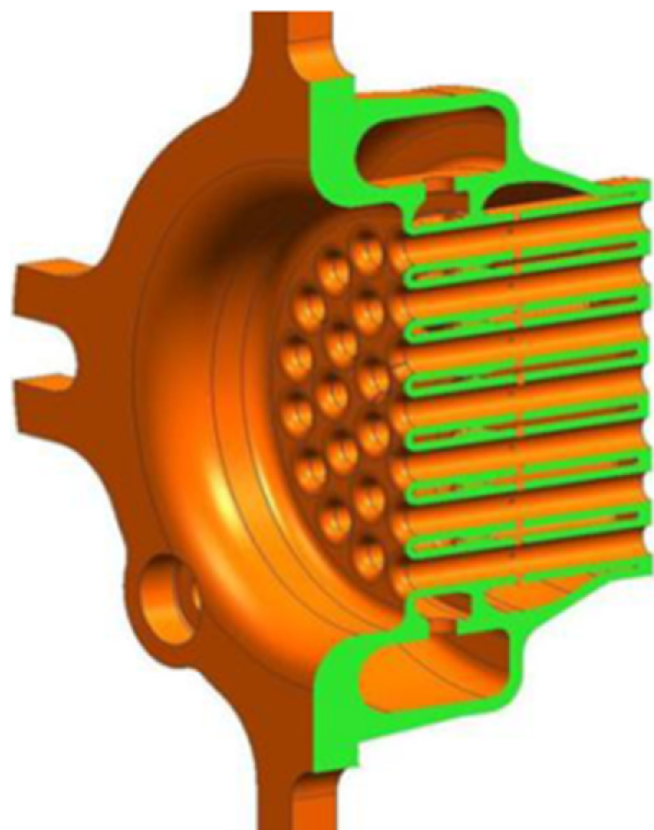


Fig. 7. GE Energy multitube micromix injector design details [58].

into the air stream via small apertures in the tube walls in the JICF configuration, spaced evenly around each tube at the same axial location. This allows for premixing within the fuel nozzle before it enters the combustion chamber.

NO_x Emissions Performance: The multiple MT mixer nozzles were employed in full can combustion systems capable of converting energy rates exceeding 10 MW under conditions approximating F-class gas turbine operation, operating at a pressure of 17 atm. with a fuel composition of roughly 66 % H_2 and 34 % N_2 by volume, and utilizing pure air at the inlet. The NO_x emissions for this setup were around 8 ppm (corrected to 15 % O_2) [57]. Recently GE Vernova validated 100 % H_2 for micromix technology in B and E class gas turbines, achieving NO_x emissions below 25 ppm [59].

3.2.3. University of Chinese Academy of Sciences

Design Principles and Key Features: The H_2 micromix injector design from the Chinese Academy of Science (CAS) comprises one central nozzle surrounded by six concentric nozzles. This injector features a novel reversal of fuel and air injection; from a common fuel plenum all seven nozzles are fueled through two $\phi 2$ mm ports each, downstream of this, air is provided through four slots (10×2 mm) [60]. This design facilitates a partial premixing within each nozzle, with a premixing length of 55 mm from the air injection slot to the combustion chamber.

Experimental and Numerical Approaches: Liu et al.'s [61] follow up study to Ref. [60] compared three RANS turbulence models for a cold flow scenario (non-reacting) with experimental data from the atmospheric rig at ≈ 277 K. Their calculations predicted similar centreline velocity along the combustion chamber in cold flow for all three turbulence models, however, when compared to experimental data an underprediction of 20 % was observed. These authors conclude that the RKE model outperforms both the Standard k- ϵ (SKE) and k- ω SST models for cold flow.

NO_x Emissions Performance: Experimentally, this design achieved NO_x

emissions of less than 10 ppm (corrected to 15 % O_2), at combustion chamber temperatures below the predicted adiabatic flame temperature of 1920 K. These emissions levels were consistent across a range of H_2 concentrations, from 0 % to 60 % vol. H_2 in CH_4 fuel blends, at atmospheric pressure and an air inlet temperature of 300 K [60]. It is important to note that while NO_x is slightly dependent on P_3 , it is strongly dependent on T_3 [50] and thus these levels may be artificially low in comparison to other designs which were tested at representative conditions.

3.3. Swirl stabilized

In swirl-stabilized injectors, angular momentum is imparted to the incoming air through mechanisms such as vanes, tangentially inclined channels, and jet crossflow, enhancing turbulence intensity and promoting oxidizer-fuel mixing. Swirl-induced adverse pressure gradients along the streamwise direction cause vortex breakdown, leading to flow reversal and the formation of a recirculation zone. This zone redistributes hot combustion products and free radicals towards the combustor's dump plane, sustaining the flame. However, in H_2 -fueled combustion systems, this mechanism increases flashback risk due to H_2 's high diffusivity and flame speed.

3.3.1. Parker Hannifin

Design Principles and Key Features: Parker Hannifin developed a burner concept known as multi-cup injection. This is a partially premixed swirl-stabilized multipoint fuel injection system. Each mixing cup (Fig. 8-i), incorporates four axial air channels that feed multiple air slots arranged tangentially, supplying swirling air flow to the centre of the cup. The fuel ports are positioned between these swirling layers of air at a single axial location, facilitating air-fuel mixing over a short premixing distance before the fuel-air mixture is introduced into the combustion chamber. The degree of fuel-air mixing is influenced by the fuel injection location relative to the air slots and the mixing length [62]. The interaction of the crossflow swirling air and the fuel streams lead to a vigorous mixing the cup centre (Fig. 8-ii). Each burner comprises multiple mixing cups, each measuring 6–12 mm. These cups are densely packed together providing energy on the order of approximately 1 MW.

During preliminary design testing, the burner design exhibited tendencies for flashback propagating through the boundary layer at slightly elevated pressures (>3 atm.) especially when operated on pure H_2 [63]. However, the final design demonstrated robust flashback resistance across a wide range of operational conditions and fuel compositions, including up to 100 % H_2 with 30 % CO_2 dilution [64].

The manufacturing process of the injector utilized 840 macro-lamination technology. This method involves the bonding of various metal sheets or plates, each precision-machined or chemically etched to incorporate specific features. Such a technique enables the construction of a cohesive structure with complex internal manifolds, ensuring

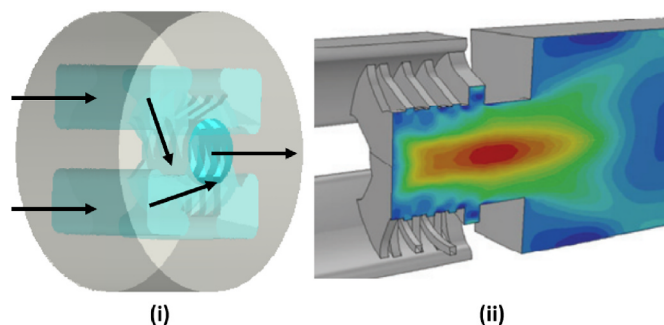


Fig. 8. Parker Hannifin macro-laminated micromix burner (i) single mixing cup isometric view with air flow directions marked, adapted from Ref. [62] (ii) contours of mean velocity, extracted from CFD [63].

precise control over the air and fuel flows.

NO_x Emissions Performance: At $P_3 = 12.4$ Bar and a T_4 of 1950 K, with a 4 % pressure drop. The combustor, operating on a fuel mixture of 50 % H₂ and 50 % natural gas without any diluent, achieved NO_x emissions just under 30 ppm (corrected to 15 % O₂) [65].

3.3.2. Université de Sherbrooke

Design Principles and Key Features: The Université de Sherbrooke (UdS) has developed a swirl-stabilized JICF multi-fuel micromix injector design, capable of utilizing H₂, Natural Gas, Propane, and Jet A-1 [66]. This design features a high swirl number ($S_n = 0.9$) burner, aimed at enhancing the recirculation of combustion products compared to bluff-body configurations, such as those in Section 3.1. Notably, previous studies on JICF bluff body stabilized geometries have not identified any issues with flame stability. Fuel is injected directly into the swirler induced recirculation zone (Fig. 9). Investigations covered burners with 30–100H₂ injection holes, ranging from 0.25 to 0.40 mm. It was determined that holes smaller than 0.30 mm exhibited a reduced discharge coefficient, attributed to limitations in the manufacturing process quality, thereby establishing 0.30 mm as the minimum viable hole size. The prototype injector was manufactured using Direct Metal Laser Melting (DMLM), a form of additive manufacturing.

