

CRANFIELD UNIVERSITY

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**Design, Development and Testing
of a High-Pressure Hydrogen
Micromix Combustion Rig**

School of Aerospace, Transport and Manufacturing
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Abstract

The aviation industry has been improving aircraft performance and cutting back emissions for decades now. The increasing urgency of climate change has been pushing this effort to become more intense leading in recent years to the adoption of the target of full decarbonisation by 2050. Significant reductions in non-carbon-containing emissions have been targeted by the industry as well.

In that context, the use of liquid hydrogen (LH_2) as a combustible fuel for aircraft propulsion is a promising solution. Hydrogen guarantees carbon-free flights at mission level, yet, state-of-the-art aircraft combustor technologies are not suitable for low- NO_x hydrogen combustion. Consequently, alternative combustion concepts and technologies are under research, and micromix technology is one of them.

This thesis presents the design, development and deployment of a high-pressure combustion rig for hydrogen micromix burners, and describes the process from conception to testing of three different injector geometries. In doing so, it highlights the challenges of designing the components and systems to operate with hydrogen, whilst ensuring safety. Based on the experience gained through the deployment of the experimental setup, potential problems have been identified and solutions have been suggested to improve it. This aspect of the work contributes towards future research efforts of developing larger-scale combustion rigs for testing hydrogen.

Within the context of the rig development, different design philosophies and manufacturing routes are explored for micromix burners. The limitations and safety considerations for the different approaches are detailed, and guidelines are offered on how the setup may be improved. The successful implementation of a fabrication strategy that combines additive manufacturing with traditional machining of features with sub-millimetre dimensions ($0.3mm$) is a significant contribution to developing micromix burners. It further opens an area of research into the limitations and potential effects of applying additive manufacturing to future micromix combustors.

NO_x emissions measurements of three injector configurations with different momentum flux ratios (MFRs) taken at elevated pressures, air-inlet temperatures and equivalence ratios are presented. The results denote the impact of these parameters on NO_x emissions and the sensitivity of the emission to changes in MFR. Comparisons with LES results further highlight the need to accurately represent phenomena that affect the momentum flux ratio (MFR) in the simulations. Failure

to do so provides a misleading correspondence of NO_x levels with MFR. When compared to a state-of-the-art kerosene burner at similar pressure and inlet temperature conditions, hydrogen micromix yielded lower NO_x by 50% for the "worst" injector configuration.

Keywords

Hydrogen; Hydrogen Combustion; Hydrogen Micromix; Momentum Flux Ratio; Experiments; Experimental Combustion; Emissions Measurements; NO_x Emissions; High Pressure; High Temperature; Rig Design.

Acknowledgements

I have written the "Acknowledgments" section for this thesis, many times in my head. But now that it is time to actually type the words, I just find it very difficult. The past five years have been quite a ride, most of the time a hard one, but with the help and support of the people mentioned in this section, life as a PhD student was easier. This is a bit of a long section, and not necessarily sensible so brace yourselves, people! To anyone whom I may have forgotten to include here, I apologise, but my gratitude is of course extended to them.

I would like to start by thanking Prof. Bobby Sethi and Dr Devaiah Nalianda, for giving me this unique opportunity to work on such an exciting project. Not many people get the chance to work on experimental hydrogen combustion and are trusted to pull off such a job. And what an enjoyable time it has been burning hydrogen! For their trust, and all their help I am deeply grateful to both. And to Devaiah an extra bit more, for not allowing me to quit all the times that I really wanted to do so. I would also like to thank my colleagues and friends Dr Xiaoxiao Sun, Dr Charith Wijesinghe and Dr Parash Agarwal with whom we worked together on ENABLEH2 at various phases. Xiaoxiao and Parash were there from the start and together we started building what became the hydrogen combustion rig. Charith, who joined us later significantly contributed to the success of the experimental campaign, with his experience and knowledge. So, thank you all three for everything! I would also like to thank my reviewers Dr Pavlos Zachos and Dr Sue Impey. Their feedback was always critical and to the point, and helped me not only form the story of my PhD, but also derisk it from the very early days.

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Now, since this, for me is a milestone, it is a unique chance to express gratitude to people on paper, so please allow me to go a bit back in time, to recognise the

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I want to further express my gratitude to my friends back in Greece, Alexandros, Thomas, Dimitris, George, Areti, Yiannis and others I may be missing, who all these years kept in contact, despite me being awful at texting and calling them and of course for all their mental support!

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complain and cry and cheer numerous times, and mind you, not just during the PhD time, but pretty much forever. They have been the pillars of my development, those who supported me every step of the way and were there to console me on every mishap. They are the people who shaped me.

For the end, please allow me a personal statement. This period, in a sense, has been a strange time in my life and on occasion, in my effort to keep in touch with the real world, its grievances took a toll on me, higher than usual. My biggest consolation in those times, a reminder that there are numerous ways to run our world, alternatives to the crushing forces of capitalism, I found it in the books and various talks of the late Professor David Graeber. I am grateful to have come across his work and amazing spirit, may he Rest in Power!

This is not the end of the story, merely a beginning!

Alexandros

Cranfield, 9 September 2023

To my parents and siblings

To anyone who may read this work, in the hope they find it
interesting and useful

...We will know how to accommodate ourselves for a time. For, you must not forget, we can also build. It is we the workers who built these palaces and cities here in Spain and in America and everywhere. We, the workers, can build others to take their place. And better ones! We are not in the least afraid of ruins. We are going to inherit the earth; there is not the slightest doubt about that. The bourgeoisie might blast and ruin its own world before it leaves the stage of history. We carry a new world here, in our hearts. That world is growing this minute.

Buenaventura Durruti

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Nomenclature

Abbreviations

<i>AGP</i>	air-gate panel
<i>AM</i>	additive manufacturing
<i>CAD</i>	computer aided design
<i>CARS</i>	coherent anti-Stokes Raman scattering
<i>CFD</i>	computational fluid dynamics
<i>CLD</i>	chemiluminescence detection
<i>DAQ</i>	data acquisition
<i>ECU</i>	electronic cooler unit
<i>EDM</i>	electrical discharge machining
<i>FAR</i>	fuel-to-air ratio
<i>FEM</i>	finite element method
<i>FS</i>	full-scale
<i>FTF</i>	flame transfer function
<i>IRZ</i>	inner recirculation zone
<i>JiCF</i>	jet-in-cross-flow
<i>LDA</i>	laser Doppler anemometry
<i>LDI</i>	lean direct injection
<i>LDV</i>	laser Doppler velocimetry

<i>LES</i>	large-eddy simulations
<i>LH₂</i>	liquid hydrogen
<i>LTO</i>	landing and take-off
<i>MFC</i>	mass-flow controller
<i>MFR</i>	momentum flux ratio
<i>ORZ</i>	outer recirculation zone
<i>PB</i>	Pebble Bed
<i>PDA</i>	phase Doppler anemometry
<i>PIV</i>	particle image velocimetry
<i>PLIF</i>	planar laser induced fluorescence
<i>RANS</i>	Reynolds-averaged Navier-Stokes
<i>Rd</i>	instrument reading
<i>SAF</i>	sustainable aviation fuels
<i>SOTA</i>	state-of-the-art
<i>VI</i>	virtual instrument

Chemical Substances

<i>CH</i>	methylidyne
<i>CO</i>	carbon monoxide
<i>CO₂</i>	carbon dioxide
<i>H</i>	atomic hydrogen
<i>H₂</i>	hydrogen
<i>H₂O</i>	water
<i>HNO₂</i>	nitrous acid
<i>HNO₃</i>	nitric acid
<i>N</i>	atomic nitrogen

N_2	nitrogen
NO	nitric oxide
NO_2	nitrogen dioxide
NO_2^*	electronically excited NO_2
NO_x	oxides of nitrogen
O	atomic oxygen
O_2	oxygen
O_3	ozone
OH^*	electronically excited OH radical
OH^-	hydroxyl radical
SO_2	sulfur dioxide
SO_x	sulfur oxides

Dimensionless Numbers

Le	Lewis number	-
Ma	Mach number	-
Sc	Schmidt number	-

Greek Symbols

Δ	difference	-
Φ	equivalence ratio	-
α	coefficient of thermal expansion	K^{-1}
β	diameter ratio, component uncertainty - absolute value	-
ϵ	expansion factor	-
ε	uncertainty component - percentage error value	-
ν	Poisson's ratio	-
ϱ	density	$kg\ m^{-3}$

σ	normal stress	N mm^{-2}
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Indices and Other Physical Quantities

C_p	specific heat under constant pressure	$\text{J kg}^{-1} \text{K}^{-1}$
$EEINO_x$	energy emission index of nitrogen oxides	g MJ^{-1}
$EINO_x$	emission index of nitrogen oxides	g kg^{-1} of fuel
LHV	lower heating value	MJ kg^{-1}
$\dot{Q}$	rate of heat transfer	J s^{-1}
h	Planck constant	$\text{m}^2 \text{kg s}^{-1}$
$\dot{m}$	mass flow	$\text{kg s}^{-1}, \text{g s}^{-1}$

Roman Symbols

A	cross-sectional area	m^2
C	discharge coefficient	-
D	diameter	mm
E	Young's modulus	MPa
J	momentum flux ratio	-
M	molecular weight of a substance	g mol^{-1}
N	number of	-
P	Pressure	Pa, bar
R	specific gas constant	$\text{J kg}^{-1} \text{K}^{-1}$
T	temperature	K
U	total uncertainty	ppmv
b	uncertainty from systematic errors	-, ppmv
n	sample size, number of moles	-, mol
s	standard deviation, uncertainty from random errors	-, ppmv
t	thickness	mm

u	velocity	m s^{-1}
v	wave frequency	s^{-1}
x	mass fraction of a substance	-
y	molar fraction of a substance	-

Superscripts

∞	far-field conditions/here refers to the air cross-flow
$\bar{X}$	sample average
AG	air gates
a	absolute
air	air
b	burnt, participating in the combustion process
c	cooling, not participating in combustion
cg	calibration gas
con	converter
$corr$	corrected
des	design
dn	downstream, usually in respect to the flames
f	fuel
g	gauge
in	inlet, instrument
inj	injectors
j	jet
l	linearity
min	minimum
ref	reference case

<i>rep</i>	repeatability
<i>s, dr</i>	span drift
<i>st</i>	stoichiometric
<i>th</i>	thermal
<i>t</i>	turbulent (referring to a dimensionless number)
<i>up</i>	upstream, usually in respect to the flames
<i>vap</i>	vapour
<i>w</i>	water
<i>z, dr</i>	zero drift

CHAPTER 1

Introduction

1.1 General Context

The consequences of climate change are already evident in the form of extreme weather phenomena and have been driving most sectors of human activity towards reductions of emitted greenhouse gases (GHGs), the most prominent of which is CO_2 .

Among these sectors, the aviation industry contributes approximately 2% of anthropogenic CO_2 emissions [4]. With the predicted growth of air traffic (CHAPTER ONE of [36]) and a potentially faster shift of other sectors such as power generation and automotive towards environmentally friendly technologies, this percentage contribution of CO_2 from aviation may grow.

Until recently, the efforts of the aviation industry focused on emissions reductions by technological improvements targeting the efficiency of the propulsion system or aircraft-drag reduction. Such technological advancements positively impact the reduction of emissions but cannot meet the ambitious targets set recently by the industry (see Figure 1.1), as set out in the Waypoint 2050 document [71]. To achieve the target of net-zero carbon emissions by the year 2050 [71], radical solutions are required such as the use of alternative fuels. To that end, non-fossil hydrocarbon-based sustainable aviation fuels (SAF) and hydrogen are the most prominent solutions. Hydrocarbon-based SAF fuels produced by sustainable feed stocks can offer high reductions in life-cycle CO_2 emissions (up to 80% according to [62]), while hydrogen if produced by renewable energy sources, can eliminate carbon-related emissions. Hydrogen for power generation and propulsion can be utilised in two ways: in fuel

cells where chemical energy is turned into useful electrical energy and the only emission is water (H_2O), and as combustible fuel in air where the products are water vapour and nitrogen oxides (NO_x).

