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On the Development of an Experimental Rig for Hydrogen Micromix Combustion Testing

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Abstract

This work describes the development of a combustion rig, aimed at testing hydrogen-fuelled micromix burners for aero gas-turbines at pressures up to 15barg, inlet-air temperatures up to 600K and equivalence ratios (Φ) from lean-blow-out to 0.5. It discusses the test facility used, and the design procedure of the experimental apparatus: the requirements of it, the design choices and implementation of instrumentation. Emphasis is placed on the design and manufacture of the burner. Comparison between Additive Manufacturing (AM) and micro-machining techniques for the sub-millimetre injection points shows that further research is needed in this area, to achieve adequate geometric accuracy of the injection holes economically. This rig forms a unique facility for hydrogen micromix testing, offering simultaneous measurements of NO_x emissions, Flame-Transfer–Function (FTF) and flame imaging.

Introduction

Hydrogen as a fuel has the potential to decarbonise civil aviation. No carbon-related emissions, wider flame stability limits than kerosene and faster reaction rates make it a very attractive fuel for gas turbines. Micromix combustion is a promising concept for achieving ultra-low NO_x emissions using hydrogen as the fuel; it is based on the Jet-in-Crossflow (JiC) principle (Figure 1), which creates numerous, miniature, non-premixed flames, resulting in intense mixing of fuel and air, reducing localised stoichiometric, hot regions. Leaner combustion, enabled by the wider stability limits, results in lower flame temperatures, and combined with improved mixing and lower residence times of combustion gases in the combustor, ultra-low-NO_x emissions are also achieved. Micromix also has inherently low risk of flashback and auto-ignition. However, it still presents several challenges that must be addressed. Potential issues with thermoacoustic (TA) instabilities can impact combustor integrity. Dependence of flame behaviour on geometric and flow parameters also needs to be better understood, to avoid issues such as flame to flame interaction, that lead to high NO_x emissions.

Within the scope of the ENABLEH2 project, three experimental rigs are being developed at Cranfield University. These rigs will study NO_x emissions, flame behaviour and TA response of hydrogen micromix flames at pressures up to 15barg and inlet temperatures up to 600K. Altitude relight characteristics will also be studied. This paper describes the first of the three rigs. Together with numerical studies, the objective is to mature hydrogen micromix combustion to Technology Readiness Level (TRL) 4.

To date research on the technology has focused mainly on numerical work with experimental studies being limited to atmospheric pressure conditions. Aachen University initially tested an Auxiliary Power Unit GTCP 36-300, modified for a micromix combustor and showed promising results in NO_x emissions[1] . Focusing on industrial applications, experiments at Aachen provided data on NO_x for various combustor energy densities using fuel injectors from 0.3mm up to 0.7mm in diameter [2]. This up-scaling to 0.7mm[2] and larger diameters [3] moves away from some desirable micromix characteristics, yet yielding low NO_x emissions. Along with numerical efforts, the impact of geometric (injector size, mixing and offset distance etc – Figure 2) and flow parameters (momentum flux ratio and equivalence ratio) on flame anchoring and stability and subsequently on NO_x was assessed[2–4].

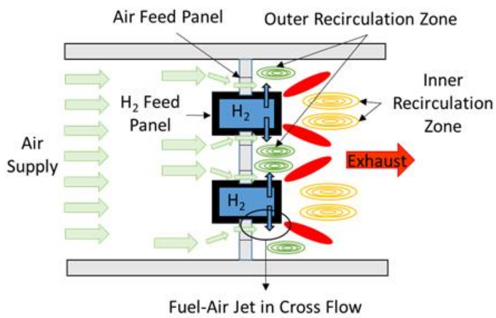

Figure 1- JiC on a micromix burner[5]

At Cranfield University extensive numerical studies have been performed over the last decade. Initially the work focused on assessing different, single-injector configurations in terms of high-temperature regions and NO_x for hydrogen [6,7] and comparing combustion performance with other fuels [8]. Holes in the air feed panel (Figure 1), referred to as air gates, direct the flow into the fuel jet. Impact of injector diameter and air gate size on NO_x was studied and results showed that smaller sizes yield lower NO_x until a limit value is reached [5]. The shape of the air gates also affects flame behaviour and NO_x, with flatter shapes showing the potential for lower emissions [9]. These studies have also explored the limitations of the predictive capabilities of RANS simulations. Numerical studies on TA have shown that potentially, hydrogen micromix combustors will suffer TA instabilities at frequencies higher than those of kerosene [10].