NO_x Emissions Performance: Notably, the system achieved NO_x emissions below 10 ppm under ambient pressure conditions, with T_3 of 950 K and a T_4 of 1550 K.

3.3.3. Seoul National University

Design Principles and Key Features: Seoul National University (SNU) with the aim to address the challenges in design and manufacturing of micromix injectors as detailed in Section 3.1 developed a swirl-stabilized JICF geometry (Fig. 10-i) [67]. This design achieves swirl by strategically positioning fuel injection points within the nozzle, leveraging insights from various studies that have shown swirl-stabilized flames can reduce NO_x formation. In this setup, air enters the 10 mm nozzle at the upstream end, while H₂ is supplied downstream through a side tube and injected through four 0.8 mm holes in the nozzle. This configuration allows for partial premixing of air and fuel over a 5 mm length within the nozzle before entering the combustion chamber. The precise location of fuel injection points, denoted as the fuel injection distance (h) in Fig. 10-i, is crucial for generating the desired swirl effect, thus optimizing combustion efficiency, and minimizing NO_x emissions.

Different fuel injection distances were examined (0, 1.5, 2.25, 3.0, and 3.75 mm), influencing the fuel-induced swirl number (S_f) alongside variations in the flame structure and NO_x emission characteristics. Changes in S_f , influenced by nozzle structure modifications and equivalence ratio adjustments, significantly affected flame structure. At low swirl ($\Phi_g = 0.60$, $Y_h = 0$ and 0.30), flames maintained a singular core, but as S_f exceeded ($\Phi_g = 0.60$, $Y_h = 0.45$ and 0.60, and $Y_h = 0.60$ $\Phi = 0.64$), flames dispersed radially, transitioning to a Lifted Quadruple Flame (LQF) with four separate cores lifted from the dump plane (Fig. 10-ii). A further increase in S_f to ($\Phi_g = 0.60$, $Y_h = 0.75$ and $Y_h = 0.60$ $\Phi = 0.66$ and 0.68) led to the formation of an Attached Quadruple Flame (AQF), characterized by the shortest flames (Fig. 10-ii). NO_x

emissions decreased progressively with S_f , with AQF exhibiting the lowest emission index due to shorter, more separated flame cores. NO_x emissions reduction was attributed to reduced residence time.

3.4. Co-flow

Co-flow injectors introduce fuel and oxidizer into the combustion chamber through coaxial flow channels. The co-flowing oxidizer is typically highly turbulent, promoting vigorous streamwise mixing upon interaction with the fuel. Similar to swirl-stabilized injectors, recirculating regions in co-flow configurations can increase the risk of flashback.

3.4.1. Mitsubishi Hitachi Power Systems

Design Principles and Key Features: MHPs developed a multi-cluster combustor design, incorporating multiple cluster burners arranged in a ring within a can combustor. Each cluster burner, composed of several key elements, produces a singular flame. A key element is defined by a fuel nozzle and an air hole installed coaxially. This design achieves low-NO_x combustion by rapidly mixing fuel and air through multiple fuel-air coaxial jets (Fig. 11).

These jets, each featuring a central fuel jet encircled by an annular air stream, generate turbulence immediately downstream from the air hole exit. This turbulence amplifies wave-like disturbances at the fuel-air boundary, enhancing rapid mixing and fuel dispersion, thus facilitating homogeneous mixing that precludes high-temperature zones prone to NO_x formation [69].

Further, various burner head plates were tested in single cluster experiments [68]. The burner head consists of a perforated plate, with air holes strategically inclined to impart a swirling motion to the airflow. Fuel is injected from nozzles located within these air holes, creating a short premixing channel. This swirling action causes the airflow to converge towards and then diverge from the burner's central axis, generating a vortex breakdown at the converging-diverging boundary that anchors the flame and forms a downstream recirculation zone. The flame is then stabilized in the recirculation zone that forms downstream. This imparts a lifted flame characteristic protecting against the potential of flashback.

Moreover, the lifted flame feature facilitates increased mixing distance between the fuel and air significantly reducing NO_x formation. This design features a central pilot burner that provides flame stability, surrounded by main burners that are primarily responsible for the low-NO_x capabilities.

NO_x Emissions Performance: Atmospheric pressure tests revealed that a burner with a 5 mm flame lift-off length and a 1.5 mm fuel injection hole could achieve NO_x concentrations below 6 ppm for H₂-rich fuels across various H₂ levels [69]. The multi-cluster combustor attained around 10 ppm NO_x operating on syngas (50 % CO, 20 % H₂, and 20 % N₂ by volume) without diluent at 80 % load of a F-class gas turbine [68]. MHPs has announced ongoing development of a 1650 °C class multi-cluster combustor for 100 % H₂, aiming to complete combustion tests by 2025 [70].

4. Comparative analysis and development of hydrogen micromix combustion

4.1. Design and experimental analysis

It should be noted that most of the micromix designs reviewed here are at TRL 4 or below, and NO_x emissions data is derived from small-scale laboratory experiments. However, some early-adopter designs have progressed to higher TRL levels, such as those from KHI, MHPs, and GE. These designs have undergone full-scale experimental validation and continue to report promising results in NO_x emissions reduction, demonstrating their potential viability for industrial applications. The comparison revealed that regardless of the flame stabilization

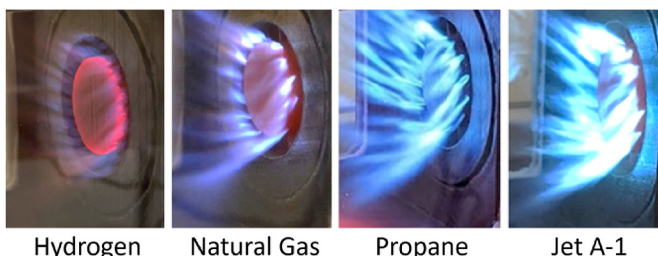


Fig. 9. Multi-fuel micromix burner from Sherbrooke University [66].

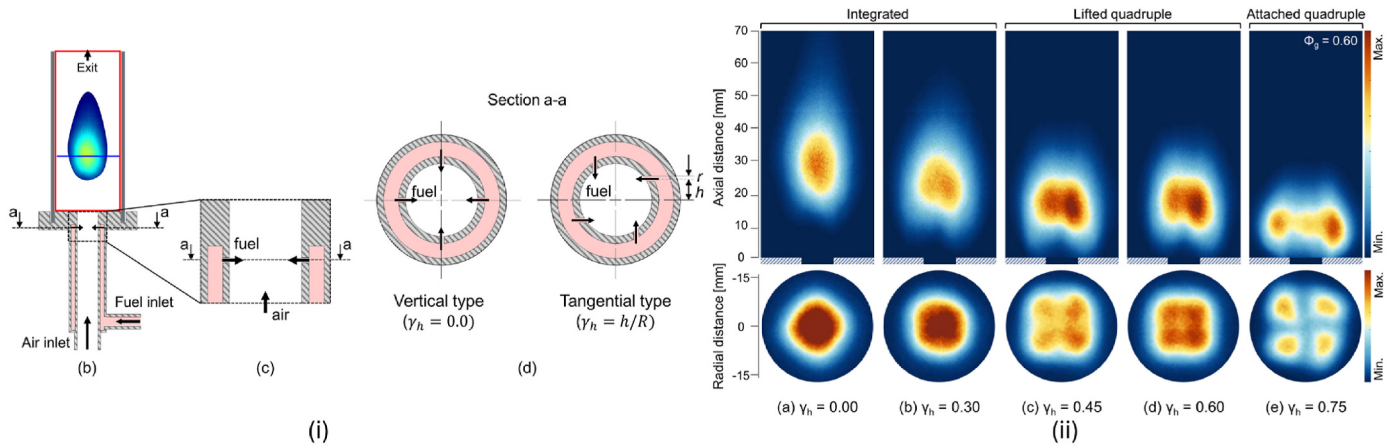


Fig. 10. (i) Fuel induced swirl type micromix burner (ii) impact of γ_h for fixed Φ [67].