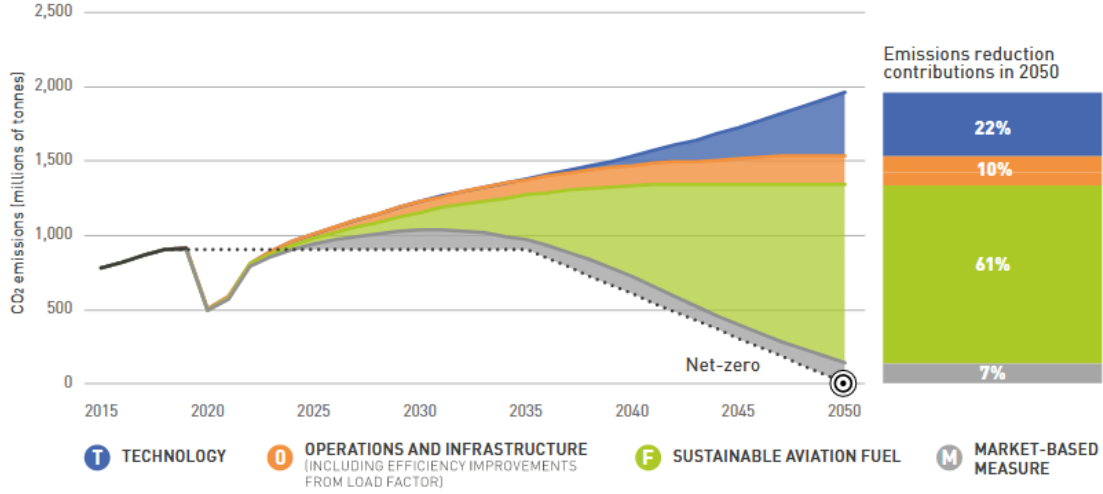


FIGURE 1.1: Predictive scenario of contributions towards net-zero by 2050. Technological contributions towards electrification and deployment of SAF play a major role. The scenario stands for predicted traffic growth of 3.1% per annum till 2050. Image taken from [71]

The idea of hydrogen as combustible fuel for aircraft propulsion is not new. A series of NASA studies from the 1950s to the 1970s were conducted to evaluate the potential of hydrogen mainly for military aircraft [19], [52]. More recently though, with technological advances and the urgency of climate change towards carbon-neutral aviation, interest in hydrogen has reemerged. Major companies have committed to delivering hydrogen aircraft in the coming decades. Characteristic examples are those of Airbus with the Zero-e project, planning to create a demonstrator by 2035 [3], ZeroAvia recently flew a twin-engine aircraft and is heading towards flight certification tests [72], and a Rolls Royce collaboration with easyJet that recently fired a modified gas turbine engine running purely on hydrogen[44].

The potential of hydrogen to de-carbonise aviation lies in the fact that there is no carbon in its molecule, hence, the elimination of all carbon-related emissions. Yet, in the case of hydrogen combustion, the products (mentioned previously) still have an effect on climate and human health. In brief, water vapour can have an impact on climate in two ways: by acting as a greenhouse gas along with carbon dioxide (CO_2) or by the formation of cloud-like structures that are the condensation trails.

Contrail formation, expansion and residence time depend on the local atmospheric conditions, as well as the particles present in the exhaust jet of an aircraft engine.

Persisting contrails and contrail cirrus clouds can have a negative impact on climate through positive radiative forcing (RF). That is, heat radiated from the surface of the earth towards space, is absorbed by these structures and reflected back to the earth, thus trapped, increasing the temperature of the lower atmosphere. Radiative forcing of contrails can have a reverse effect by reflecting solar radiation back into space, depending on the characteristics of the contrails. Research denotes that contrails are believed to primarily lead to positive radiative forcing, although the uncertainties are high and further research is required [38].

Contrail formation by hydrogen combustion is believed to be much shorter in residence time compared to kerosene engines, due to the lack of soot particles that can act as nuclei for the formation of ice crystals. The amount of water produced though is 9 times that of kerosene, denoting increased potential for contrail formation. Trajectory optimisation and cruising at lower altitudes can help tackle this issue, having a positive effect on contrail formation, but with the disadvantage of imposing a penalty on fuel burn.

NO_x emissions, consist of NO and NO_2 and have an impact both on climate and human health. NO_x produced by aircraft engines around the vicinity of airports lowers the air quality and can have adverse effects on human health, causing respiratory problems. These are emissions produced during landing and take-off (LTO) cycles and account for a small percentage of the total NO_x produced during a typical aircraft mission. Most of the engine NO_x is produced at the cruise phase at altitudes of about $10km$. Those emissions affect the climate by potentially contributing to global warming, although the uncertainties on their net radiative effect are high (CHAPTER THREE of [36]). Moreover, NO_x contribute to the depletion of the ozone layer, allowing more harmful ultraviolet radiation from the sun to reach the earth's surface.

In hydrogen combustion, NO_x emissions are produced primarily through the thermal mechanism, using atmospheric nitrogen, due to the high temperatures of hydrogen flames. The extended Zeldovich Mechanism is used to describe thermal NO production:



According to this mechanism, for temperatures above $1800K$ NO forms at exponential rates with respect to the increasing temperature. The exponential increase in

NO_x production is attributed to the rapid dissociation of O_2 and N_2 beyond $1800K$. Another factor that affects NO_x formation is the residence time of the hot gases in the combustor, since the chemistry of NO_x formation is slow compared to the hydrogen/air combustion. Higher residence times thus lead to increased NO_x formation.

Taking into account the above discussion, and the fact that hydrogen produces flame temperatures of about $2600K$ at stoichiometric conditions¹, it is necessary to operate hydrogen combustors at lean equivalence ratios (Φ) and achieve very good mixing, to avoid the creation of local zones of stoichiometric combustion, i.e., hot spots. Moreover, shorter combustors and injection technologies that guarantee lower residence times can further improve NO_x emissions performance.

Regarding the operating equivalence ratio, the stability limits of hydrogen flames are wider than those of kerosene (Figure 1.2) allowing for leaner combustion, hence lower flame temperatures. State-of-the-art combustion systems utilise partial premixing to achieve more homogeneous fuel-air mixtures and lower NO_x emissions. Such

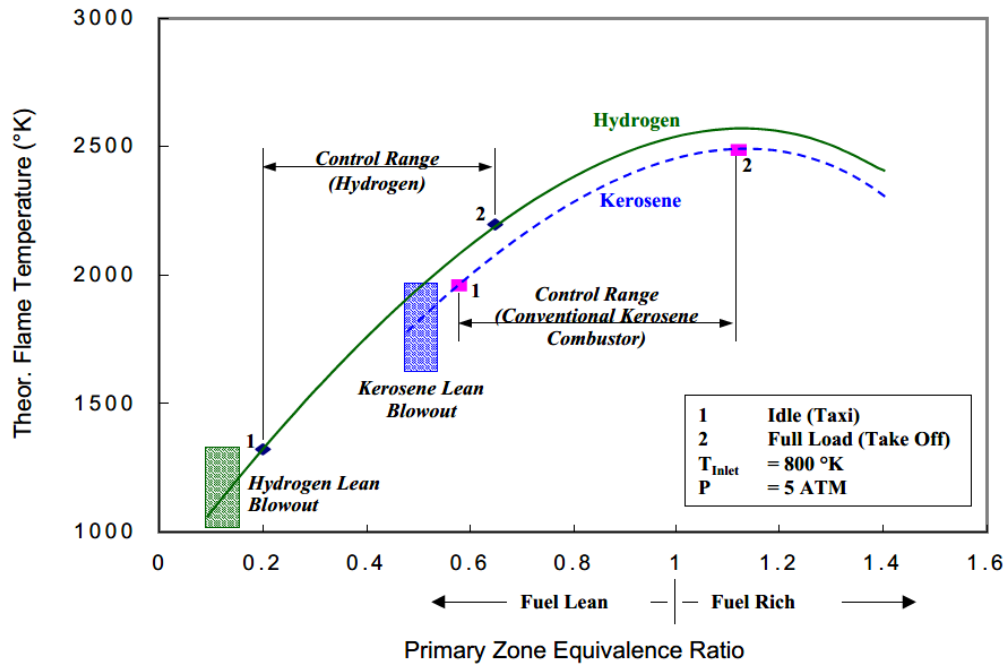


FIGURE 1.2: Comparison of hydrogen and kerosene flame temperature against equivalence ratio [10]

systems can give rise to auto-ignition and flashback issues, which can lead to flame instability. These issues can be more pronounced with hydrogen as a fuel, given its flammability and low ignition energy. Thus, the use of state-of-the-art technologies

¹For a given equivalence ratio, flame temperature is also dependent on combustor inlet pressure and temperature (P_3 , T_3)

is not suitable for hydrogen. The utilisation of diffusion concepts for hydrogen is more appealing, yet good mixing quality would be a major issue. In order to achieve better mixing characteristics, researchers at Aachen University devised in the 1990s the concept of micromix [17].

The basic idea behind micromix is to create a very large number of miniaturised flames, in order to improve fuel and air mixing characteristics. It is based on the jet-in-cross-flow (JiCF) principle, where a jet of fuel penetrates a cross-flow of air at a 90° angle (Figure 1.3). The small spatial scale, along with the very good mixing properties of the JiCF allow more homogeneous fuel-air mixtures to form, lowering the probability of the appearance of stoichiometric hotspots. Improved local mixing leads to lower flame temperatures and lower NO_x emissions. Moreover, the multitude of flames creates the opportunity for radial fuel staging with high spatial resolution and thus control of the temperature radial distribution. The potential benefits of fuel staging include improvements in the life expectancy of the combustor liner and the high-pressure turbine. In addition, a controlled temperature distribution can lead to reductions or even avoidance of dilution air, which in turn leads to a shorter combustor. Finally, tuning the radial distribution of fuel flow could serve as a means of control of thermoacoustic instabilities. The concept is also inherently safe against flashback due to the injector geometry, and the fact that no premixing of fuel and air is involved.

The ideal position for micromix flames is in the shear layer that forms between the two interacting streams and the two recirculation zones (inner and outer vortices – Figure 1.3) that form around the streams. This position avoids the flames entering either of the recirculation zones, which could lead to merged flames and hence higher temperatures, as well as increased residence time, both of which lead to higher NO_x . A key flow parameter that affects mixing characteristics, flame position and residence times, and subsequently NO_x , is the momentum flux ratio (MFR), denoted by J and defined as

$$J = \frac{\rho_j u_j^2}{\rho_\infty u_\infty^2} \quad (1.1)$$

where, ρ is the density and u is the velocity. The subscripts j and ∞ denote the penetrating jet and cross-flow air, respectively. Geometric parameters such as fuel injector size and air-supply channel dimensions (Figure 1.4) determine the momentum flux ratio (MFR) by affecting flow velocities. Moreover, the offset distance (Figure 1.4) has an effect on the size of the outer recirculation zones (ORZ) and hence the created shear layer. The MFR is used to represent these effects and thus determines the flame position and orientation by affecting the fuel-jet penetration

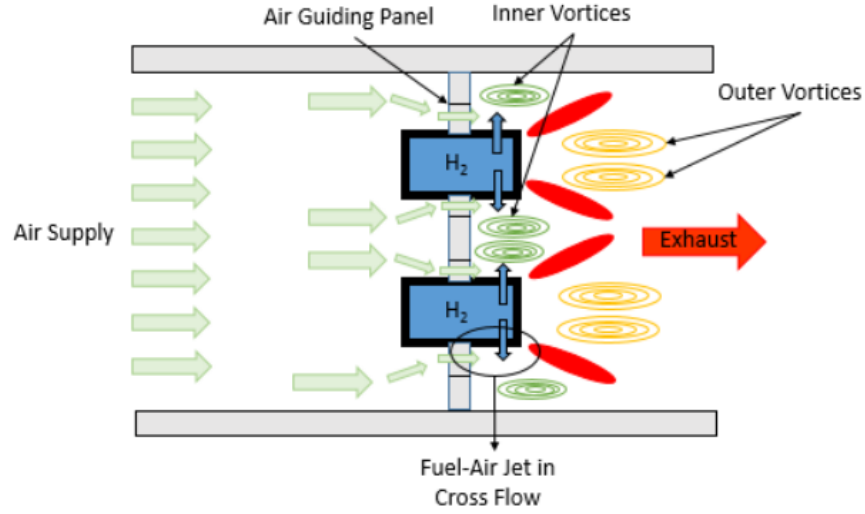


FIGURE 1.3: Illustration of jet-in-cross-flow micromix flames [2]

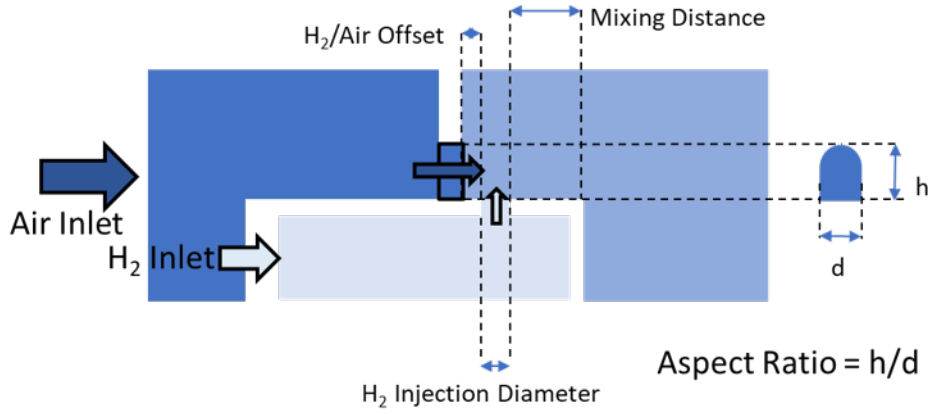


FIGURE 1.4: Geometric parameters of a micromix injector [2]

depth in the air cross-flow (Figure 1.3). A low momentum flux ratio can lead to penetration depth below a critical value, a downwash effect on the jet and hence the presence of a reaction zone in the inner recirculation zone (IRZ) (Figure 1.3), creating merged flames. With a high MFR, and subsequently increased penetration depth, the jet can overshoot to the outer recirculation vortex (Figure 1.3) yielding merged flames in that region. In both cases, the hot products enter recirculation systems increasing their residence time in the combustor which leads to increased NO_x formation.