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The experimental apparatus described here will test five burner designs at a range of pressures, air-inlet temperatures and equivalence ratios as already described. The lack of experimental data on NO_x and flame behaviour for micromix at higher pressures is the main drive for the development of this rig. Such data, covering a wide range of operating conditions can be used to calibrate numerical models and bridge some of the discrepancies currently reported. In turn, more accurate, calibrated CFD models will speed up the development procedure by reducing required time and costs for technology maturation, as larger experimental efforts will be limited to designs that are promising based on the results of numerical models.

Test Facility

This section provides information on the supporting infrastructure required to supply high-pressure, high-temperature air. The operation of the fuel delivery system is described, and details of safety provisions are given.

Air Handling System

A pair of compressors is utilised and can deliver air up to 4kg/s at 15barg. The mass flow is much greater than that is needed for the rig but can be regulated down to the desired values.

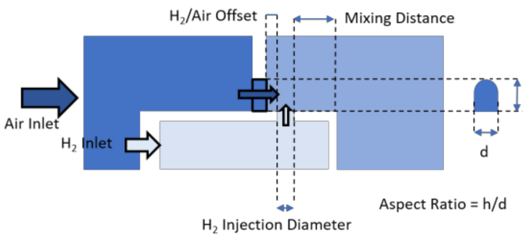


Figure 2 - Varied Geometric Parameters for micromix burner

The Pebble Bed Heater

Heat is added to the compressed air from the Pebble Bed (PB) Heater. The PB was built in the 1960s to provide non-vitiated, hot air for supersonic combustion experiments[11]. It is a pressure vessel with three layers of internal insulation and an external frame made of carbon steel. Alumina pebbles are deposited at the bottom of the vessel up to a height of around 1m. During the warming phase, a kerosene flame is used to heat the pebbles building the thermal energy content of the PB. During the test phase, the flow path is reversed and air from the compressors passes through the pebble volume, removing heat before being directed to the test section. The PB has a heating rate for air of 1kg/s at 1800K[11]. The facility has recently been upgraded with a remote, digital control system developed in LabView, allowing for safer operation of flow regulating valves and for the collection of critical temperatures and pressures. Air flow metering is performed using 2 orifice plates installed upstream of the PB.

Fuel Supply and Safety System

The fuel supply system comprises of a combination of solenoid and non-return valves (Figure 3). Due to the high diffusivity of hydrogen and its wide flammability limits (4-75% volumetric), the fuel supply system also includes a gaseous- nitrogen system for purging.

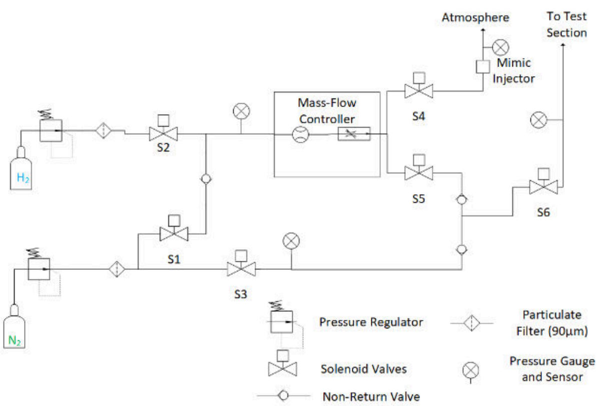


Figure 3 - Schematic of the fuel/purge system

The whole fuel supply system has five different modes of operation, determined by the operation of the solenoid valves (Figure 3):

- Standby: S2 only is open. Hydrogen flows up to the fuel mass-flow controller (MFC)
- Bypass: S2 and S4 are open. Hydrogen flows through the mimic injector line and is vented outside the test house. This allows for the MFC to settle to the requested mass-flow value.
- Pre-start/Purge: As in by-pass but S3 and S6 open to allow nitrogen to purge the main line and the rig
- Start/Run: S3 and S4 close and S5 opens. Nitrogen stops flowing through the rig and hydrogen switches from the mimic injector line to the rig. The ignitor runs as well.
- Shutdown: S2 closes while the other solenoids and the MFC open. Nitrogen flows through all the tubing and the rig.

Solenoids are controlled by an electromechanical system. Fuel mass flow metering and control is achieved through a Bronkhorst mass-flow controller consisting of an F-113AI flow meter and an F-002AI control valve. Pressure transducers and gauges installed at critical points of the lines monitor H_2/N_2 pressure.