	1. Low-NO _x	2. Flashback-resistant
Single air hole	Rapid mixing 	Flashback-resistant <ul style="list-style-type: none"> • Short premixing section • Air-stream-surrounded fuel jet
	Dispersion of fuel 	Lifted flame
Multi-air hole		

Fig. 11. MHPS micromix injector design principle [68].

methods chosen all micromix designs share common objectives:

- **Mixing Efficiency Enhancement:** The target of lean combustion across all power and operating conditions requires a uniform H_2 -air mixture. This is achieved through flow geometries designed to promote thorough mixing, thereby minimizing thermal gradients and hotspots, which are precursors to elevated NO_x emissions.
- **Micro-Scale Flame Management:** Miniaturization of flame structures is crucial to avoid flame merging or interaction. Such conditions lead to prolonged residence times for NO_x precursors, culminating in increased NO_x emissions. Combustion systems are designed to mitigate these interactions, thereby maximizing combustion efficiency, and reducing emissions.

- **Flashback and Autoignition Prevention:** By maintaining the velocity of the H_2 -air mixture above the H_2 laminar flame speed it is possible to reduce the risk of flashback and autoignition. Careful design thus ensures that any upstream flame propagation is effectively quenched, safeguarding against autoignition.

These objectives are vital for maintaining low NO_x emissions, flame stability and operational safety in H_2 -fueled combustion systems. Additionally, micromix combustor designs present unique aerodynamic and thermodynamic considerations due to their miniaturized, multi-injector configurations. Critical technical aspects include ensuring uniform flow distribution upstream of wide injector array, aerodynamic interactions between cooling flows and closely arranged miniature flames, and managing aerodynamic transitions from combustors with

broad flame fronts to turbine nozzle guide vanes. These factors collectively influence combustion stability, thermal management, and emissions performance, underscoring the need for detailed investigations to optimize micromix combustion chamber integration.

Table 2 provides unique identifiers (ID #) for each design and schematic views where blue demarcates air-gate extent, green for fuel path, and grey for physical geometry. Radial patterns shown as additional inset, otherwise geometries are cartesian grids. ID #'s is assigned to aide in discussion and link the data in Table 2 through 4.

The bluff body-stabilized designs, such as those from AU and CU (2, ID 1), focus on shape, size, and strength of the recirculation zones for better flame stabilization and mixing. In contrast, the swirl-stabilized designs of Parker Hannifin, UdS, and SNU, as illustrated in Table 2 with IDs 6, 7, and 8, respectively, utilize the angular momentum of the incoming air to provide enhanced mixing and flame stability. The co-axial design with a small premixing distance from MHPS (Tables 2 and ID 10) coupled with an angular momentum of swirling air provide a lifted flame stabilization in the vortex generated downstream of injector plate, enhancing mixing and reducing the high temperature zones prone to NO_x formation.

The NO_x emission performance across the different designs indicates

Table 2
Low-NO_x micromix injector design schematic.

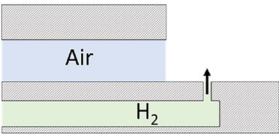
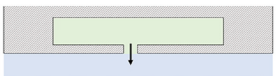
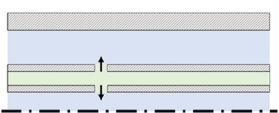
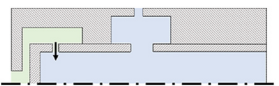
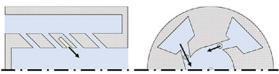
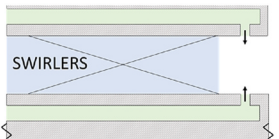
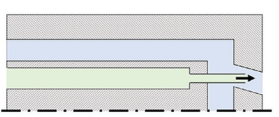
ID# & Ref	Schematic Blue-air, green – H ₂	Flame Characteristics
1 [15, 44]		diffusion, JICF, bluff body stabilized
2 [30]		diffusion, JICF, bluff body stabilized
3 [10]		partial premix, JICF, lean direct injection
4 [58]		partial premix, JICF, lean direct injection
5 [60]		partial premix, JICF, lean direct injection
6 [62]		partial premix, axial injection, swirl stabilized
7 [66]		partial premix, JICF, swirl stabilized
8 [67]		partial premix, JICF, swirl stabilized
9 [68]		partial premix, co-flow, lifted flame stabilized

Table 3
Summary of experimental rig NO_x emissions.

ID# & Refs	Fuel	Operating Conditions	NO _x Emissions
1 [15]	H ₂	100 % thermal load of 1.17 MW gas turbine	<35 ppm for all loads
2 [30]	H ₂	P ₃ =Atmospheric, T ₃ = 560K, Φ = 0.4	<10 ppm for optimized design
3 [10]	H ₂	P ₃ = 7 bar, T ₃ = 700K	<10 ppm for all Φ
4 [58]	H ₂	100 % thermal load of F-class (GE) gas turbine	<10 ppm
5 [60]	H ₂ +CH ₄	P ₃ =Atmospheric, T ₃ = 300K	<10 ppm for all H ₂ content
6 [65]	H ₂ +CH ₄	P ₃ = 12.4 bar, T ₄ = 1950K	<30 ppm
7 [66]	H ₂	P ₃ =Atmospheric, T ₃ = 950K	<10 mm
8 [67]	H ₂	Range of swirl number (S _p)	Lowest NO _x at highest S _p
9 [68]	H ₂ -rich fuels, syngas	P ₃ =Atmospheric	<6 ppm for H ₂ -rich fuels, <10 ppm for syngas

a strong correlation with the design's ability to ensure thorough mixing and avoid hot spots. While most designs achieved NO_x emissions below 10 ppm at mid-load conditions, specific operating conditions and design nuances significantly influenced their performance. Table 3 provides an overview of the NO_x emissions data recorded for each of these studies. Of note here are the natural gas - H₂ blends used by CAS, GE, and Parker-Hannifin, which set these data apart. Further, these data represent a wide range of inlet air temperature and combustion chamber pressures.

However, comparing NO_x emissions in ppm terms can be misleading [77]. Indeed, it has been argued [44] that indexed emissions, EINO_x g NO_x per kg of fuel burned, used in the aviation industry also fall short when transitioning to H₂ as a fuel, because of H₂'s three times higher energy density by mass compared to kerosene. Therefore, these authors support and encourage the use of an energy-based emission index or EEINO_x (Eq. (10)) [78]. This approach provides a more accurate comparison of NO_x emissions in different fuels, considering the differences in energy content:

$$EEINO_x = \frac{EINO_x}{LHV} \quad (10)$$

4.2. Numerical model analysis

The numerical models currently employed to simulate H₂-air combustion in these systems have revealed limitations [46]. While they have provided valuable insights into the flow physics and flame characteristics of H₂ micromix injectors, guiding design improvements, they lacked accuracy in modelling the preferential diffusion of H₂ and hence the NO_x emissions predictions [44]. The predicted NO_x emissions varied compared to the experimental data [72] and the variation increased when using reduced chemistry models [40]. Efforts have been made to improve predictive capabilities by including detailed chemistry models [79], but they increase the computational cost by the order of ten [42] and hence are not suitable for preliminary design studies or the design of experiment studies. This gap underlines the necessity for more experimental data for further refinement and validation of numerical models with reduced chemical kinetics, especially to better model preferential diffusion of H₂ and its effects on combustion characteristics. Table 4 outlines a variety of physical models and reaction mechanisms used by various authors to simulate H₂ micromix combustion and their results in the predictions NO_x. In addition to those listed in Table 4 H₂-air combustion reaction mechanisms from Kéromnès et al. [80] comprising 12 species and 33 reactions, and Ó Conaire et al. [81] comprising 10 species and 21 reactions, are also available.