Numerical models can provide a qualitative understanding of how NO_x changes with the change of momentum flux ratio (Figure 1.5), yet such models require validation through experimental results. Currently, there is a scarcity of experimental data that allow the validation of numerical models. The research presented in this thesis aims to provide a data set for NO_x emissions in order to assess the predictive

capabilities of state-of-the-art (SOTA) numerical tools. The importance of such an assessment is understood if one considers the suggested sensitivity of NO_x production with momentum flux ratio (J) (Figure 1.5): inaccurate predictions of NO_x for a certain value of J could imply that a design considered by numerical studies as low- NO_x , in reality, produces high amounts of NO_x . This example highlights the importance of producing experimental data sets that will help understand the predictive capabilities of numerical models.

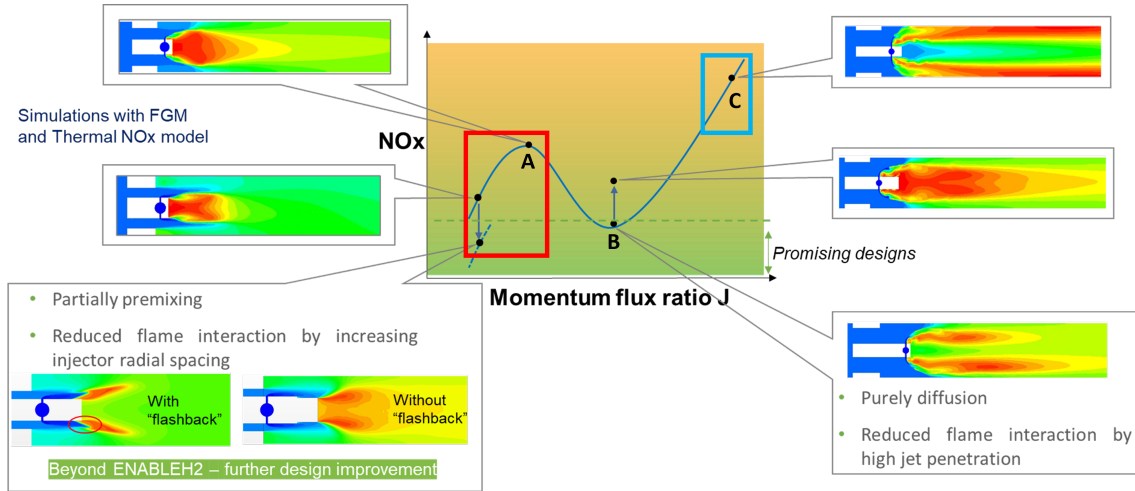


FIGURE 1.5: Qualitative representation of the relationship between momentum flux ratio (J) and NO_x emissions. (Image taken from [67])

For the past four years, Cranfield University, with the ENABLEH2 project, has been leading a consortium of academic institutes and industrial partners towards maturing technologies that will enable the use of liquid hydrogen (LH_2) for aircraft propulsion. The present thesis describes the efforts of designing, building, and testing a new high-pressure, high air-inlet temperature experimental rig for hydrogen-fuelled micromix burners, as part of the ENABLEH2 project.

1.2 Scope and Objectives of the Work

The aim of this work was to design, develop and test an experimental rig for hydrogen micromix combustion at high pressures and air-inlet temperatures, in order to assess the impact of operating parameters and the momentum flux ratio on NO_x emissions. To that end, the following objectives were set:

1. Definition of the rig requirements, specifications - maximum operating pressure, air-inlet temperature - and matrix of test conditions

2. Design and manufacture of the test section components
3. Identification of suitable techniques for the manufacture of micromix burners
4. Design and implementation of said micromix burners
5. Development of the fuel supply and safety systems
6. Setup of the measurement and monitoring systems of the rig (emissions, thermoacoustics, pressure and temperature monitoring and control supply of fuel and air)
7. Preliminary tests to ensure the safe operation of the system and identify potential issues
8. Setup improvements wherever possible, with a focus on the emissions measurement system
9. Tests of the main experimental campaign for NO_x emissions results acquisition. Experimentally measured NO_x in conjunction with numerically derived results are compared and used to help gain an understanding of the effects of the control parameters on emissions.

1.3 Contribution to Knowledge

The contribution to knowledge of this research lies in the quantification of emissions from hydrogen micromix combustion systems for the characterisation of the impact of momentum flux ratio on NO_x , at different pressures and air-inlet temperatures. State-of-the-art numerical tools present deficiencies in their predictive capabilities when it comes to hydrogen combustion, due to characteristics of hydrogen such as its high diffusivity, and a lack of understanding of the behaviour of chemical kinetics at higher pressures. These deficiencies highlight the importance of creating high-quality experimental data sets. Such experimental data should cover a wide range of operating conditions in order to allow validation and potentially the calibration of numerical tools.

This work attempts to cover, in part, the scarcity of experimental datasets in the public domain regarding hydrogen combustion, by producing such a data set for NO_x emissions. The specific contributions of the research can be summarised as follows:

1. NO_x emissions results acquired at different operating conditions, for three different injector geometries provide insights into the increasing trend of emissions with pressure, air-inlet temperature and equivalence ratio. The high sensitivity of NO_x on flow phenomena associated with the effect of momentum flux ratio is also suggested.
2. Comparison of experimentally measured NO_x with values and temperature contours derived from large-eddy simulations (LES), points out deficiencies of numerical modelling. In particular, reliance on CFD can lead to the sub-optimal design of low- NO_x micromix burners. The reason for this is that the dependency of NO_x from the momentum flux ratio (MFR) as predicted by CFD appears to be shifted on the MFR axis.
3. The comparison also identifies the requirement in CFD simulations to accurately represent physical phenomena that affect the momentum flux ratio. In experiments significant heat transfer from the flames towards the fuel channels of the micromix burner increases the fuel temperature, changing its density and subsequently the momentum flux ratio. This was not captured by the LES and is suggested as one of the reasons behind discrepancies of NO_x (against equivalence ratio) trends between experimental and numerical results.

1.4 Research Contributions

Further to the contribution to knowledge, this work also contributes to answering the following research questions:

1. What are the main challenges when designing components for a high-pressure, high-temperature hydrogen combustion rig?
2. What good practices can be followed towards safety when performing hydrogen combustion experiments?
3. Are state-of-the-art manufacturing techniques suitable for the design of a safe hydrogen micromix burner and its intricate fuel passages and injection holes?
4. How can emissions measurement setups cope with the high water content of hydrogen combustion?

1.5 Thesis Structure

The thesis is organised into four main chapters, presented below:

Chapter 2 -Literature Review: Here a review is presented of past work on the topics explored in the thesis. A brief presentation of the more recent history of hydrogen in aviation sets the scene. It is followed by a section that presents combustion facilities and rigs around the world and discusses important design aspects and capabilities. A focused discussion on past research around hydrogen micromix combustion follows as micromix is the main topic of this thesis. The final sections argue the reasons behind the development of a new experimental rig for hydrogen micromix combustion and the research gaps.

Chapter 3 - Methodological Approach: The third chapter is a presentation of the approach followed and the tools utilised towards the design of the rig and implementation of required measurements. The equipment used and measurement techniques applied, are discussed too. It also presents the processing procedures for the acquired results and the calculations for the presented metrics.

Chapter 4 - Design and Development of the Hydrogen Combustion Rig: The fourth chapter discusses the design and development of significant components of the experimental apparatus. It highlights key aspects of the process in the form of challenges presented and lessons learnt during the different phases from initial design all the way to the testing campaign. The limitations of the setup are discussed next and the chapter concludes with a presentation of the limitations of the current setup and suggestions to improve it.

Chapter 5 - Hydrogen Combustion Tests: In this chapter, the experimental campaign is detailed, with an initial discussion on the realised test cases and micromix configurations tested. This is followed by a short overview of the pressure drops of different configurations, the presentation of NO_x emissions and a comparison between experimental and numerical results.

CHAPTER 2

Literature Review

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2.1 Introduction

The potential advantages and disadvantages of hydrogen combustion and the characteristics of micromix technology were briefly discussed in the previous chapter. This chapter begins with a brief discussion of the reasons why current combustor technologies are not suitable for hydrogen along with a presentation of emerging concepts for hydrogen combustion. The literature review continues with a presentation of experimental combustion facilities around the world and their capabilities. A review of past research on hydrogen micromix follows which highlights the scarcity of experimental data at high-pressure and high-temperature conditions. Bringing the discussion of the previous sections together, the final section argues the reasons for developing a new combustion rig for hydrogen micromix, presents the requirements for such a rig and finally points out the research gaps that this work addresses.

2.2 Hydrogen Combustion for Aviation

The main advantage of hydrogen over hydrocarbon fuels, as already discussed, is the elimination of carbon-related emissions, at mission level, yet its direct implementation in currently serving engines is not feasible. Even if other technical issues such as tank sizing of an aircraft and fuel heat management could be overseen, the use of current combustors and their technologies is prohibitive. The limitations are imposed by design characteristics such as

1. the small number of large injectors designed for liquid fuels
2. the length of these combustors and the use of dilution air
3. the utilisation of premixing or partial premixing in some concepts

Large injectors for non-premixed flames do not promote the mixing of hydrogen and air and would lead to large, high-temperature, near-stoichiometric flames and subsequently high levels of NO_x . On the other hand, the premixing of hydrogen and air creates a high risk of autoignition and flashback, given the wide flammability range of hydrogen and its high flame speeds. Flame arrestors would be required to avoid flashback, or injector configurations with high bulk-flow velocities so that flames cannot propagate upstream. Current combustors also utilise patterns of dilution holes where the air is injected to cool the inner wall of the liner, lower the temperature of the hot gases, or be used for lean combustion downstream of the primary zone (as is the case for RQL combustors). The existence of dilution holes extends the required length of the combustor, increasing residence time and thus favours further NO_x formation. The extra dilution air may not be necessary for hydrogen combustors and instead, be used for combustion in significantly leaner mixtures. Combined with the high flame speeds of hydrogen, shorter combustors should be expected.

Two technologies have emerged in the past three decades that could potentially be implemented in aviation gas turbine combustors burning hydrogen. These are the multi-point Lean Direct Injection (LDI) [46] and micromix [17]. More recently two more suggested technologies, the HYLON burner [47] and the lean azimuthal flame (LEAF) combustion technology [53] have been proposed, although at earlier stages of development. The common characteristic of all these concepts is the effort towards improving the mixing quality of fuel and air.

Micromix has been briefly presented in the previous chapter, and past work on the technology is in detail discussed in section 2.4 since it is the technology in focus for this thesis.

Multi-point lean direct injection (LDI), is effectively a technology similar to micromix in some respect, as it relies on the creation of a large number of small flames. LDI burners, depending on their design could implement short premixing zones, or air swirling [46] towards lowering NO_x emissions. Five such configurations were tested by Marek et al [46] at a range of pressures, air-inlet temperatures and equivalence ratios, with hydrogen and Jet A, for a comparison of NO_x emissions on the basis of the same temperature rise. All the configurations with hydrogen showed levels of NO_x very close to that of Jet A, but with no significant improvements. The authors suggested that further numerical and experimental work along with design optimisation could yield significant improvements. More recent work on LDI appears to have shifted towards testing with liquid fuels [70].

The HYLON burner, currently under development by researchers at CNRS, implements swirled coaxial flows for both air and hydrogen, with the air surrounding the hydrogen jet [47]. Atmospheric PIV testing at different momentum flux ratios of air and fuel denoted the effect of geometry configuration - mainly the axial position of the hydrogen injector - and swirl, as well as fuel injection velocity on the flame stabilisation position and flame shape [47]. The researchers claim the burner can provide great mixing characteristics of fuel and air.

The lean azimuthal flame combustor was developed at Cambridge University and is based on flameless combustion. It utilises azimuthally distributed fuel injection points at the bottom of the burner, with the main air injected at an angle from a number of points in the bottom plane. A number of high-speed jets of air are also injected from the top of the burner [53]. The counter-flow creates an entrainment of combustion products which favours mixing. Tested at atmospheric pressure, lean azimuthal flames yielded ultra-low NO_x and good stability characteristics [53]. Both the HYLON and LEAF technologies are at a very early stage of development but appear promising for future aircraft gas turbine combustors.