Safety Provisions

The handling of any flammable substance must be accompanied with extreme precautions. Hydrogen is a highly flammable gas which requires procedures tailored to its behaviour. For example, its high diffusivity and wide flammability range must be accounted for to avoid the creation and ignition of leaks. Two emergency-stop buttons are placed in the test house. Such buttons cut-off hydrogen flow closing S2 (Figure 3) and open the purging line. The test house doors remain open during testing for ventilation. Pressure switches installed on these doors ensure that in case one of them closes, the fuel supply is cut-off, and the system is purged. Finally, hydrogen detection sensors are installed on the ceiling, triggering an alarm, and purging the system if H_2 concentration reaches 25% of the lower flammability limit in the test house. Four fans circulate air continuously during rig operation to avoid build-up of hydrogen to dangerous concentrations.

Rig Maximum Operating Conditions

The maximum operating pressure for the rig was set to 15barg based on the capability of the compressors already described. Maximum air-inlet temperature of 600 K was dictated by the fact that it is close to the actual compressor discharge temperature of a modern turbofan engine at cruise. Maximum air mass flow was set to 150g/s. Tests are planned for pressures at atmospheric, 5barg, 10barg and 15barg.

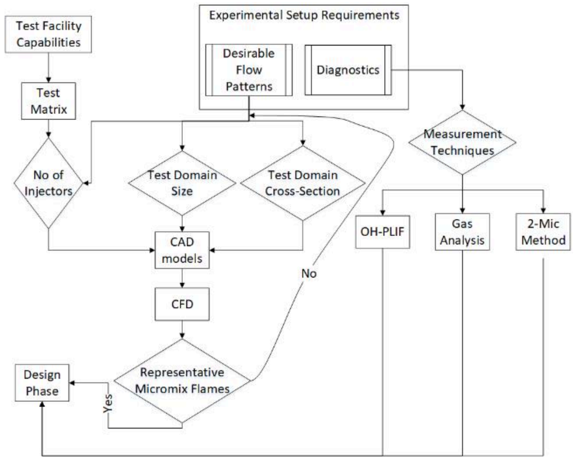


Figure 4 - Procedure to define specifications

Rig Development

This section first sets the requirements of the experimental rig and provides the procedure behind defining the specifications. Secondly, gives an overview of the setup operation and finally discusses the design choices for certain critical components.

Requirements and Specifications

The requirements were that the experimental setup be able to produce a small number of flames, representative of micromix and perform measurements of:

- NO_x emissions at the whole range of operating conditions.
- Flame-Transfer-Function (FTF)at atmospheric pressure.
- Flame Imaging at the whole range of operating conditions.

Once the generic requirements were set, the setup for the rig was specified as shown in Fig. 4.

Based on the maximum air mass flow, and typical combustor dome Mach number, the velocity of the test section inlet is determined. The mass-flow of each injector is affected by its size. Theoretically, the smaller the injectors, the closer the combustion characteristic will resemble the micromix concept. However, the dimension of the hydrogen injection orifice is limited by manufacturing techniques (see below). The size of the injectors was set to 0.3mm diameter. Then, by assuming that the flow is subsonic, and with a lean fuel-air ratio, the mass flow rate of hydrogen and air for each injector is calculated. Eventually, it was determined that the air supply is sufficient for approximately 50 air gates.

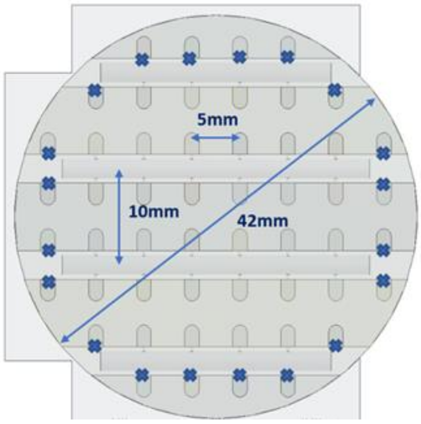


Figure 5 - Layout of injectors and air-passages for the baseline configuration. X symbols mark the positions of only air-passages.

The domain size was set to a cylindrical test section of 42mm in diameter with 32 injectors (Figure 5). Numerical simulations revealed that this combination provided representative micromix flames for the central injectors. Figure 6 shows that the central injectors all produce similar flames, unaffected by the conditions at the wall and are thus representative of the flames in a large micromix array. Fuel is not injected downstream of the air gates around the outer circumference of the injector plate to prevent overheating of the optical windows.