4.3. Thermoacoustic instabilities

Thermoacoustic instabilities originate from the interaction between

Table 4

Summary of numerical models and applications.

ID#/ Ref	Solver	Turbulence Model	Combustion Model	Reaction Scheme	Status
1 [33, 36]	STARCCM+	RKE	Hybrid EBU & thermal NO	Fernandez-Galisteo [71]	Verified at atmospheric pressure, $T_3 = 560\text{K}$ qualitative NO_x trend agreement quantitative NO_x offset for all Φ
1 [72]	STARCCM+	RKE	EDC & thermal NO	Modified Li et al. [41]	Verified at atmospheric pressure, $T_3 = 560\text{K}$ qualitative NO_x trend agreement quantitative NO_x offset increases with Φ
1 [40]	STARCCM+	RKE	FGM & thermal NO	Modified Li et al. [41]	Verified at atmospheric pressure, $T_3 = 560\text{K}$ qualitative NO_x trend agreement quantitative NO_x offset for all Φ
1 [40]	STARCCM+	RKE	CC & thermal NO	Modified Li et al. [41]	Verified at atmospheric pressure, $T_3 = 560\text{K}$ qualitative NO_x trend agreement quantitative NO_x offset for all Φ
1 [42]	STARCCM+	RKE	CC & full NO	Modified Li et al. [41] + Goswami et al. [43]	Verified at atmospheric pressure, $T_3 = 560\text{K}$ quantitative agreement in NO_x at 10x computational cost c.f. hybrid-EBU
1 [45] 2 [30]	STARCCM+ ANSYS Fluent	k- ω SST RKE	FGM & thermal NO EDC	C. V. Naik [73] GRI 1.2 [53]	Sc = 0.2 calibrated against LES (experimental validation pending) Verified at atmospheric pressure, qualitative NO_x agreement
3 [74]	NCC (NASA)	k- ϵ with wall function [75,76]	Intrinsically low-dimension manifold	ILDm	Not available
5 [61]	ANSYS Fluent	RKE, SKE, k- ω SST	Non-reacting	Non-reacting	Run at ambient conditions ($T_3 \approx 280\text{K}$)

fluctuating heat release rates and acoustic pressure waves within the combustion chamber. H_2 , characterized by its high flame speed and rapid chemical kinetics, can intensify these instabilities, causing oscillatory combustion behaviours that negatively impact combustor efficiency, structural integrity, and operational stability. Experimental and numerical studies on H_2 micromix combustors indicate that such instabilities, while typically occurring at higher frequencies due to compact flame structures and shorter combustion timescales, remain critical considerations during combustor development and operation [44]. Abbot et al. [82] numerically investigated the sensitivity of thermoacoustic behaviour in H_2 micromix combustors to key combustor dimensions, suggesting that the predicted growth rates of high-frequency longitudinal modes are significantly influenced by the design of the combustion system. Based on this analysis, reference [44] recommends strategies to mitigate thermoacoustic instabilities such as fuel staging, passive damping, and active control systems.

4.4. Manufacturing and materials

As noted in the review of the above micromix designs, many of these designs are very complex, with complicated fuel channels and air passages complicating the manufacturing of such detailed geometry. Furthermore, H_2 is highly diffusive and porous, so it is susceptible to leakage if injectors are made of several components, which necessitates the need to cast the entire injector array as a single component.

The materials used must not only withstand the harsh conditions present in the combustion chamber but also be resistant to H_2 embrittlement (HE). These challenges present significant milestones for material and manufacturing technologies for these injectors. Additive manufacturing and 3D printing techniques are becoming increasingly popular for this type of manufacturing process. However, the results obtained using these techniques were not always satisfactory and may lack the precision required [52]. Commonly used materials in gas turbine components, such as nickel-based superalloys and stainless steels, are susceptible to HE that can lead to a reduced fatigue life and an increased risk of H_2 -induced cracking [80]. Further, turbine components such as fuel injectors, combustion liners, and blades experience material degradation due to prolonged exposure to H_2 -rich environments. Current research in advanced coatings and material modifications is aimed to enhance resistance to H_2 -assisted degradation [81].

5. Maturation roadmap for hydrogen micromix in aviation

H_2 micromix combustion technology has progressed to TRL9 in the stationary gas turbine industry where some of the manufacturers have successfully demonstrated DLN H_2 micromix combustion technology. However, in order to bring H_2 gas turbines into widespread commercial aviation use, FlyZero laid out a comprehensive roadmap of technologies and enablers across all aspects of the engine [83]. The FlyZero roadmap for combustion does not apply TRL levels to the activities but identifies essential and competitive developments being complete by 2035 and mature technology available by 2050. ENABLEH2 also produced a technology roadmap with additional focus on regulatory aspects and LH_2 production [9]. These provide comprehensive and detailed roadmaps for taking LH_2 aircraft propulsion systems from the current low TRL through to TRL9 by 2050.

For this study, however, a specific roadmap for H_2 micromix combustors is presented in Fig. 12, it includes the lessons learnt from stationary gas turbine community and hence could be widely used by both aviation and power industry. It does not consider upstream and downstream requirements, such as fuel storage, transfer and pumping, nor does it consider manufacturing readiness levels.

Immediate Term – 2030 Horizon.

- Identify promising H_2 micromix combustion technologies that have the potential to meet fundamental performance, operability, and emissions requirements.
- Improve the understanding of physical behaviour of liquid and gaseous H_2 such as ultra-low viscosity, high thermal capacity, high diffusivity etc. using experimental methods.
- Assess the optimal H_2 injection temperature for improved cycle thermal efficiency, injector plate trailing edge mechanical integrity and low NO_x emission.
- Enhance numerical modelling capabilities to better understand the flow physics of H_2 -air mixing, turbulence-chemistry interactions, flashback dynamics, NO_x emissions, and thermoacoustic instabilities.
- Conduct lab-scale experiments to validate existing numerical models and to develop validated reduced-order models.
- Perform comprehensive technoeconomic and environmental risk assessments to identify engine cycles with minimal environmental impact, utilizing the validated reduced-order models.

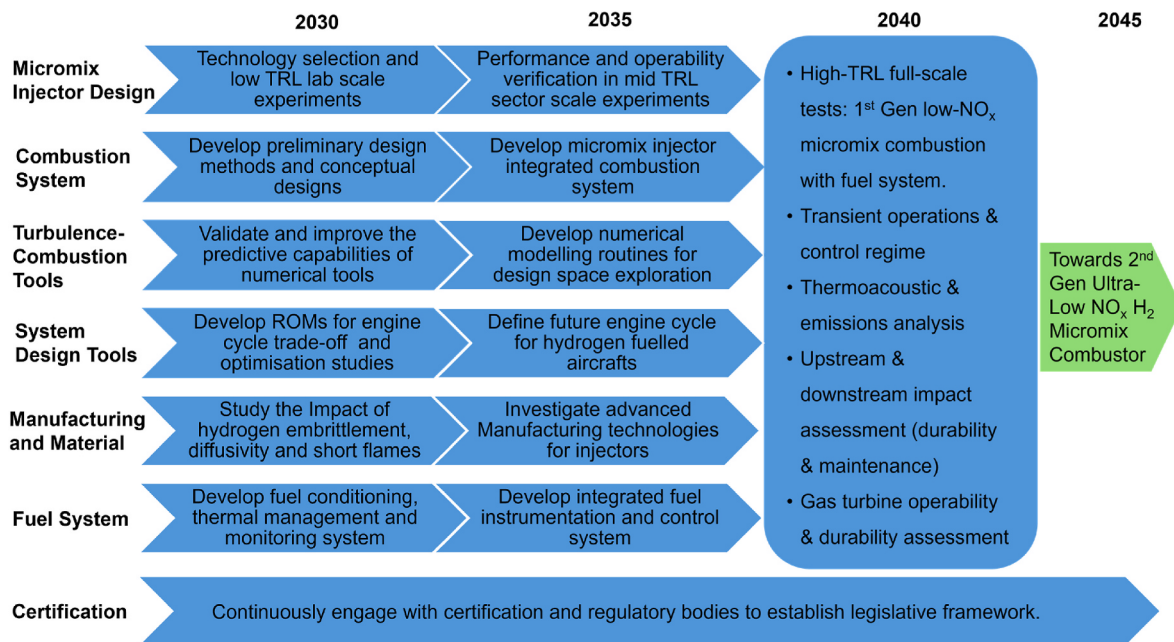


Fig. 12. Roadmap for H₂ micromix combustion system.