For all the aforementioned technologies, further development requires extensive experimental work that will allow researchers to understand the performance of such combustors in terms of emissions and operability limits and perform design improvements. Numerical work can also assist this process, but the current deficiencies of numerical models when it comes to hydrogen combustion further highlight the significance of experimental testing. Reliable experimental data for hydrogen gas turbine

combustion concepts are still scarce, especially at elevated or engine-representative conditions (high pressures and high inlet temperatures). Yet such data can improve our understanding of flow and chemistry interactions and have an impact on improving the predictive capabilities of numerical models.

2.3 Experimental Combustion Rigs

A short literature survey covering combustion testing rigs and facilities is presented here, in order to set the scene for the design and development of the rig presented in this work. The intention for this part of the literature review was to understand the process and design choices and find guidelines (or a methodology) on how to design and develop a combustion rig. Some of the works presented here were useful for that purpose, however, much of this literature was discovered after the ENABLEH2 rig design was settled.

Several combustion facilities and rigs are reported in the relevant literature, but, to this author's knowledge, only a few of them have the capability of testing at elevated or high pressures (from $5bar$ all the way to $60bar$), with pre-heated inlet air ($400K$ to $1000K$) and large air mass-flows (order of kg/s). In most cases, such facilities are also equipped with three types of measurement instrumentation: devices for emissions analysis, combustion dynamics and diagnostics, such as flame imaging, flow field characterisation and in some cases, flame temperature measurements. Such rigs are usually developed within larger facilities in national or international laboratories. The reviewed facilities and the capabilities they offer in terms of testing conditions, measurements and diagnostics, are summarised in Table 2.1. For a more complete overview of combustion rigs around the world, the reader is referred also to the thesis of Kroniger [40] and the paper of Slabaugh et al. [60].

What is evident from Table 2.1, is that for pressure capability of the order of $30bar$ or above, the available maximum air mass flow does not reach the order of kg/s and is significantly lower [11], [29]. Exceptions to this are the HBK-S rig at the German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt - DLR), combustion rigs at the facilities of NASA Glenn Research Centre (GRC), facilities at the Office National d'Etudes et de Recherches Aérospatiales (ONERA) and the facility at Zucrow Laboratory of Purdue University. The first three are laboratories of national and international scale, while the latter is the only facility that belongs to a university.

Organisation/Rig	P (MPa)	$T_{air,in}$ (K)	$\dot{m}_{air}$ (kg/s)	Measurements
NASA[9], [14], [33]				
CE5	3.04	866	9	smoke, emissions (CO, CO_2, NO_x)
CE9	3.04	839	16.8	O_2 , OH-PLIF, liquid droplet size,
ASCR	6.08	978	17.2	flame temperature
ONERA[13]				
MICADO 1	3	900	3	gas analysis and soot
MICADO2	4	900	4	optical diagnostics capability
M1	3	900	4	smoke, gas analysis, flow velocity (LDV, PIV), PLIF (OH, kerosene , CO), CARS (gas temperature)
DLR[20], [58], [61]				
HBK-S	4	1000	1.3	OH-Chemiluminescence, emissions, PIV PLIF (OH, CH, kerosene),
BOSS	2	900	2.3	PDA, LDA, CARS, Mie Scattering, emissions, combustion dynamics
Purdue University[60]	4	800	4	emissions, PIV, OH-PLIF, CARS
Cardiff University[57], [69] (GTRC)	1.6	900	5	OH-Chemiluminescence PIV, OH-PLIF, emissions, combustion dynamics
NETL/SimVal[59], [63]	2.31	810	1.23	emissions, combustion dynamics, optical diagnostics capability
Virginia Tech.[28]	0.93	650	1.27	PIV, visible flame imaging
Penn State University[11], [43]	3.8	870	0.18	Chemiluminescence (OH, CH), combustion dynamics, OH-PLIF emissions
Paul Scherrer Institut[29]	3	823	0.3	PIV, OH-PLIF

TABLE 2.1: Overview of major combustion testing facilities. Capabilities and applied measurements summarised

What stands out in most of these facilities is the effort to combine measurements of emissions, combustion dynamics and diagnostics, with a focus placed on the latter. Optical access allows a range of diagnostics to be applied with spatial and temporal resolution usually: from flow field velocities (eg. PIV), mixing characteristics of fuel and air in reacting and non-reacting conditions (PLIF), reaction zone imaging and temperature measurements (eg. OH^* -chemiluminescence, PLIF, CARS).

An interesting observation is that in most cases of the surveyed literature, although detailed descriptions are provided for the test section design features, a design methodology is rarely presented and justification of design choices is usually omitted.

Moreover, although the development of such an apparatus is an iterative process, the complications and issues arising along the way (such as component failure, and setup malfunctions) and the improvements required are almost never presented. The only exceptions noticed by this author are by Slabaugh et al. [60] regarding the Purdue University rig, Schneider et al. [58] for the BOSS rig at DLR and from Runyon [57]. In [60] Slabaugh et al. provide reasoning behind crucial design choices of the test section. These can be summarised in the use of water cooling combined with a thermal barrier coating for the hot sections and a two-window configuration that decouples thermal and mechanical loads. This is common practice in most high-pressure combustion rigs with optical access. The authors also present a methodology for the calculation of loads on the test section and windows and the heat transfer analysis for the required cooling water flows. Schneider et al. [58] discuss the design philosophy of the Big Optical Single Sector (BOSS) rig at DLR. A double-wall configuration was used for the whole test section with cooling airflow between the inner liner and outer pressure casing. CFD and FEM simulations were utilised to inform the design in terms of required cooling as well as for the evaluation of thermal and mechanical loads on the hot components of the test section. Another good example of a detailed presentation of a combustion facility, including the apparatuses used, aspects of the design, instrumentation, data acquisition and control, is the Ph.D. thesis of Runyon [57] which presents the combustion rigs of Cardiff University.

Most of the aforementioned publications describe the test sections, facilities, data acquisition (DAQ) and control systems in some detail. Only in a few cases [57], [58], [60] do they offer insights into the thought processes and methodology implemented for the development of such systems.

One might argue that each combustion experiment has different characteristics and requirements, and on that basis, the presentation of the design philosophy can be considered of no particular value. It is this author's view that however different each experiment may be, an insight into the thinking that goes behind the design and development process along with the challenges that are encountered and identified best practices can be useful in guiding the prospective designer. To that end, this thesis addresses such aspects of the new hydrogen micromix combustion rig.

2.4 Hydrogen Micromix Combustion

The micromix concept was originally devised by researchers at Aachen University in the '90s as part of research efforts within the Euro-Quebec Hydro-Hydrogen Pilot Project (EQHHPP)[17]. The concept was suggested as a combustion mode for alternative gaseous fuels such as hydrogen in an effort to reduce NO_x emissions for aircraft gas turbine combustors. From the late '00s research at Aachen focused on developing the concept for industrial gas turbines carrying out experimental and numerical studies, in collaboration with Kawasaki Heavy Industries (KHI). Researchers at Cranfield University also developed an interest in hydrogen micromix combustion in the early 2010s with a range of numerical studies initially and more recently with experimental work that is described in the present thesis. These two institutions and their collaborators are, to the author's knowledge, the ones to carry out intensive research around JiCF type of micromix combustion. More recently numerical studies from other institutions have emerged, such as [18]. This section reviews the relevant experimental and numerical work that has been conducted for the JiCF concept for hydrogen.

Work at Aachen University

Researchers at Aachen University have continued the development of the micromix technology in the past almost 15 years, through numerical simulations and atmospheric-pressure experimental tests, initially focusing on pure hydrogen micromix and subsequently working on hydrogen blends too. In the early works of this era, burners featuring sub-millimetre hydrogen injectors ($0.3mm$ diameter for the smallest) were tested in a jet-in-cross-flow concept creating non-premixed, miniaturised flames. From early on they identified flame patterns, arising from interactions between flow and flame, that affect NO_x emissions [22], [23]. By testing micromix configurations with different air-gate and fuel injector sizes - achieving different energy densities - they noticed that the increase in energy density led to a shift of the flames towards the hydrogen segments and a sudden increase in NO_x with increasing equivalence ratio [23]. This was attributed to flame-to-flame interaction and increased residence times due to hot gases recirculating in the inner recirculation zone (IRZ). Change from an air-gate configuration to an open gap led to a smoother increase in emissions with equivalence ratio. In [22] the effect of momentum flux ratio (MFR) was studied by varying the area of the air-gate panel (AGP) in two case studies. It was concluded that above a critical value of MFR, the fuel jet penetrates the recirculation zone in

front of the AGP increasing unmixedness, and residence time and subsequently leading to a sudden increase in NO_x . This phenomenon though did not appear to be affected by pressure drop or energy density changes. Hence, momentum flux ratio was identified as an essential design parameter for micromix combustors.

Research efforts at Aachen subsequently focused on increasing the energy density of micromix injectors while keeping very low NO_x values. Funke et al. tested configurations with increased fuel injection sizes and wider injector spacing. It was shown experimentally that no flame lifting or merging of flames occurred even in high equivalence ratios [21]. In conjunction with numerical results, it was suggested that in some cases cool air penetrates the region between adjacent flames, keeping low temperatures and low NO_x . These campaigns led to the establishment of design laws for geometric parameters of the micromix burners that allowed significant up-scaling of the energy density, while the flame position and stabilisation were retained, leading to very low NO_x . Increased injector size and lower number of injectors were also presented as an advantage towards less complex manufacturing. A numerical study by Haj Ayed et al. [30] in 2014 showcased the potential of such design laws. CFD simulations at atmospheric pressure and elevated air-inlet temperature showed flames separated in all directions and cool air penetrating the regions around the flames in an improved burner design. At increased equivalence ratios, the generation of a hot streak was reported due to the cool air reducing the reaction rates and leading unburnt hydrogen to be consumed further downstream. Still, NO_x emissions remained low at the increased energy density conditions.

In 2015 further advancements were presented with a burner bearing fewer fuel injectors of larger size (1mm diameter) [24]. The configuration followed the design laws for upscaling taking into account a parameter called blockage ratio (BR) and the normalised injector circumferential distance. The hydrogen segments of the burner incorporated a heat shield and temperature measurements at a number of points along the shield. Experimental results confirmed the application of design laws, as NO_x emissions were observed to be at similar levels to those of injectors of smaller fuel injection diameters and the observed flames did not appear to merge. Moreover, it is reported that the heat shield yielded acceptable material temperatures. A further improvement in NO_x emissions was attempted by Haj Ayed et al. with atmospheric tests on three micromix configurations: a reference configuration taken from [22] was compared to two improved designs [32] of varying energy density and jet penetration depth. All three designs presented sudden increases in NO_x beyond the design point equivalence ratio (the design point was considered at $\Phi = 0.4$). Both

the two improved designs showed reduced NO_x compared to the reference configuration and their behaviour was quite similar, though the configuration of increased energy density performed marginally better. Numerical simulations employed for an explanation of the better performance of the increased energy density burner denoted that the increased air-gate height allowed cool air to effectively surround the flame from the outer sides, leading to significant reductions in the temperature field, which explained the lower NO_x emissions. Building on their previous work, compiling the different design laws developed, the Aachen group presented effectively a design methodology for low NO_x hydrogen micromix burners at different energy density levels, with different geometric characteristics [25]. To that end, a number of configurations were explored numerically and two of them were tested experimentally, showcasing the applicability of the methodology towards burners of different sizes yielding similar, low levels of NO_x .

In [41], Kroniger studied experimentally the effect of pressure on NO_x , as well as on flame initiation and anchoring using a micromix geometry with an injector size of $0.8mm$ in diameter. The experiment was complimented by a numerical campaign (RANS) with simulations at high pressure comparing two different models for turbulence-chemistry interaction, namely the Laminar Flame Concept (LFC) and the Eddy Dissipation Concept (EDC). The experimental results showed an increase in NO_x with pressure and a closer matching with the LFC model. A derived correlation of NO_x with pressure yielded $NO_x \propto P^{0.5}$, which seems to fare well with the experimental results. According to the CFD results, pressure appears to drive the flame upstream, towards the fuel injection point.

A novel micromix configuration was proposed in 2022 by Kroniger to extend the operation of micromix combustors to mixtures of hydrogen with natural gas [42]. This design brings the hydrogen injection point to a lower level compared to the air-gate exit, inside a "horse-shoe" type, two-step configuration. OH-Chemiluminescence tests were performed at atmospheric pressure and accompanied by RANS and LES simulations. It was shown that this configuration in comparison with the standard micromix design, retains flame stability even when hydrogen concentration goes down to 60%vol..

Micromix combustor integration studies have also been performed by the research group. A Honeywell/Garrett GTCP 36-300 Auxiliary Power Unit (APU) gas turbine, was fitted with a hydrogen micromix combustor and the results were compared with kerosene, performing at idle and full load tests and measuring NO_x emissions

and noise levels [26]. The micromix combustor yielded significantly reduced emissions at all operating points, and a much smoother increase with load compared to kerosene. In terms of noise, although micromix did not produce significantly higher pressure levels compared to kerosene, the perceived noise was considered more annoying for hydrogen micromix. Moreover, Kawasaki Heavy Industries demonstrated in 2021 continuous, smooth operation of a power-generation M1A-17 gas turbine incorporating a hydrogen micromix combustor, which achieved a peak power output of 1635kW and 65ppm NO_x emissions (corrected to 15% O_2 and humidity of 60%) [34].