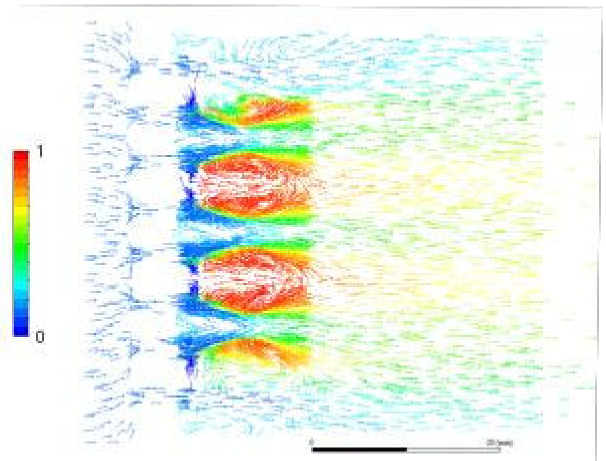


Figure 6 - Numerical Simulation showing flow vectors coloured temperature for a circular domain with 32 injectors.

Rig Functional Overview

The functionality of the main rig components is described in Figure 7. Hot air from the PB flows axially through the rig, never mixing with the fuel. Fuel enters

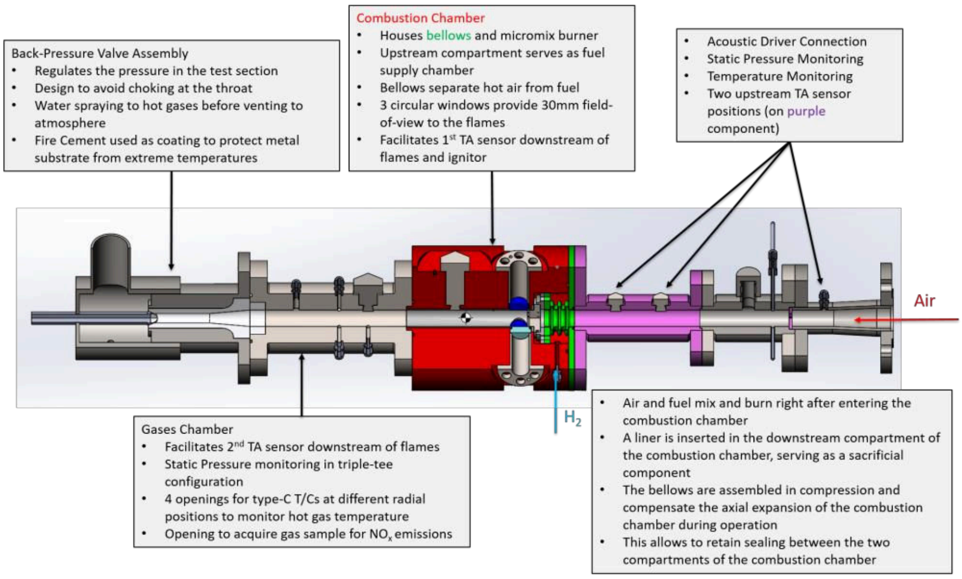


Figure 7 - Section View and short description of the main Rig Components

the combustion chamber upstream compartment and flows through internal channels shaped in the burner (Figure 7).

Design Choices Rationale

The design choices of the combustion chamber (and liner) and the burner (i.e., the most critical components) are explained. The material chosen for less critical components that do not come into contact with combustion gases is Stainless Steel 304, a grade that can withstand high mechanical loads at the elevated temperatures of inlet-air.

Combustion Chamber

A combustion chamber diameter of 42mm was chosen for the combustion chamber as described in a previous section. To allow for safe fuel delivery to the burner, the combustion chamber was split in two compartments. The upstream compartment with an inside diameter of 125mm serves as a fuel chamber (Figure 8). During operation, the main chamber temperature rises due to the heat conducted from hot combustion products, whereas the fuel chamber remains at lower temperatures because of the high heat capacity of hydrogen. Therefore, thermal expansion is expected for the combustion chamber, primarily in the axial direction as the rig becomes hotter downstream. This could compromise sealing between the two compartments and gases could flow towards the fuel chamber. The bellows are employed to solve this problem.