Short Term – 2035 Horizon.

- Develop a conceptual design for a H₂ combustion system, inclusive of fuel conditioning and delivery systems able to safely manage and control the H₂ flows over the range of pressures and temperatures from the cryogenic liquid and vapor storage to the fuel metering unit and the fuel injectors.
- Use validated and calibrated CFD models for rigorous design space exploration and optimization of the H₂ combustion system. Details such as the diffuser design are yet to be investigated fully.
- Investigate advanced materials and manufacturing processes suitable for the requirements of (potentially highly intricate) H₂ fuel injection systems. Examine fuel and control systems crucial for the operation of H₂ combustion-based gas turbines, addressing components such as cryogenic pumps, cryogenic valves, cryogenic metering devices, pre-burners, heat exchangers, fuel temperature regulation, and ignition systems etc. [84].
- Engage with the stationary gas turbine community to capitalize the lessons learnt.
- Investigate and develop robust H₂ leak detection, fire/detonation/detonation to deflagration hazards, fire suppressants.
- Conduct sector-scale rig experiments to visualize flames, monitor flow fields, measure thermoacoustic response, and quantify emissions. Generate comprehensive datasets for further calibration of CFD models and reduced order models.
- Conduct thorough investigations into H₂ fuel handling and operational safety.

Medium Term - 2040 Horizon.

- Full annular rig experiments of the H₂ combustion system with an integrated fuel system under engine-representative conditions, focusing on transient operations and the behaviour of fuel conditioning and control systems.
- Study fuel staging strategies to manage overall emissions and thermoacoustic characteristics throughout various mission phases under representative conditions.
- Evaluate and confirm the altitude relight capabilities of the H₂ combustion system.

- Assess take-off and landing cycle and mission-level emissions, including NO_x emissions, water vapor, and contrail formation.
- Formulate detailed emissions-cost models to assess the life-cycle atmospheric impact, using parameters such as the total effective radiative forcing.
- Demonstrate a full system prototype in an operational environment, evaluating the complete H₂ combustion system within gas turbine engine.
- Examine the impact of integrating H₂ combustion system with upstream and downstream engine components i.e., high water content etc.
- Scale up manufacturing capabilities to achieve cost-efficient production.
- Work with aviation authorities to establish regulations that support the safe operation of H₂-fueled aircraft.

Long Term - 2045 Horizon.

- Investigate additional enhancements to the H₂ combustion gas turbine, such as the application of cooled-cooling air, further NO_x reductions in mission-level emissions, and exploring the trade-offs between fuel consumption and NO_x emissions at reduced turbine entry temperatures.

6. Conclusion

H₂ micromix combustion technologies have been identified as key enablers for low NO_x emissions in gas turbine applications. This is achieved by improved fuel air mixture homogeneity ensuring lean burn and thus uniform temperature profile, in turn limiting NO_x formation. Further, the micro-scale flames reduce hot gas residence time.

Flashback and auto ignition prevention remains a major challenge for H₂ combustion. By maintaining H₂-air mixture velocities above flame speeds, micromix effectively quenches upstream flame propagation. Many flame stabilization techniques have been explored, each with opportunities and challenges.

Validated numerical models are critical for combustor design. Combustion models developed for hydrocarbons have limitations and are not yet fully calibrated for H₂-air combustion where preferential diffusion has a first-order impact. This leads to the use of complex

chemistry models which increase computational cost significantly.

A new technology maturation roadmap aimed at aviation has been presented. Detailing goals over various timescales, it seeks to advance the technology towards higher readiness levels by addressing the technical challenges by 2040.

Two active research themes are identified:

- *H₂-Air Flow Physics and Flame Characteristics*: Advances in the fundamental flow physics of H₂-air mixing, reaction, flashback, NO_x emissions, and thermoacoustic instabilities are required. A range of experimental rigs for H₂ combustion research are required across the flight envelope. Furthermore, investigation of integrated fuel systems should be considered.
- *Material and Manufacturing Advancements*: Improvements in the materials and manufacturing techniques is required due to the intricate geometries proposed. Materials must withstand H₂ embrittlement and exposure to the combustion environment while remaining suitable for precision manufacturing techniques to maintain low NO_x emissions.

Continued research and development efforts are essential to maximize the potential of H₂ as a clean fuel for the future. Advancing knowledge of flame characteristics, mixing processes, and NO_x formation mechanisms in these systems is critical to TRL advancement. This will require a collaborative effort across industry and academia, integrating numerical and experimental activities.

CRedit authorship contribution statement

Gaurav Singh: Writing – original draft, Visualization, Investigation, Conceptualization. **B. Deneys J. Schreiner**: Writing – original draft, Visualization, Supervision. **Xiaoxiao Sun**: Supervision. **Vishal Sethi**: Supervision.

Funding statement

This project has received funding from European Union's Horizon research and innovation program 2020 under grant agreement No. 769241 (ENABLEH2), Clean Sky 2 Joint Undertaking under grant agreement No. 886840 (UTOPEA) and UKRI ATI project under grant No. 10003388 (ONEHeart).

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.