It can be seen from the previous discussion that the development of hydrogen micromix for industrial gas turbines, placed the focus of research mainly on achieving high energy density from the burners while retaining very low NO_x characteristics, and more recently in fuel flexibility. Scaling up the energy density leads to increasing the size of the fuel injectors, which from an industrial gas turbine perspective, is advantageous when it comes to contamination/particles in the incoming fuel/air (a smaller injector can get blocked easier), especially when fuel flexibility is required. For an aircraft gas turbine combustor though, such increased energy densities may not be necessary and contamination is less likely when only hydrogen is considered.

Numerical work at Aachen mainly utilised RANS simulations coupled with simplified combustion models as described in [5], [21], [22], [24], [25], [30]. Such simulations, are limited in their predictive capabilities of flame temperatures, mixing characteristics and eventually NO_x predictions. Yet, they are useful at the early stages of development of concepts such as micromix, for qualitative comparisons with experimental results and for providing a general insight as to the physical phenomena that might take place within and around the flames. The limitations are mainly due to the turbulence-chemistry interaction models used and the simplified, one-step hydrogen/air reaction mechanisms. Although usually dismissed, it is important to note that in such simulations, only the thermal NO_x is taken into account (Zeldovich mechanism) and other routes, such as the NNH are usually omitted, which further reduces the predictive capability of the models. Of course, in the high temperatures of hydrogen micromix combustion, the thermal mechanism is dominant and the simplification of only accounting for this mechanism is not irrational. When numerically-derived temperature fields were compared with experimental flame images (at visible wavelengths), flame patterns and dimensions did not seem to be accurately represented in the simulation results [21], [31]. Of course, it can be argued that neither the temperature field nor the visible-flame photos necessarily depict the reaction zones accurately. OH^- concentrations for both the CFD and the

experiment - through OH^* -Chemiluminescence as in [42] or OH-PLIF - would be better metrics of flame shape and size comparisons. Slightly more complex reaction mechanisms and turbulence-chemistry interaction models, used in [31], [32], [41], [42] showed improved accuracy in terms of NO_x when compared with corresponding experimental results. Such simulations though are certainly useful as, at least at atmospheric pressure, seem to capture the trends in NO_x changes. The discrepancies of numerical models in NO_x prediction are more pronounced with changes in parameters such as pressure, as evident in [41].

Work at Cranfield University

Research on hydrogen micromix at Cranfield University has focused primarily on developing the micromix technology for aircraft gas turbine combustors. Until recently only numerical work had been conducted. In the early stages of the work, different, simplified injector geometries were explored and compared [37], [39], [51]. In [39] Khandelwal assessed two cases of a micromix configuration with four inlets in the same plane at 90° to each other injecting in a cross-flow of air. In the first case, all four inlets injected hydrogen while in the second case, fuel in two of the inlets was replaced with air. The second configuration showed better mixing and lower temperatures, improving the NO_x levels predicted. In a similar study, Murthy suggested two slightly different geometries: one bore a diverging, tapered main-air inlet, while the second has the fuel inlets distributed in different axial planes implementing a two fuel-inlets/two air-inlets strategy [51]. The tapered geometry denoted better temperature and flow characteristics, yielding lower NO_x . In both of these publications, the authors also observed very short high-temperature regions implying short reaction zones, leading to the suggestion that micromix combustors could potentially be significantly shorter than kerosene ones, and avoid the requirement for cooling air. Karakurt employed one of the designs of Khandelwal[39] and performed simulations for hydrogen, kerosene and methane for a range of equivalence ratios [37]. Hydrogen showed the highest temperatures for corresponding equivalence ratios between the fuels and produced higher levels of NO_x compared to methane. The authors suggested that further improvements are required for the micromix geometry to improve mixing quality.

More recently, interest shifted to exploring numerical models that may be more suitable for primarily non-premixed hydrogen combustion, within the context of the work on micromix. The micromix geometries used resembled those of the Aachen studies. The focus was mainly on NO_x emissions predictions [6] and work to identify

appropriate reaction mechanisms [2], [6] as well as appropriate estimations of the thermophysical properties of hydrogen/air mixtures [8], [45], [68]. Moreover, numerical studies were conducted exploring the effect of design parameters on micromix flames and emissions [2], [65], and the potential thermoacoustic issues in micromix combustors [1], [48], [64].

The study by Babazzi et al. compared four reaction mechanisms coupled with the Flamelet Generated Manifold (FGM) combustion model in RANS simulations. The four mechanisms provided similar temperature and flame-shape results, with small discrepancies [6]. For NO_x predictions, the researchers followed two approaches: a CFD post-processing tool against coupling of CFD with a Chemical Reactors Network (CRN). These were then compared with experimental results by Aachen University as given in [32]. The hybrid CFD-CRN approach was closer to the experimental results [6].

In a 2018 study, RANS simulations were performed to investigate the effect of diffusion parameters (Schmidt and Lewis numbers), as well as turbulence, on the flame lengths, shape and temperature [8]. Hydrogen micromix flames were found to be highly sensitive to changes in these parameters, denoting the limitations of RANS modelling in predicting flame shapes and temperatures. Such results also point out the need to properly calibrate such values in order to improve the predictive capabilities of CFD tools that offer lower computational costs (compared to tools of higher computational requirements such as LES). López-Juárez et al. in another study attempted to calculate the values of these diffusion parameters (Lewis and Schmidt), for a range of pressures, temperatures and equivalence ratios using correlations from the literature [45]. They subsequently mapped the potential flame regime concluding that hydrogen micromix flames can be considered transition flamelets and combustion is always dominated by mixing. Using the calculated parameters the researchers performed RANS simulations of a single flame for different turbulent Schmidt numbers (Sc_t), validating against an LES case and choosing $Sc_t = 0.2$ as the best estimate for the combustion model that compromises between NO_x predictions and flame structure accuracy. It was also concluded that the resultant flame temperatures and structure strongly depend on the combustion and turbulence models. Sun et al. though, found that non-premixed regions dominate hydrogen micromix, with only small, marginally premixed regions existing, and suggested that such mapping of the flame regimes as is done by López-Juárez ([45]) cannot be used to categorise the micromix flames [68]. Moreover, the results of their sensitivity study of turbulent Lewis (Le) and Schmidt (Sc) numbers ([68]) act as further evidence that turbulent mixing dominates JiCF hydrogen micromix.

In terms of injector configurations, the geometries researched by Cranfield are similar to those of Aachen, since the potential of such configurations was shown in a number of studies as discussed already. Based on such a geometry, Agarwal et al. performed a preliminary design space exploration, varying the size of the air-gate and hydrogen inlet diameter, using CFD simulations at high pressure and air-inlet temperatures [2]. The analysis concludes that improved NO_x emissions can be achieved with a small fuel injector size (suggested 0.3mm diameter) and appropriate air-gate size, although the effect of other geometric parameters needs to be investigated further. A more detailed investigation of the influence of geometric parameters on flame characteristics and NO_x production was published by Sun et al [65]. This work took into account parameters such as offset and mixing distance, vertical and horizontal injector distance and air gate and fuel injector dimensions. The simulated configurations were selected in order to cover different regimes of flame shape, length and degree of flame interaction. The analysis showed that geometric parameters can strongly influence flame shapes, positions and interactions and subsequently residence time and NO_x production. Besides the momentum flux ratio (dependent on geometry) that regulates injection depth, air-gate dimensions and offset distance also affect flow characteristics, such as the size and position of the recirculation zones and the flow of cooler air around the flames as researchers at Aachen also noted [24], [32]. Further to this, a number of different air-gate shapes were also simulated at constant MFR in the same publication [65]. Flatter and wider shapes were shown to produce significantly lower temperatures and subsequently NO_x . This is attributed to the cool air entrainment in the recirculation zones and around the flames, keeping adjacent flames separate.

An important point to be noted, besides the typical limitations of the RANS approach stated by most researchers, is that careful consideration is required when choosing the reaction mechanism to be coupled with the combustion model when performing simulations at high pressure. When pressure increases the chemical kinetics of the reaction are affected and discrepancies in predicting the OH-fraction occur between different mechanisms [2]. Such discrepancies also highlight the necessity of performing experiments at elevated pressures and inlet temperatures that will provide a better understanding of the effects of the operating conditions on flame shape, reaction zone temperatures and NO_x emissions.

Another topic of study for micromix has been that of thermoacoustic instabilities. Typically combustion dynamics are explored at a later stage of the development of a combustor since such instabilities are dependent on the geometry. McClure et al. and Sun et al. having performed RANS and LES simulations in order to derive

flame transfer functions (FTFs) suggested that hydrogen micromix may be more susceptible to higher frequency instabilities compared to kerosene [48], [64]. Sun et al. also point out that different instability regimes may be related to the geometric characteristics of the micromix configuration and that injector design choices may positively impact thermoacoustics. Similar conclusions were reached by Abbott et al. who simulated a sector of a conceptual micromix combustor at different engine representative conditions by CFD and lower-order acoustic modelling networks [1]. The latter study also claims that due to the similarity of FTFs derived, different operating conditions may have an insignificant effect on the predicted behaviour of the micromix combustor [1].

2.4.1 Summary of Findings on Experimental Hydrogen Micromix

Experimental testing, with the exception of [26], [34], [41], was limited to testing at atmospheric pressure and elevated air-inlet temperatures, measuring NO_x emissions and imaging the visible flames. With regard to [26], [34], where tests are performed with an actual gas turbine at different operating conditions, no insight is provided into the exact pressure, air-inlet temperature and equivalence ratio values of the tests. NO_x emissions are only reported against the operating point expressed as engine load. In [41] NO_x emissions experimental results are presented for different pressure levels (up to $1.1MPa$) and the effect of pressure is discussed.

Moreover, some of the Aachen studies present experimental results at atmospheric pressure, considering the effect of injector geometric parameters and momentum flux ratio on NO_x emissions. Yet the impact of these parameters on NO_x is not explored in any of the high-pressure experiments. The burner configurations that are used in most of the experimental studies carry enlarged fuel injection points ($0.5mm$, $0.8mm$ and $1mm$ in diameter) and the shape of the air gates differs from the corresponding air gates of the configurations presented in this thesis.

During the efforts to design and manufacture the micromix burners for this work, it was noticed that the relevant literature around micromix did not provide information on manufacturing aspects. This led to providing recommendations for state-of-the-art manufacturing techniques that are suitable for micromix combustor fabrication considering the tolerance requirements, as well as the safety requirements.

2.5 Rationale and Research Gaps

2.5.1 Rationale of the Experimental Work

The necessity of performing experimental tests at different pressures, air-inlet temperatures and equivalence ratios for hydrogen combustion is justified if we consider the following:

- The overall scarcity of experimental data sets on hydrogen combustion at different operating conditions
- The limitations of state-of-the-art numerical tools in terms of their predictive capabilities for hydrogen combustion. Numerical models are adapted primarily for hydrocarbon fuels. Thus, the particularities of hydrogen, such as its high molecular diffusivity, or the effect of operating conditions such as pressure and reactant temperature in chemical kinetics of the H_2 /air mixture as well as on NO_x formation, can bring these models to their limits.

To that end, a new rig for hydrogen micromix combustion was designed, developed and deployed at Cranfield University.

Rig Requirements

An experimental apparatus for such tests should have the capability of providing a multitude of measurements under a range of operating conditions. For low technology readiness levels (TRL), as in the case of micromix, such a rig shall be capable of testing burners with a small number of injectors and a variety of injector geometries. In addition, results shall be acquired at a wide range of conditions for operating temperatures, pressures, and equivalence ratios. Such data can be used to improve the predictive capabilities of or validate numerical models that in the case of hydrogen present deficiencies as already discussed.

NO_x emissions measurements are significant on the basis of verifying that the proposed concept performs within, or outperforms currently serving technologies, potentially acting as proof of concept at such early stages of technology development. NO_x data at high-pressure and temperature conditions can also be used for the validation of numerical models.

Optical access is also of high significance: it can allow a range of diagnostics to be applied that can provide information on flame structures and temperatures, as

well as information on mixing. Flame imaging data can prove invaluable in understanding the behaviour of micromix flames. They can provide insights into the flow and physics underlying hydrogen micromix at different operating conditions and for different geometric configurations. Moreover, the depicted flame patterns, as well as flame temperatures, can be employed to validate, as well as calibrate numerical models.

In a similar fashion data on thermoacoustics, such as the derivation of FTFs can improve the predictive capabilities of lower-order codes for thermoacoustics by means of calibration.