Optical access is achieved through three circular openings, at 90º between them. The circular geometry allows for low stress concentration on the component. The field-of view was set to 30mm in diameter. Evidence from numerical simulations [9] suggests that the length of micromix flames is within the designed field-of-view for various burner designs yielding different flame shapes. At lower pressure and temperature conditions (atmospheric), longer flames up to 50mm are expected as indicated by numerical simulations. (Figure 9).

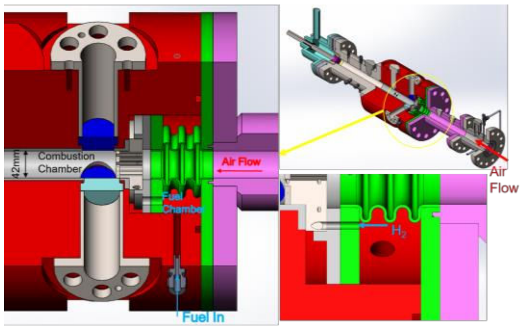


Figure 8 – Explanation of fuel flow path inside fuel chamber and burner internal galleries

Larger openings were not practicable because their position and size would cause structural issues for the liner as well as significant distortion of the combustion flow.

A wall-thickness of 100mm offers the advantage of high-thermal inertia, allowing the testing domain to remain at an elevated temperature between successive combustion tests, without the need to reheat.

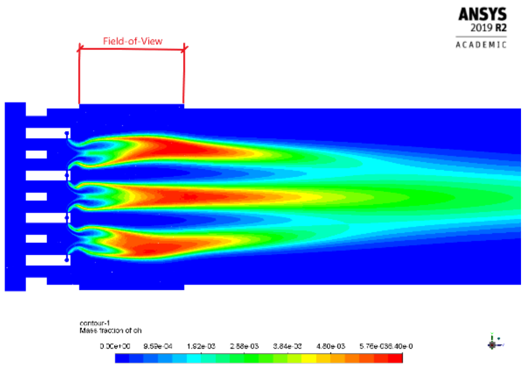
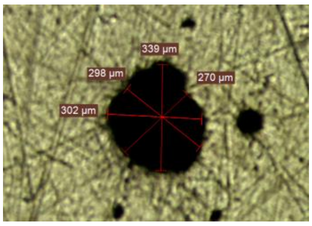
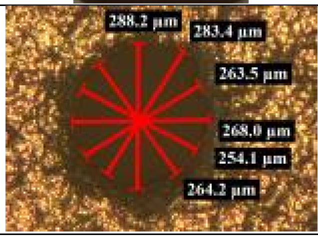
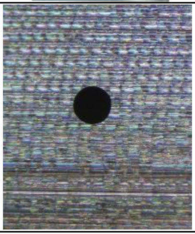


Figure 9 - Flame length against the size of field-of-view. Simulation at atmospheric pressure

Table 1 - Comparison of 0.3mm diameter holes, fabricated with different techniques

<table>
<tr><td>Material</td><td>Alloy 625</td><td>Stainless Steel 316L</td><td>Stainless Steel 316L</td></tr>
<tr><td>Technique</td><td>DMLS</td><td>BJT</td><td>Micro-EDM</td></tr>
<tr><td>Test Piece</td><td></td><td></td><td></td></tr>
<tr><td>Representative inspected nominal 0.3mm hole</td><td>
</td><td>
</td><td></td></tr>
<tr><td>Tolerances on nominal diameter</td><td>-30μm to +39μm</td><td>-46μm to -12μm</td><td>-10μm to +10μm</td></tr>
</table>

Moreover, it can potentially contain a small-scale detonation. Since the configuration is essentially not-cooled, extreme temperatures could damage the inner wall. To avoid a scenario where the whole component would need to be replaced, an internal liner is used. The material used for both the liner and combustion chamber is Stainless Steel 316L, due it its high mechanical strength and operability temperature limit of 1200K.

Micromix Burner

Key focus of this work was the development of the micromix burner prototype. The main challenges were the creation of injection points of 0.3mm in diameter, as outlined earlier, and ensuring safe fuel delivery.
Given the high diffusivity of hydrogen, modular burner construction would create the potential for multiple leak paths through the interfaces of the connected pieces and pose a risk of unwanted deflagration or even detonation. A one-piece design was thus selected, carrying internal channels for fuel flow towards the injectors (Figure 10). The one-piece design minimises the number of leak paths for hydrogen. Hydrogen flowing through the internal channels, also acts as coolant for the hot surfaces of the burner that are close to the flames. This design could be realised by employing metal AM.