References

- [1] Etn Global. 'Hydrogen gas turbines – the path to a zero emissions gas turbine', Brussels, Belgium [Online]. Available: <https://etn.global/wp-content/uploads/2020/01/ETN-Hydrogen-Gas-Turbines-report.pdf>. [Accessed 15 July 2024].
- [2] Schefer RW, Wicksall DM, Agrawal AK. Combustion of hydrogen-enriched methane in a lean premixed swirl-stabilized burner. *Proc Combust Inst* Jan. 2002;29(1): 843–51. [https://doi.org/10.1016/S1540-7489\(02\)80108-0](https://doi.org/10.1016/S1540-7489(02)80108-0).
- [3] Laget H, Griebel P, Gooren L, Hampf F, Jouret N, Lammel O. Demonstration of natural gas and hydrogen cocombustion in an industrial gas turbine. *J Eng Gas Turbines Power* Apr. 2023;145(4):041007. <https://doi.org/10.1115/1.4056046>.
- [4] Hannemann F, Koestlin B, Zimmermann G, Haupt G. Hydrogen and Syngas Combustion: Pre-Condition for IGCC and ZEIGCC. 2005. Available: URL: <https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=f3e686019ac1ddb082893b139a2b6d7f44c5e2fa>.
- [5] Dennis R, Long HA, Jesionowski G. A literature review of NO_x emissions in current and future state-of-the-art gas turbines. *J Eng Gas Turbines Power* Mar. 2024;146(3):030801. <https://doi.org/10.1115/1.4063836>.
- [6] Consulting AFry. Hydrogen as gas turbine fuel'. White Paper; Mar. 2022 [Online]. Available: https://afry.com/sites/default/files/2023-01/hydrogen_as_gas_turbine_fuel_v002.pdf. [Accessed 4 July 2024].
- [7] Silverstein A, Hall EW. Liquid hydrogen as a jet fuel for high-altitude aircraft. *Apr 1955*;15 [Online]. Available: <https://ntrs.nasa.gov/citations/19930088689>. [Accessed 14 December 2023].
- [8] Sosounov V, Orlov V. Experimental turbofan using liquid hydrogen and liquid natural gas as fuel. In: 26th Joint propulsion conference. Orlando, FL, U.S.A.: American Institute of Aeronautics and Astronautics; Jul. 1990. <https://doi.org/10.2514/6.1990-2421>.
- [9] Rolt A, et al. Technology and scenario evaluation studies and benchmarking. United Kingdom: Cranfield University; 2023. Deliverables, Documents, reports D1.4, <https://cordis.europa.eu/project/id/769241/results>. [Accessed 4 July 2024].
- [10] Marek C, Smith T, Kundu K. Low emission hydrogen combustors for gas turbines using lean direct injection. In: 41st AIAA/ASME/SAE/ASEE Joint propulsion conference & exhibit. Tucson, Arizona: American Institute of Aeronautics and Astronautics; Jul. 2005. <https://doi.org/10.2514/6.2005-3776>.
- [11] Perry R, Sloop JL. Liquid hydrogen as a propulsion fuel, 1945–1959. *Technol Cult* Jan. 1980;21(1):136. <https://doi.org/10.2307/3104021>.
- [12] World Economic Forum, 'Could hydrogen-powered aviation be a reality by 2035?', World Economic Forum. Accessed: July. 2, 2024. [Online]. Available: <https://www.weforum.org/agenda/2022/07/how-to-achieve-net-zero-in-aviation/>.
- [13] Airbus. 'The green hydrogen ecosystem for aviation, explained | Airbus', AIRBUS, Sustainability [Online]. Available: <https://www.airbus.com/en/newsroom/news/2021-06-the-green-hydrogen-ecosystem-for-aviation-explained>. [Accessed 2 July 2024].
- [14] Cecere D, Giacomazzi E, Di Nardo A, Calchetti G. Gas turbine combustion technologies for hydrogen blends. *Energies* Sep. 2023;16(19):6829. <https://doi.org/10.3390/en16196829>.
- [15] Funke HH-W, Beckmann N, Kein J, Horikawa A. 30 Years of dry-low-NO_x micromix combustor research for hydrogen-rich fuels—an overview of past and present activities. *J Eng Gas Turbines Power* Jul. 2021;143(7):071002. <https://doi.org/10.1115/1.4049764>.
- [16] Capurso T, Laera D, Riber E, Cuenot B. NO_x pathways in lean partially premixed swirling H₂-air turbulent flame. *Combust Flame* Feb. 2023;248:112581. <https://doi.org/10.1016/j.combustflame.2022.112581>.
- [17] Lefebvre AH, Ballal DR. Gas turbine combustion. third ed. CRC Press; 2010. <https://doi.org/10.1201/9781420086058>.
- [18] Bozzelli JW, Dean AM. O + NNH: a possible new route for NO_x formation in flames. *Int J Chem Kinet* Nov. 1995;27(11):1097–109. <https://doi.org/10.1002/kin.550271107>.
- [19] Skottene M, Rian KE. A study of NO_x formation in hydrogen flames. *Int J Hydrogen Energy* Oct. 2007;32(15):3572–85. <https://doi.org/10.1016/j.ijhydene.2007.02.038>.
- [20] Harrington JE, Smith GP, Berg PA, Noble AR, Jeffries JB, Crosley DR. Evidence for a new NO production mechanism in flames. *Symp Int Combust* 1996;26(2):2133–8. [https://doi.org/10.1016/S0082-0784\(96\)80038-5](https://doi.org/10.1016/S0082-0784(96)80038-5).
- [21] Purohit AL, Nalbandyan A, Malte PC, Novoselov IV. NNH mechanism in low-NO_x hydrogen combustion: experimental and numerical analysis of formation pathways. *Fuel* May 2021;292:120186. <https://doi.org/10.1016/j.fuel.2021.120186>.
- [22] Konnov AA, Colson G, De Ruyck J. NO formation rates for hydrogen combustion in stirred reactors. *Fuel* Jan. 2001;80(1):49–65. [https://doi.org/10.1016/S0016-2361\(00\)00060-0](https://doi.org/10.1016/S0016-2361(00)00060-0).
- [23] Dahl G, Suttrop F. Engine control and low-NO_x combustion for hydrogen fuelled aircraft gas turbines. *Int J Hydrogen Energy* Aug. 1998;23(8):695–704. [https://doi.org/10.1016/S0360-3199\(97\)00115-8](https://doi.org/10.1016/S0360-3199(97)00115-8).
- [24] Ayed AH. Numerical characterization and development of the Dry low NO_x high hydrogen content fuel micromix combustion for gas turbine Applications.pdf. Japan: University of Hyogo; 2017 [Online]. Available: https://u-hyogo.repo.nii.ac.jp/record/2997/files/doc_the_16-7.pdf.
- [25] Funke HHW, et al. Experimental and numerical study on optimizing the dry low NO_x micromix hydrogen combustion principle for industrial gas turbine applications. *J Therm Sci Eng Appl* Jun. 2017;9(2):021001. <https://doi.org/10.1115/1.4034849>.
- [26] Davies TW, Beér JM. Flow in the wake of bluff-body flame stabilizers. *Symp Int Combust* Jan. 1971;13(1):631–8. [https://doi.org/10.1016/S0082-0784\(71\)80065-6](https://doi.org/10.1016/S0082-0784(71)80065-6).
- [27] Mahesh K. The interaction of jets with crossflow. *Annu Rev Fluid Mech* Jan. 2013; 45(1):379–407. <https://doi.org/10.1146/annurev-fluid-120710-101115>.
- [28] Pratte BD, Baines WD. Profiles of the round turbulent jet in A cross flow. *J Hydraul Eng* 1967;93:53–64.
- [29] Steinberg AM, Sadanandan R, Dem C, Kutne P, Meier W. Structure and stabilization of hydrogen jet flames in cross-flows. *Proc Combust Inst* 2013;34(1):1499–507. <https://doi.org/10.1016/j.proci.2012.06.026>.
- [30] You CH, Lee HY, Hwang SS. Low NO_x combustion characteristics by hydrogen micro jet flame in cross flow. *J Mech Sci Technol* Jan. 2023;37(1):445–55. <https://doi.org/10.1007/s12206-022-1242-z>.
- [31] Funke HH-W, et al. 'Numerical and experimental characterization of low NO_x micromix combustion principle for industrial hydrogen gas turbine applications'. 2. Combustion, Fuels and Emissions, Parts A and B, Copenhagen, Denmark: American Society of Mechanical Engineers; Jun. 2012. p. 1069–79. <https://doi.org/10.1115/GT2012-69421>.
- [32] Ayed AH, Kusterer K, Funke HH-W, Kein J. CFD based improvement of the DLN hydrogen micromix combustion technology at increased energy densities. *Am Sci Res J Eng Technol Sci Nov.* 2016;26(3):3.
- [33] Funke HH-W, et al. Experimental and numerical study on optimizing the DLN micromix hydrogen combustion principle for industrial gas turbine applications.