2.5.2 Research Gaps

The research gap identified by the literature review, which this work attempts to address, is the following:

The lack of experimental data that captures the impact of momentum flux ratio (MFR) on NO_x emissions of hydrogen micromix combustion systems at a range of operating conditions. NO_x emissions appear to be highly sensitive to changes in momentum flux ratio (see section 1.1 and [65]). This means that small changes in certain geometric features of the configuration, or changes in equivalence ratio, both of which change the MFR, can have a big impact on NO_x emissions. Such experimental data sets are needed in order to improve the predictive capabilities of numerical models so that such models do not produce designs that appear to produce low- NO_x but in reality, prove high- NO_x .

Further to this gap, two areas were identified where research contribution is made, although they do not represent gaps in knowledge. The following points summarise these contributions that provide valuable information to prospective researchers of experimental hydrogen micromix combustion:

1. Providing the public domain with a detailed account of the challenges, best practices identified and recommendations for the design of a high-pressure, high-temperature hydrogen combustion rig, since the rig described in this work was designed and built from scratch.
2. Providing information on the design and manufacture of a micromix burner with respect to safe fuel delivery, considering the increased risk of hydrogen leakage. A one-piece component produced by additive manufacturing (AM)

minimises the potential leak paths compared to a modular design. Size limitations on the produced features by AM impose the use of traditional techniques for the full fabrication of the component.

CHAPTER 3

Methodological Approach

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3.1 Introduction

In this chapter, the approach followed for the development and testing of the experimental setup is presented. The discussion initiates with aspects of experiment design and provides details on the control parameters and the matrix of proposed test conditions. The selection of the micromix configurations tested is briefly discussed. An overview of the NO_x and flow metering measurement techniques is given and details regarding the instrumentation used and the testing procedures are provided. The chapter concludes by detailing data-handling processes.

3.2 Overview of the Combustion Rig

The rationale behind the need to develop a high-pressure, high-temperature hydrogen micromix combustion rig has been discussed in section 2.5.1 of this thesis. This section gives a brief overview of the experimental apparatus so that the following sections are easier to contextualise. Moreover, explanations are provided with regard to specifications such as the domain size and maximum operating conditions.

The experimental apparatus was developed for combustion tests with different micromix injector configurations at high pressures (up to $15bar_a$) and high temperatures for the air-inlet (up to $600K$). Based on the requirements, as set out in section 2.5.1, a small number of micromix injectors per burner configuration needed to be tested. Maximum achievable pressure was limited by the facility capabilities to $15bar_a$. The maximum air-inlet temperature for the tests was set to $600K$. This upper limit for air inlet temperature was imposed by the use of a modified immersion heater which was originally proposed to serve as the heating device for inlet air. Although at a later stage, the idea was abandoned for the sake of using the Pebble Bed Heater (Appendix A), rig design had progressed to a point where changing the maximum air inlet temperature was not possible. Maximum air mass-flow through the rig was $142g/s$ at the $15bar_a$ case at an air-inlet temperature of $300K$ (see Section 3.4).

Measurements for the current setup are limited to NO_x emissions. The rig is also equipped with sensors for pressure dynamics for thermoacoustics measurements and has optical access provisions for flame imaging through OH^* -Chemiluminescence or OH-PLIF.

A CAD model representation of the test section provides a brief description of its characteristics (Figure 3.1). The design choices and challenges of its critical components are described in more detail in a dedicated chapter (Ch. 4).

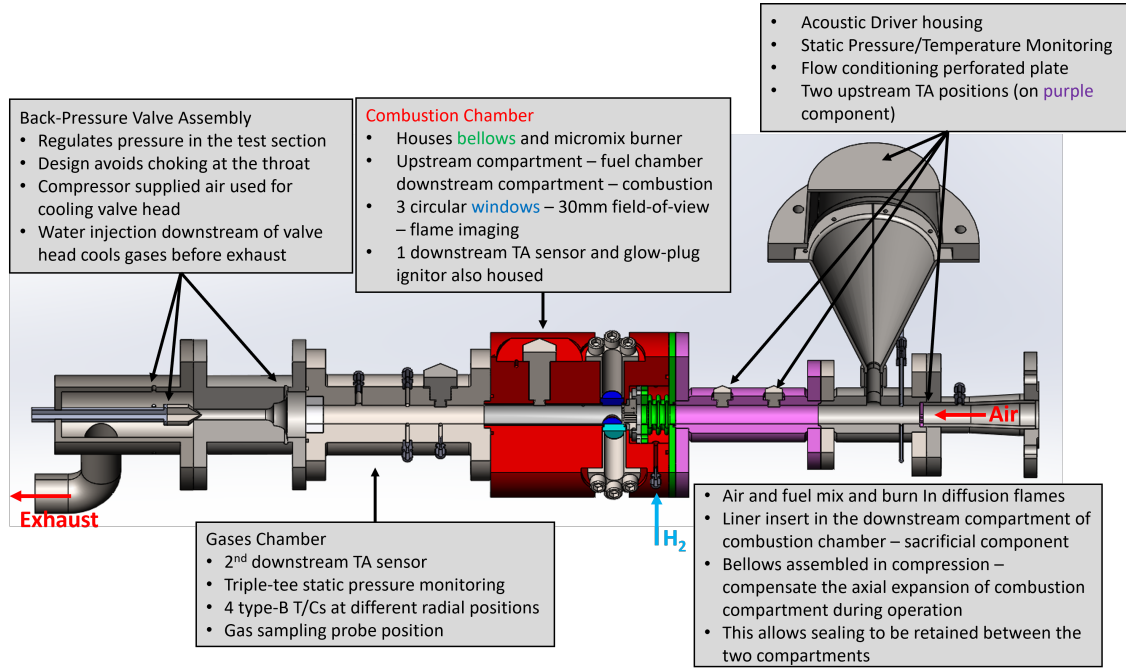


FIGURE 3.1: Overview of the designed rig (CAD representation) with brief descriptions of the main components

3.3 Control Parameters

Combustor pressure (P), air-inlet temperature ($T_{air,in}$), equivalence ratio (Φ) and momentum flux ratio (J) are the four control parameters in this experiment. These parameters were chosen primarily on the basis of their potential impact on NO_x production since, their effect on mixing characteristics, flame structures and eventually NO_x emissions is not well understood. The lack of experimental data under such conditions should also be seen in conjunction with deficiencies of numerical tools such as CFD (see 2.4) in predicting flame temperature and NO_x production. Momentum flux ratio (MFR) is another parameter that in different regions yields different flame shapes and patterns which can have a significant effect on mixing, flame temperatures, residence times and subsequently NO_x emissions. The momentum flux ratio is affected by the densities and velocities of the fuel and oxidiser. For a specific operating point (of the rig), the density of each fluid (ρ) is determined by its pressure and temperature. Velocities on the other hand are determined by the mass flow and the cross-sectional area of the channel the fluid flows through ($\dot{m} = \rho u A$,

where u is the fluid velocity and A is the cross-sectional area). Hence, the momentum flux ratio as a control parameter in this thesis is represented by different burner geometric configurations.

3.4 Design of a Test Matrix

The test matrix is a set of operating points that are combinations of pressure, air-inlet temperature and equivalence ratio values applied as test conditions for all the tested injector configurations. An ideal test matrix covers the requirement for a wide range of conditions, with a preference towards elevated pressure and air inlet temperature, in alignment with the main aim of the rig as described in section 1.2. For this rig, it was derived using the upper limit values for pressure and air-inlet temperature. The ideal requirement for a plethora of operating points was balanced by the need to conduct the experiments in a reasonable time frame and cost. Hence, combinations of four pressure levels, three air inlet temperatures and three equivalence ratios composed the desirable test matrix (Table 3.1), intended for three micromix configurations with momentum flux ratio values representing distinct flame regions.

$P(bar_a)$	$T_{air,in}$	Φ
1	300	0.3
		0.4
		0.5
5	450	0.3
		0.4
		0.5
10	450	0.3
		0.4
		0.5
15	300	0.3
		0.4
		0.5
	450	0.3
		0.4
		0.5
	600	0.3
		0.4
		0.5

TABLE 3.1: Proposed matrix of test cases

3.4.1 Mass Flow Calculations of the Test Matrix

Desirable air mass flow at the test conditions was calculated based on a reference case, of $P_{ref} = 20bar_a$ and $T_{ref} = 860K$ air inlet temperature, considered representative of cruise for a Year-2050 ultra-high bypass ratio turbofan engine [2]. The total air mass flow of the rig for the reference case was calculated based on the flow per air passage as given in [2]. The total number of air passages was calculated based on a sizing methodology, part of the ENABLEH2 work, presented in [66]. This was taken as the reference air mass flow ($\dot{m}_{ref}$). The calculation of air mass flows for the rest of the P , $T_{air,in}$ combinations is derived from the reference value and the requirement to retain a constant Mach number (Ma) in the combustor. Thus the mass flow of air for each case is

$$\dot{m}_{air} = \dot{m}_{ref} \frac{\rho_{air}}{\rho_{ref}} \sqrt{\frac{T_{air}}{T_{ref}}} \quad (3.1)$$

where densities (ρ) are calculated by the equation of state for ideal gases $P = \rho RT$. R denotes the specific gas constant and T is the gas temperature. For different equivalence ratios, air mass-flow was kept constant for a specific pressure/air-inlet temperature combination and fuel mass-flow was regulated as per

$$\dot{m}_f = 0.0294 \cdot \Phi \cdot \dot{m}_{air}$$

where the value of 0.0294 denotes the stoichiometric fuel-to-air ratio (FAR) for hydrogen/air combustion. The reason for changing fuel flow instead of air is that fuel mass flow was easier and faster to control and could be regulated to better accuracy and with less fluctuation around the set value.

3.4.2 Selection of Micromix Injector Configurations

We have seen already that the momentum flux ratio (J) is a parameter of interest expressed through the injector geometric characteristics. Three micromix configurations were chosen for experimental testing, representing a range of momentum flux ratio values that according to CFD simulations produced distinct flame patterns and were expected to produce different levels of NO_x (Figure 1.5). The choice of the three injector designs was based on a design-of-experiment procedure conducted in the context of the ENABLEH2 project, as described in [65]. For this experimental campaign, the fuel injection diameter was kept at $0.3mm$ for all the configurations. Air-gate dimensions, offset and mixing distance and injector spacing varied between the three designs. Two of the configurations represented lower values of J situated in the region of the red rectangle of Figure 1.5 (denoted as low and medium J) and the third design had significantly higher values of J , in the region of the blue rectangle in Figure 1.5. More details for the geometries of the injector configurations are provided in Section 5.2.1.

3.5 Measurements and Instrumentation

This section discusses the monitoring and measurement sides of the experimental setup. The main parameters of interest are briefly presented, followed by the chosen measurement techniques and instruments utilised.

3.5.1 Quantities of Interest

As outlined in the preceding discussion, the focus of the measurements of these experiments is on NO_x emissions produced by the micromix flames at different operating conditions. Pressure dynamics upstream and downstream of the flames for flame transfer function (FTF) measurements and flame imaging were also of interest.

Static pressure, temperature and mass flow monitoring are essential primarily because they allow the experimenter to set the desired operating point of the rig. Moreover, monitoring pressure both upstream and downstream of the flames provides information on pressure losses across the micromix burners. Temperature measurement of the hot combustion gases contributes to safety, in cases where the rig gets too hot or there is a flame-out event followed by a sudden drop in temperature. In the following sections, the measurement techniques along with the relevant instrumentation are presented.

3.5.2 Measurement Techniques

This section presents the techniques implemented for the measurement of the main quantities of interest, namely NO_x emissions and mass flows of air and fuel, with the focus steered to NO_x . A portable gas analyser using the chemiluminescence detection (CLD) method is employed to measure NO_x . Air flow is metered through an orifice plate device and fuel flow through a thermal flow meter.

3.5.2.1 NO_x Emissions

The CLD method is a widely used technique for NO_x measurements, suggested by Aerospace Recommended Practice (ARP) 1256D [55] and the Environmental Protection Agency (EPA) Method 7E [50], as the technique to be used for total

NO_x measurements from aircraft or stationary gas turbines. CLD yields total NO_x as a sum of NO and NO_2 . The measurement is based on the reaction of NO with O_3 , to produce NO_2 , part of which (approximately 10% - [55]) is NO_2^* (R4). The NO_2^* spontaneously returns to its ground state emitting a photon (R5) the light of which is then detected by a photodiode. Underlying this principle is the proportional relationship between the concentration of nitric oxide ($[NO]$) present, and the intensity of the emitted light when NO concentrations are low [55].



where $h\nu$ is the energy carried by the photon, with h being the Planck constant and ν the frequency of the photon. It can be seen from reactions (R4) and (R5), that total NO_x is measured as NO . This means that the NO_2 content of the sample needs to be turned into NO before entering the chemiluminescence chamber. This conversion can take place with the help of some catalyst.

Reaction (R6), where M is a third body, can be considered part of the system of reactions defining the technique, as M can be a quenching factor for reaction (R5), through collisional energy transfer, and can affect the measurement.