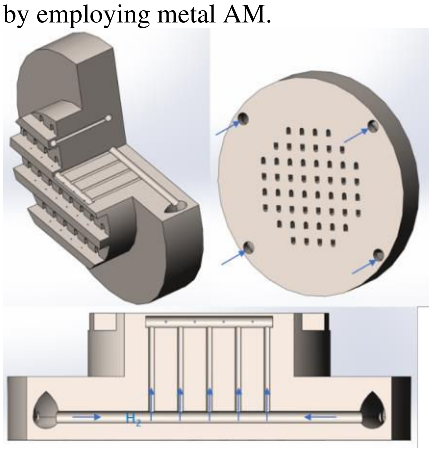


Figure 10 - CAD model for the baseline configuration of the manufactured burner geometry

Accurate creation of the injection points with AM though was doubtful as the State-of-the-Art techniques like Direct Metal Laser Sintering (DMLS) are close to the limit for such features. In order to decide, 0.3mm openings produced by DMLS, Binder Jetting Technology (BJT) and micro–Electric Discharge Machining (micro-EDM) were compared (Table 1). Micro-EDM produced the most promising results and was selected to produce the injection points on the burner prototype. It should be noted that the final machined prototype could not be inspected, due to lack of direct line-of-sight to the holes. This procedure will be used for manufacturing all the burner configurations.

Measurement Techniques and Instrumentation

Monitoring Instrumentation

Temperature and static pressure are monitored at the air-inlet of the rig and at the downstream end of it, right upstream of the B/P valve (Figure 5). An overview of the equipment is given in Table 2.

Table 2 - Overview of Monitoring Equipment

Monitored Parameter	Instrument	Range	Error FS
Static Pressure	Omega PXM-319	0-20 barg	+/- 0.25%
Inlet Air Temperature	Type-K T/Cs	73K to 1520K	+/-0.75%
Hot Gas Temperature	Omega XMO - Type-C T/Cs	<1810K	+/-0.75%

Gas Analysis

A Horiba PG-250 portable gas analyser is utilised to measure NO_x emissions. The measuring principle is chemiluminescence detection method (CLD) where NO_x is measured as NO. NO_2 in the sample is turned to NO before the measurement [12]. The lower detection limit is <1ppm at a range of 100ppm[13]. The selected operating range is 0 to 25ppm. Sample extraction relies on the pump of the analyser, as the insertion of a probe is difficult for this rig, due to the small size of the domain. A heated line transfers the sample to an electronic cooler unit where the sample is conditioned before entering the analyser [14].

Thermoacoustics Setup

The FTFs are determined using a multiple microphone method [15,16]. For these experiments four dynamic pressure transducers are used, two upstream of the burner and two in the combustion zone together with an acoustic driver upstream of the upstream transducers. For these experiments a conventional loudspeaker is used as the acoustic driver, and Kistler Type6021-A pressure sensors are selected as they can sustain temperatures up to 700ºC. The operating range is up to 100 bar and the frequency range covers from 0.5Hz to 20kHz.

Flame Imaging with low-repetition OH-Planar Laser Induced Fluorescence (OH-PLIF) is scheduled at a later stage. OH-PLIF will allow the study of flame behaviour and flame anchoring position.

Conclusions

The rig described here is, in many aspects, unique as it allows:

- Testing of hydrogen micromix injectors at a range of conditions up to 15barg and 600K inlet-air.
- Exploration of the lean-blow-out limits of hydrogen at these conditions.
- Simultaneous application of measurements of NO_x emissions, flame front imaging and FTF acquisition

Such tests for hydrogen micromix, to the authors' knowledge, have not been performed previously or their results are not published in the open literature.

A significant finding comes from the investigation of manufacturing procedures for the burner.

- State-of-the-art additive manufacturing techniques are considered sufficient for the burner body, but inadequate to create sub-millimetre injectors.
- Micro-EDM provided the desirable injector quality but is still a costly process compared to AM.

The size of the injection points is not expected to change much for a real size micromix combustor. Hence, further research is required in the manufacturing procedure, to allow for the creation of micromix burners, acceptable in terms of injector dimensional quality and feasible in terms of costs. Finally, results from this rig will act as proof-of-concept for the micromix technology for aviation. Ultra-low NO_x emissions at operating conditions representative of a turbofan engine operation close to cruise will be the stepping stone to drive technology maturation and shift the work from mostly numerical and small-scale experimental, to larger-scale experiments.

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