- In: Volume 4A: combustion, fuels and emissions. Montreal, Quebec, Canada: American Society of Mechanical Engineers; Jun. 2015, V04AT04A008. <https://doi.org/10.1115/GT2015-42043>.
- [34] Funke HH-W, Boerner S, Krebs W, Wolf E. Experimental characterization of low NOx micromix prototype combustors for industrial gas turbine applications. In: Volume 2: combustion, fuels and emissions, parts A and B. Vancouver, British Columbia, Canada: ASME; Jan. 2011. p. 343–53. <https://doi.org/10.1115/GT2011-45305>.
- [35] Funke HH-W, et al. Experimental and numerical characterization of the dry low NOx micromix hydrogen combustion principle at increased energy density for industrial hydrogen gas turbine applications. In: Volume 1A: combustion, fuels and emissions. San Antonio, Texas, USA: American Society of Mechanical Engineers; Jun. 2013, V01AT04A055. <https://doi.org/10.1115/GT2013-94771>.
- [36] Funke HH-W, Dickhoff J, Keinz J, Ayed AH, Parente A, Hendrick P. Experimental and numerical study of the micromix combustion principle applied for hydrogen and hydrogen-rich syngas as fuel with increased energy density for industrial gas turbine applications. *Energy Proc* 2014;61:1736–9. <https://doi.org/10.1016/j.egypro.2014.12.201>.
- [37] Fraunhofer IPT, 'Additiv gefertigte Wasserstoff-Brennkammer - Fraunhofer IPT', Fraunhofer-Institut für Produktionstechnologie IPT. Accessed: February, 20, 2024. [Online]. Available: <https://www.ipt.fraunhofer.de/de/projekte/additiv-gefertigte-mmx-brennkammer.html>.
- [38] Siemens Digital Industries Software. Simcenter STAR-CCM+ User guide. Siemens; 2024., version 2306.
- [39] Haj Ayed A, Kusterer K, Funke HH-W, Keinz J, Striegan C, Bohn D. Improvement study for the dry-low-NOx hydrogen micromix combustion technology. *Propuls Power Res Sep*. 2015;4(3):132–40. <https://doi.org/10.1016/j.jprr.2015.07.003>.
- [40] Funke HHW, Beckmann N, Keinz J, Abanteriba S. Comparison of numerical combustion models for hydrogen and hydrogen-rich syngas applied for dry-low-nox-micromix-combustion. *J Eng Gas Turbines Power* Aug. 2018;140(8):081504. <https://doi.org/10.1115/1.4038882>.
- [41] Li J, Zhao Z, Kazakov A, Dryer FL. An updated comprehensive kinetic model of hydrogen combustion. *Int J Chem Kinet* Oct. 2004;36(10):566–75. <https://doi.org/10.1002/kin.20026>.
- [42] Striegan C, et al. Numerical combustion and heat transfer simulations and validation for a hydrogen fueled "micromix" test combustor in industrial gas turbine applications. In: Volume 4B: combustion, fuels and emissions. Charlotte, North Carolina, USA: American Society of Mechanical Engineers; Jun. 2017, V04BT04A038. <https://doi.org/10.1115/GT2017-64719>.
- [43] Goswami M, Bastiaans RJM, de Goeij LPH, Konnov AA. Modeling study of H₂/Air combustion and NOx formation at high pressures. In: *Proc. 8th asia-pac. Conf. Combust.* 10-13 dec. 2010 Hyderabad India; 2010. p. 874–81.
- [44] Sun X, Sethi V, Singh G. And others, 'Final report for the single sector H₂ micromix combustor segment performance and NOx emissions assessment. United Kingdom: Cranfield University; 2023. Deliverables, Documents, reports D3.3, <https://cordis.europa.eu/project/id/769241/results>. [Accessed 4 July 2024].
- [45] López-Juárez M, Sun X, Sethi B, Gauthier P, Abbott D. Characterising hydrogen micromix flames: combustion model calibration and evaluation. In: *Volume 3: ceramics; coal, biomass, hydrogen, and alternative fuels*, virtual, online. American Society of Mechanical Engineers; Sep. 2020, V003T03A008. <https://doi.org/10.1115/GT2020-14893>.
- [46] Zghal M, Sun X, Gauthier PQ, Sethi V. Comparison of tabulated and complex chemistry turbulent-chemistry interaction models with high fidelity large Eddy simulations on hydrogen flames. In: *Volume 3: ceramics; coal, biomass, hydrogen, and alternative fuels*, virtual, online. American Society of Mechanical Engineers; Sep. 2020, V003T03A014. <https://doi.org/10.1115/GT2020-16070>.
- [47] Sun X, Agarwal P, Carbonara F, Abbott D, Gauthier P, Sethi B. Numerical investigation into the impact of injector geometrical design parameters on hydrogen micromix combustion characteristics. In: *Volume 3: ceramics; coal, biomass, hydrogen, and alternative fuels*, virtual, online. American Society of Mechanical Engineers; Sep. 2020, V003T03A015. <https://doi.org/10.1115/GT2020-16084>.
- [48] Agarwal P, Sun X, Gauthier PQ, Sethi V. Injector design space exploration for an ultra-low NOx hydrogen micromix combustion system. In: *Volume 3: coal, biomass, hydrogen, and alternative fuels; cycle innovations; electric power; industrial and cogeneration; organic rankine cycle power systems*. Phoenix, Arizona, USA: American Society of Mechanical Engineers; Jun. 2019, V003T03A013. <https://doi.org/10.1115/GT2019-90833>.
- [49] Sun X, Martin H, Gauthier P, Sethi B. Sensitivity study on species diffusion models in turbulent combustion of hydrogen/air jet in crossflow structure. In: *Volume 2: coal, biomass, hydrogen, and alternative fuels; controls, diagnostics, and instrumentation; steam turbine*. Rotterdam, Netherlands: American Society of Mechanical Engineers; Jun. 2022, V002T03A018. <https://doi.org/10.1115/GT2022-83097>.
- [50] Singh G, Zghal M, Sun X, Gauthier P, Sethi V. Numerical investigation into the impact of operating boundary conditions on NOx formation in hydrogen micromix combustion system. In: *Volume 2: ceramics and ceramic composites; coal, biomass, hydrogen, and alternative fuels*. Boston, Massachusetts, USA: American Society of Mechanical Engineers; Jun. 2023, V002T03A019. <https://doi.org/10.1115/GT2023-103111>.
- [51] Norman PD, et al. Development of the technical basis for a new emissions parameter covering the whole aircraft operation: NEPAIR. 2003. p. 35–63. Final Technical Report Number NEPAIR/WP4/WPR/01.
- [52] Giannouloudis A, et al. On the development of an experimental rig for hydrogen micromix combustion testing. In: *European combustion meeting. The Combustion Institute; Apr. 2021* [Online]. Available: <https://coec-project.eu/event/10th-europ-ean-combustion-meeting/>. [Accessed 8 July 2024].
- [53] Kazakov A, Frenklach M. 'Reduced reaction sets based on GRI-mech 1.2', combustion keykey [Online]. Available: <http://combustion.berkeley.edu/drm/>. [Accessed 8 July 2024].
- [54] Acosta WA, Chang C. Experimental combustion dynamics behavior of A multi-element lean direct injection (LDI) gas turbine combustor. In: 52nd AIAA/SAE/ASME Joint propulsion conference. Salt Lake City, UT: American Institute of Aeronautics and Astronautics; Jul. 2016. <https://doi.org/10.2514/6.2016-4589>.
- [55] K. M. Tacina, 'Swirl-Venturi Lean Direct Injection Combustion Technology for Low-NOx Aero Gas Turbine Engines', in *Internal Combustion and Gas Turbine Engines*, in Aircraft Propulsion And Power, vol. GRC-E-DAA-TN55621. Minneapolis, Minnesota: NASA GRC, May 2018. [Online]. Available: <https://ntrs.nasa.gov/citations/20180004690>.
- [56] Liu Y, Sun X, Sethi V, Nalianda D, Li Y-G, Wang L. Review of modern low emissions combustion technologies for aero gas turbine engines. *Prog Aero Sci* Oct. 2017;94: 12–45. <https://doi.org/10.1016/j.paerosci.2017.08.001>.
- [57] York WD, Ziminsky WS, Yilmaz E. Development and testing of a low NOx hydrogen combustion system for heavy-duty gas turbines. *J Eng Gas Turbines Power* Feb. 2013;135(2):022001. <https://doi.org/10.1115/1.4007733>.
- [58] York WD, Ziminsky WS, Yilmaz E. Development and testing of a low NOx hydrogen combustion system for heavy duty gas turbines. In: *Volume 2: combustion, fuels and emissions, parts A and B*. Copenhagen, Denmark: American Society of Mechanical Engineers; Jun. 2012. p. 1395–405. <https://doi.org/10.1115/GT2012-69913>.
- [59] 'GE Vernova validates 100 % hydrogen-fueled DLN combustor technology aiming to decarbonize its industrial B- and E-Class gas turbines | GE Vernova News'. Accessed: March, 19, 2025. [Online]. Available: <https://www.gevernova.com/news/press-releases/ge-vernova-validates-100-hydrogen-fueled-dln-combustor-tech-nology-aiming-6>.
- [60] Liu X, et al. Investigation of H₂/CH₄-air flame characteristics of a micromix model burner at atmosphere pressure condition. In: *Volume 4B: combustion, fuels, and emissions*. Oslo, Norway: American Society of Mechanical Engineers; Jun. 2018, V04BT04A015. <https://doi.org/10.1115/GT2018-76276>.
- [61] Liu X, et al. Cold flow characteristics of a novel high-hydrogen Micromix model burner based on multiple confluent turbulent round jets. *Int J Hydrogen Energy* Jan. 2021;46(7):5776–89. <https://doi.org/10.1016/j.ijhydene.2020.11.012>.
- [62] Hernandez SR, Wang Q, McDonell V, Mansour A, Steinthorsson E, Hollon B. 'Micro mixing fuel injectors for low emissions hydrogen combustion'. In: *3: combustion, fuels and emissions, parts A and B*, Berlin, Germany. ASME; Jan. 2008. p. 675–85. <https://doi.org/10.1115/GT2008-50854>.
- [63] Wang Q, McDonell V, Steinthorsson E, Mansour A, Hollon B. 'Correlating flashback tendencies for premixed injection of hydrogen and methane mixtures at elevated temperature and pressure'. In: *2: combustion, fuels and emissions, orlando, Florida*. USA: ASME; Jan. 2009. p. 401–10. <https://doi.org/10.1115/GT2009-59500>.
- [64] Lee H, Hernandez S, McDonell V, Steinthorsson E, Mansour A, Hollon B. 'Development of flashback resistant low-emission micro-mixing fuel injector for 100% hydrogen and syngas fuels'. In: *2: combustion, fuels and emissions, orlando, Florida*. USA: ASME; Jan. 2009. p. 411–9. <https://doi.org/10.1115/GT2009-59502>.
- [65] Hollon B, Steinthorsson E, Mansour A, McDonell V, Lee H. Ultra-low emission hydrogen/syngas combustion with a 1.3 MW injector using a micro-mixing lean-premix system. In: *Volume 2: combustion, fuels and emissions, parts A and B*. Vancouver, British Columbia, Canada: ASME; Jan. 2011. p. 827–34. <https://doi.org/10.1115/GT2011-45929>.
- [66] Landry-Blais A, Sivić S, Picard M. Micro-mixing combustion for highly recuperated gas turbines: effects of inlet temperature and fuel composition on combustion stability and NOx emissions. *J Eng Gas Turbines Power* Sep. 2022;144(9):091014. <https://doi.org/10.1115/1.4055190>.
- [67] Choi J, Ahn M, Kwak S, Lee JG, Yoon Y. Flame structure and NOx emission characteristics in a single hydrogen combustor. *Int J Hydrogen Energy* Aug. 2022; 47(68):29542–53. <https://doi.org/10.1016/j.ijhydene.2022.06.247>.
- [68] Asai T, et al. Development of fuel-flexible gas turbine combustor. *ETN Glob*; 2016 [Online]. Available: <https://etn.global/wp-content/uploads/2018/09/Development-of-gas-turbine-combustors-for-fuel-flexibility-3.pdf>.
- [69] Asai T, Koizumi H, Dodo S, Takahashi H, Yoshida S, Inoue H. 'Applicability of a multiple-injection burner to dry low-NOx combustion of hydrogen-rich fuels'. In: *2: combustion, fuels and emissions, parts A and B*, glasgow. UK: ASME; Oct. 2010. p. 183–92. <https://doi.org/10.1115/GT2010-22286>.
- [70] Patel S. 'MHI, Mitsubishi power report breakthroughs for hydrogen combustion, ammonia burners', *POWER magazine* [Online]. Available: <https://www.powermag.com/mhi-mitsubishi-power-report-breakthroughs-for-hydrogen-combustion-ammonia-burners/>. [Accessed 15 July 2024].
- [71] Fernández-Galisteo D, Sánchez AL, Liñán A, Williams FA. One-step reduced kinetics for lean hydrogen–air deflagration. *Combust Flame* May 2009;156(5): 985–96. <https://doi.org/10.1016/j.combustflame.2008.10.009>.
- [72] Haj Ayed A, Kusterer K, Funke HH-W, Keinz J, Striegan C, Bohn D. Experimental and numerical investigations of the dry-low-NOx hydrogen micromix combustion chamber of an industrial gas turbine. *Propuls Power Res Sep*. 2015;4(3):123–31. <https://doi.org/10.1016/j.jprr.2015.07.005>.
- [73] Naik C. ANSYS chemkin theory manual 1.0 (15151). San Diego: Reaction Design; 2015.
- [74] Shih T-H, Smith T, Marek C, Iannetti A, Norris A, Liu N-S. Numerical study of a single hydrogen/air gas turbine fuel nozzle. In: *33rd AIAA fluid dynamics*