The presence of H_2O in the gas sample is also an important factor that affects the measurement of NO_x by the CLD method in two different ways. The first is related to H_2O acting as a third body according to reaction (R6), which brings the NO_2^* to its ground state preventing the spontaneous photon emission. The second effect of water on the measurement comes from the high water solubility of NO_2 which means that condensation of H_2O in the sample line leads to dilution of the NO_2 , according to [27] through reaction (R7). In both cases, the measurement of NO_x is biased towards lower values.



3.5.2.2 Mass-Flow Measurements

Air Mass-Flow Air-flow metering was achieved by the use of an in-house designed and built orifice plate. The device was designed following the guidelines of BS EN ISO 5167-1:2003 and BS EN ISO 5167-2:2003 standards. The COVID-19 pandemic, along with high lead times and costs, in a period where the supply of instruments from a third party was difficult or impossible, led to the decision to design and build the flow metering device in-house. The orifice plate was chosen for its simplicity in terms of design, manufacturing and installation. It belongs to the devices that measure fluid flows by pressure differential. Installed into a pipeline, the orifice plate restricts the flow, reducing static pressure downstream and creating a difference between its upstream and downstream. Knowing the fluid characteristics and the pressure difference, the mass flow through the orifice plate can be calculated according to BS EN ISO 5167-2:2003 [49]:

$$\dot{m} = \frac{C}{\sqrt{1-\beta^4}} \epsilon \frac{\pi}{4} d^2 \sqrt{2\Delta P \varrho_1} \quad (3.2)$$

where $\dot{m}$ is the mass-flow, C is a discharge coefficient, β is a diameter ratio, ϵ is the expansion factor, accounting for the gas compressibility, ΔP is the pressure drop across the plate and ϱ_1 is the density of the fluid, measured upstream of the orifice plate. Fluid density is calculated based on the upstream static pressure measurement and the temperature measurement with the equation of state for ideal gases. Equation (3.2) requires a static temperature value, yet thermocouples measure total temperature. Due to the low Mach numbers though, total and static temperatures do not vary significantly and the imposed error is negligible.

Fuel Mass-Flow Mass flow of fuel was measured and controlled by a third-party supplied mass-flow controller (MFC) employing the thermal principle. In this case, the instrument is a heated-tube flow meter where part of the flow is bypassed through the sensor. In this configuration, the flow passes through an electrically heated tube. Temperature is measured upstream and downstream of the heating element. The heat transfer rate $\dot{Q}$ towards the gas is proportional to the gas mass flow:

$$\dot{Q} = \dot{m} C_p \Delta T \quad (3.3)$$

where C_p is the specific heat under constant pressure of the gas and ΔT is the temperature difference measured at the two points.

3.5.3 Instrumentation

3.5.3.1 NO_x Emissions Measurement Setup

A schematic representation of the emissions setup is shown in Figure 3.2. The main instrument is a Horiba PG-250 Portable Gas Analyser, accompanied by a drain separator and an Electronic Cooler Unit (Horiba PS-200) to remove water vapour.

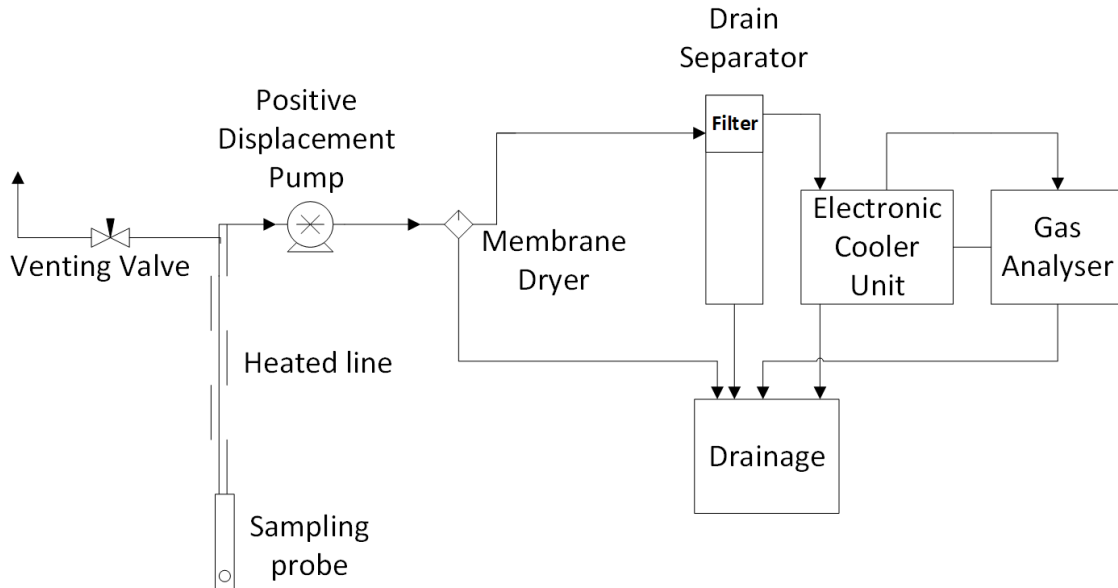
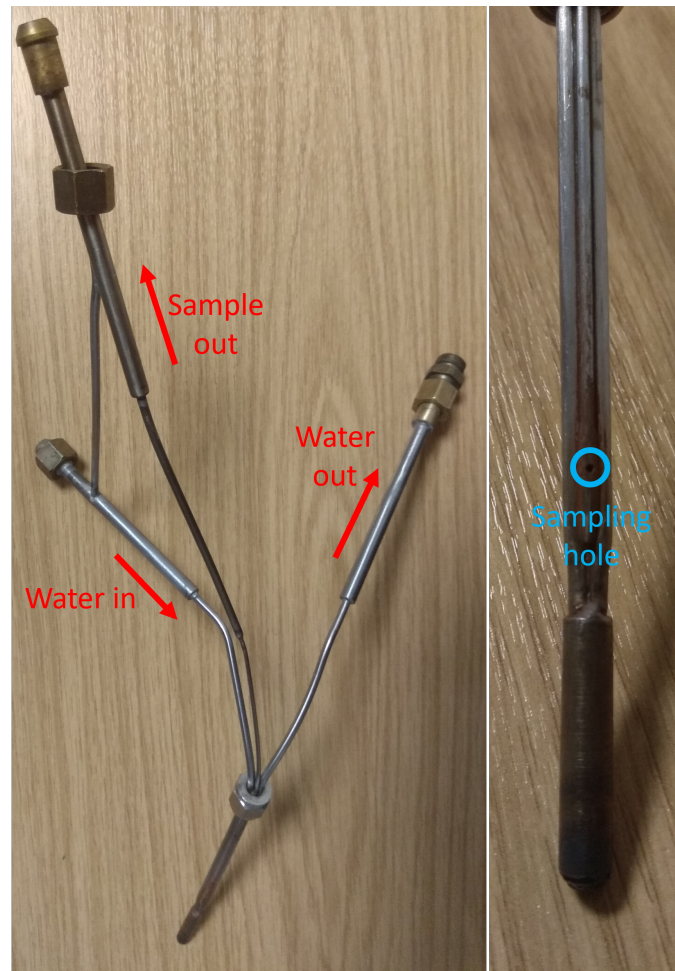


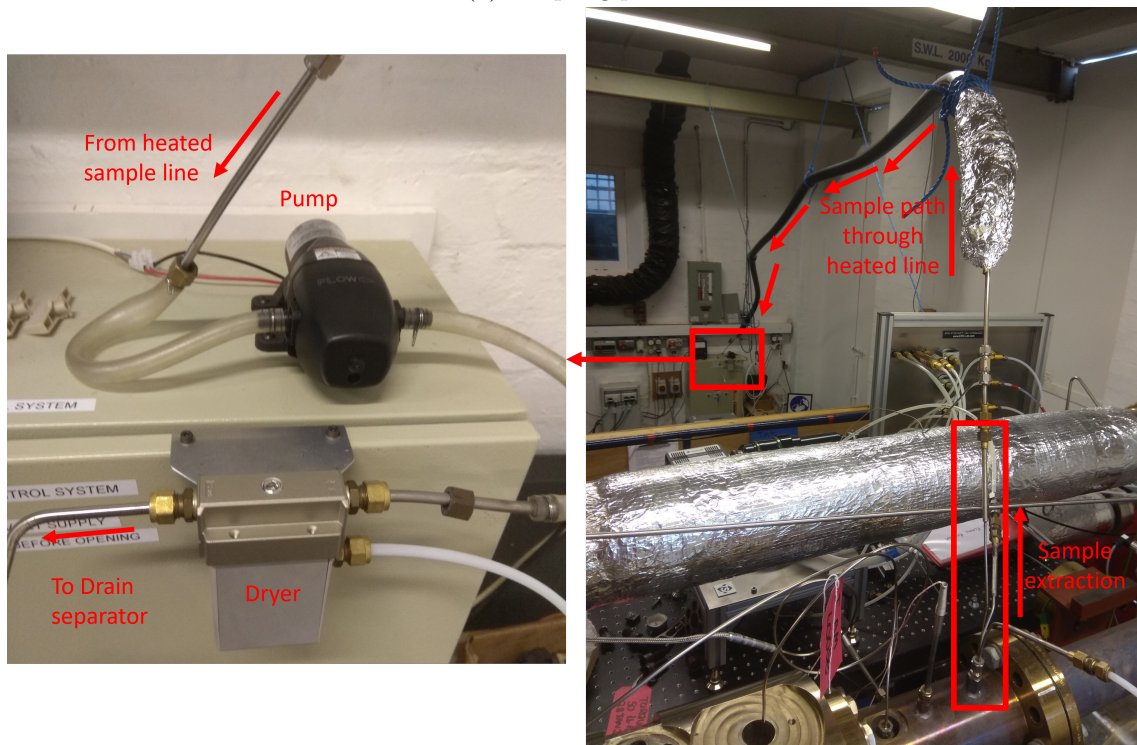
FIGURE 3.2: Schematic of the gas analysis setup and instrumentation

Sampling Probe A 1-hole, custom, in-house probe was inserted in the flow, to extract the gas sample Figure 3.3a. The probe was made of Stainless Steel 316 and included a water-cooling configuration. It was installed $9.5D$ downstream of the micromix flames (Figure 3.5), with the sampling opening facing the hot gases head-on. The hole was $0.5mm$ in diameter, to choke the sample flow, effectively bringing the pressure down to levels acceptable by the gas analyser. Dropping the pressure, while the sample was inside the probe, hence in the hot gas path, also ensured that no condensation took place due to the expected temperature drop.

Heated Sample Line A heated line kept the sample at a temperature of $120^{\circ}C$ to avoid condensation, moving it from the extraction point to the pump, covering a distance of approximately $6m$. A type-N thermocouple was installed right upstream of the heated sample line, ensuring that the hot gas temperature did not exceed the line operating limits.



(a) sampling probe



(b) components of the sampling setup

FIGURE 3.3: Details of the emissions measurement setup

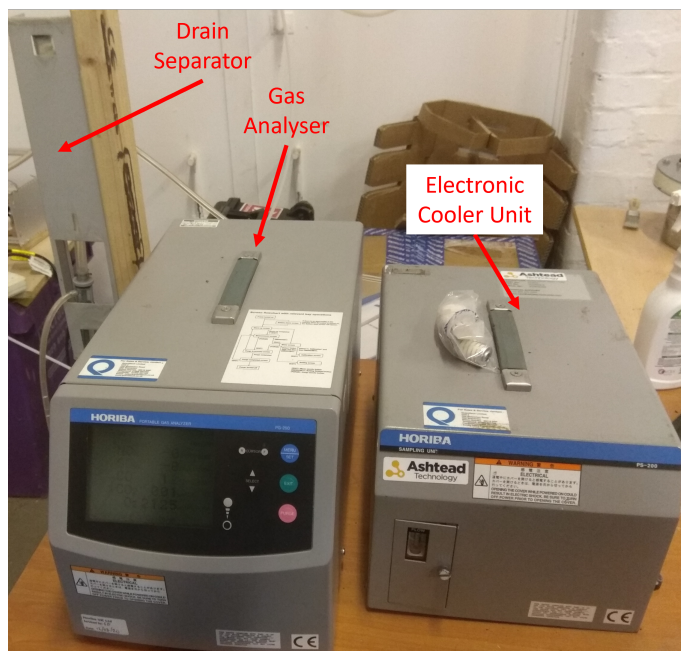


FIGURE 3.4: The gas analyser along with components for water removal

Pump and Dryer A small pump (Figure 3.3b) created suction through the heated sample line, as the sample pressure had already been regulated at the choked probe hole. The need for the pump was realised during preliminary testing, where it was noticed that the gas analyser internal pump could not draw enough sample for the measurements. A heated pump would have been more appropriate, to avoid condensation, but its supply was not possible for this experimental campaign due to high lead times.

A membrane dryer (Figure 3.3b) was also added to the line as an additional water removal stage. Due to the high volume of water produced by H_2 combustion, it was realised that condensation could not be avoided along the lines and even after the drain separator, water droplets were visible in the plastic tubing, meaning that despite the use of 3 different devices for water removal - membrane dryer, drain separator and electronic cooler unit - the amount of water in the sample was quite high. These issues will be discussed in Section 4.6.4.