- conference and exhibit. Orlando, Florida: American Institute of Aeronautics and Astronautics; Jun. 2003. <https://doi.org/10.2514/6.2003-4249>.
- [75] Shih T-H, Liu N-S, Chen K-H. A non-linear k-epsilon model for turbulent shear flows. In: 34th AIAA/ASME/SAE/ASEE Joint propulsion conference and exhibit. Cleveland, OH, U.S.A.: American Institute of Aeronautics and Astronautics; Jul. 1998. <https://doi.org/10.2514/6.1998-3983>.
- [76] Shih T-H, Povinelli LA, Liu N-S. Application of generalized wall function for complex turbulent flows. In: Engineering turbulence modelling and experiments 5. Elsevier; 2002. p. 177–86. <https://doi.org/10.1016/B978-008044114-6/50016-8>.
- [77] Douglas CM, et al. Pollutant emissions reporting and performance considerations for hydrogen–hydrocarbon fuels in gas turbines. J Eng Gas Turbines Power Sep. 2022;144(9):091003. <https://doi.org/10.1115/1.4054949>.
- [78] Charbagi V. 'ETN's Position Paper "Proposed NOx emissions reporting for hydrogen-containing fuels" is available for download!', ETN [Online]. Available: <https://etn.global/news-and-events/news/etns-proposed-nox-emissions-reporting-for-h2-containing-fuels-available-for-download/>. [Accessed 8 July 2024].
- [79] Connolly B, et al. Validation of a numerical approach to model hydrogen combustion in gas turbine engines. In: Combustion, fuels, and emissions, 3B. Boston, Massachusetts, USA: American Society of Mechanical Engineers; Jun. 2023, V03BT04A024. <https://doi.org/10.1115/GT2023-103117>.
- [80] Kéromnès A, et al. An experimental and detailed chemical kinetic modeling study of hydrogen and syngas mixture oxidation at elevated pressures. Combust Flame Jun. 2013;160(6):995–1011. <https://doi.org/10.1016/j.combustflame.2013.01.001>.
- [81] Ó Conaire M, Curran HJ, Simmie JM, Pitz WJ, Westbrook CK. A comprehensive modeling study of hydrogen oxidation. Int J Chem Kinet Nov. 2004;36(11): 603–22. <https://doi.org/10.1002/kin.20036>.
- [82] Abbot D, Giannotta A, Sun X, Gauthier P, Sethi V. Thermoacoustic behaviour of a hydrogen micromix aviation gas turbine combustor under typical flight conditions. In: *Volume 6: Ceramics and ceramic composites; coal, biomass, hydrogen, and alternative fuels; microturbines, turbochargers, and small turbomachines*, virtual, online. American Society of Mechanical Engineers; Jun. 2021, V006T03A013. <https://doi.org/10.1115/GT2021-59844>.
- [83] Hughes C, FlyZero ATI. Our vision for zero-carbon emission air travel. FZO-ALL-REP-0004 Mar. 2022 [Online]. Available: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-ALL-REP-0004-FlyZero-Our-Vision-for-Zero-Carbon-Emission-Air-Travel.pdf?mc_cid=d65a4c3c76&mc_eid=UNIQID. [Accessed 4 July 2024].
- [84] Ebrahimi A, Rolt A, Jafari S, Anton JH. A review on liquid hydrogen fuel systems in aircraft applications for gas turbine engines. Int J Hydrogen Energy Nov. 2024;91: 88–105. <https://doi.org/10.1016/j.ijhydene.2024.10.121>.



DSPACE

<https://dspace.org/>

A review of hydrogen micromix combustion technologies for gas turbine applications

Singh, Gaurav; Schreiner, B. Deneys J.; Sun, Xiaoxiao; Sethi, Vishal

2025-05-13

Elsevier

<https://doi.org/10.1016/j.ijhydene.2025.04.007>

Singh G, Schreiner BDJ, Sun X, Sethi V. (2025) A review of hydrogen micromix combustion technologies for gas turbine applications. International Journal of Hydrogen Energy, Volume 127, May 2025, pp. 295-310