Gas Analysis System The gas analysis system consisted (Figure 3.4) of the main unit, a Horiba PG-250 portable gas analyser, a drain separator and an electronic cooler unit (ECU - the Horiba PS-200). The drain separator and ECU are both devices required to remove water vapour from the sample before it enters the analyser.

The PG-250 is a unit that can measure NO (or total NO_x), SO_2 (or total SO_x), CO , CO_2 , and O_2 , simultaneously. It was chosen as it was a readily available

solution, with a small cost and it was considered to provide accurate measurements for different ranges. The main limitation was the fact that the sample needed to cool down before entering the analyser (mainly for the CO_2 sensor), which partly contributed to the problem of water condensation. The gas analyser was connected to a PC via an RS-232 connection where data was logged and saved through Horiba EDA-2000 software.

3.5.3.2 Pressure and Temperature Measurements

Pressure Monitoring Gauge pressure transducers with Voltage output were employed to monitor air and fuel static pressure. For the air-line, Omega PXM 319-020G 10V transducers were placed, upstream ($10D$) and downstream ($6.5D$) of the flames (Figure 3.5), in triple-tee configurations (Figure 3.6). This configuration ensures a smooth, averaged pressure value from three tapplings on the wall, at 90° angle between them. A sufficient length of tube also allows the hot gas to cool down to temperatures acceptable by the transducers. Similar transducers (PXM 319-070G

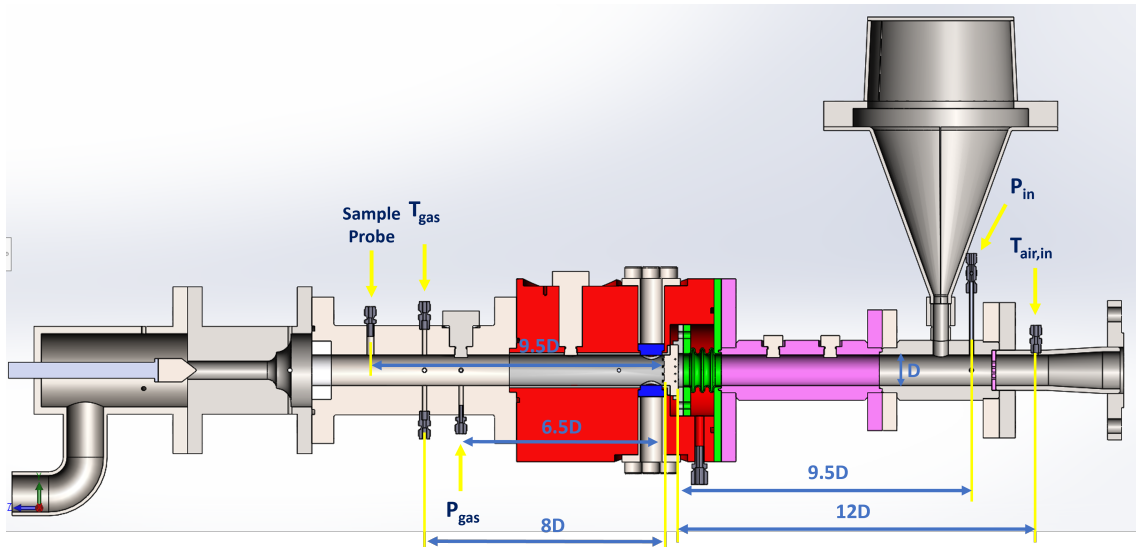


FIGURE 3.5: Section view of the rig, denoting the positions of monitoring equipment

10V) were installed along the fuel line at points of interest and at the fuel chamber. Monitoring the latter helped ensure that pressure in the fuel chamber remains higher than the combustion chamber at all times, and no hot gases flow towards the fuel lines. Atmospheric pressure was monitored with a PX 309-030A 10V absolute pressure sensor positioned inside the test house, close to the data acquisition (DAQ) system.

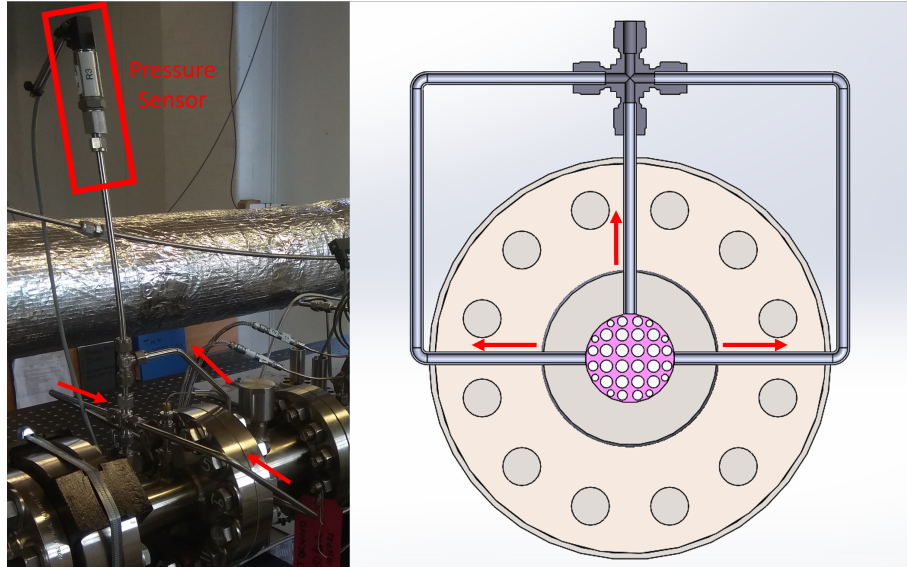


FIGURE 3.6: CAD representation of the triple-tee configuration for static pressure monitoring (right) and the realised setup (left). The red arrows denote the path of the tubing towards the sensor.

Temperature Monitoring Thermocouples (T/Cs) were used to measure the total temperature upstream and downstream of the flames (Figure 3.5). Upstream, a type-K device immersed in the airflow, approximately $12D$ off the micromix burner, monitored temperature, which was defined as the air-inlet temperature of the test section. This position was chosen far from the burner, to allow space for the thermoacoustics setup to be installed in between and avoid disturbance of the thermoacoustics signals. Four type-B thermocouples were installed about $8D$ downstream of the micromix burner, to monitor the hot gas temperature. Installation was at 90° angles between each other and different immersion depths, to allow monitoring of the radial temperature distribution. In cases where optical access was unavailable, the hot gas temperature also acted as an indicator of the existence of flames in the combustion chamber.

3.5.3.3 Mass Flow Metering

Air Flow Air mass flow was measured as already mentioned by a custom-made orifice plate (Figure 3.7). Instrumentation for the orifice plate consisted of two pressure sensors and a thermocouple. A differential pressure sensor (Omega PXM 419-070HDWU10V) read pressure drop between the upstream and downstream sides of the orifice plate (pressure tapings - Figure 3.7) and a gauge sensor (PXM 319-020G) measured static pressure on the upstream side, its tap positioned at the same axial position as the tap of the differential, at a 90° circumferential angle. The gauge

sensor value, along with the atmospheric pressure value was used to calculate the density of the fluid, as well as absolute pressure values, as required by the mass flow calculation formula [49]. The value from the thermocouple was also used in the density calculation.

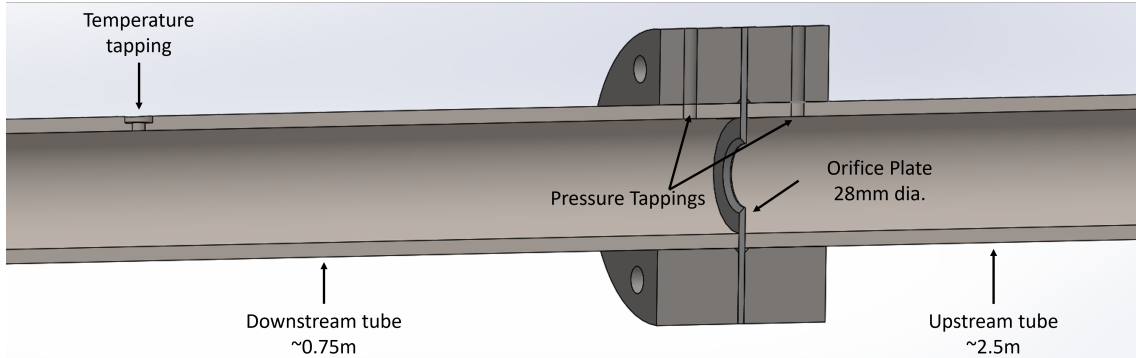


FIGURE 3.7: Section view of the orifice plate assembly (CAD model)

Fuel Flow A Bronkhorst IN-FLOW Select Series mass-flow controller (MFC) was employed to measure and control the flow of hydrogen. The instrument consisted of an F-113AI flow meter and an F-002AI control valve, calibrated to measure from 0.026g/s up to 1.3g/s of H_2 . The instrument was connected to the test house PC through USB, from which the set-point of the MFC could be controlled straightforwardly by choosing the desirable mass flow.

3.5.3.4 Instrumentation Specifications

Specifications of the instruments and sensors described in the previous paragraphs are provided in this section.

The Horiba PG-250 gas analyser was calibrated by the supplier before use, and the measurement-related specifications for the CLD sensor are given in Table 3.2

Error	Value(% FS)
Linearity	± 0.68
Repeatability	± 0.5
Zero drift	± 0.08
Span drift	± 0.92
H_2O interference	± 2

TABLE 3.2: Error specifications of the PG-250gas analyser

The mass flow meter of the Bronkhorst mass flow controller (MFC) system, an F-113AI, was calibrated to a range between 0.026g/s to 1.3g/s with an accuracy of $\pm 0.5\%Rd$ and $\pm 0.1\%FS$.

The PXM 309 series pressure sensors used, are supplied with calibration certificates denoting a "total error band" of $\pm 1\%FS$, where FS denotes the full-scale value of the sensor. The term "total error band" stands for the measured value deviation when all known error sources are accounted for according to the supplier. For the PXM 409 series, a value of $\pm 0.08\%$ off the best straight line (BSL) is determined by the supplier representing combined linearity, hysteresis and repeatability.

Type-K thermocouples used along the rig, operate with an error of $\pm 2.2^\circ\text{C}$ or $\pm 0.75\%Rd$ (Rd stands for Reading), whichever is greater. Type-B thermocouples have an accuracy of $\pm 0.5\%Rd$.

3.5.4 Data Acquisition System

The gas analyser, as already discussed, was connected straight to a test-house PC and data logging was done through the supplier's own software. For the rest of the equipment, National Instruments (NI) hardware and software (LabView) were employed. The general measuring chain for this equipment was: Sensor - ADC - cDAQ chassis (transmitting buffer) - PC (receiving buffer) - LabView.

On the monitoring side, pressure and temperature sensors, including the air mass-flow metering instrumentation were connected to a compact data acquisition chassis (cDAQ) NI 9174, through the analogue-to-digital converter (ADC) modules. For pressure sensors, the NI-9205 module was used, while for temperature, the NI-9212. A custom graphical user interface (GUI) - called a virtual instrument (VI) - was developed in NI LabView and allowed continuous monitoring and logging of fuel and air pressure, temperature and mass flow (including fuel) data. The fuel MFC was also controlled through the same VI. The logged data were saved into LabView ".lvm" form that can be accessed through Microsoft Excel.

3.6 Experimental Procedures

This section presents the procedures for the preparation of the experimental setup as well as practices followed during testing for safe operation and data acquisition.

Preparatory work on a testing day mainly refers to important procedures to ensure the safe operation of the rig and reliable measurements from the instrumentation. The steps listed below were followed:

- powering on the instrumentation early enough to bring it to steady state operation before testing
- calibration of the gas analyser. Zero and span calibration of the gas analyser was performed just before setting up the rig for testing
- LabView interface for monitoring and fuel-flow control was tested for normal operation
- hydrogen and nitrogen bottled gases were set to an initial outlet pressure at least 2.5 times the targeted combustion pressure. Nitrogen was always set to $0.5bar_a$ to $1bar_a$ higher than hydrogen to ensure purging flow through all the fuel system lines
- visual and audio checks for the operation of air-circulating fans of the safety system

3.6.1 Daily Preparations for Testing

Ignition Sequence

With all the systems set up, airflow was initially introduced in the rig. At increased pressure and inlet temperature tests, the air was at a pressure of about $3 - 4bar_a$ in the rig in preparation for ignition. Air mass flow was allowed a few minutes time to settle before initiating the ignition sequence. For ignition, the fuel flow controller was set to provide a mixture of equivalence ratio of about 0.5 to make the process a bit easier. Ignition was achieved with the use of a glow plug and was considered successful when a significant rise in temperature was observed, by the thermocouples downstream of the combustion chamber. In case of unsuccessful ignition (no temperature rise) after 30 seconds when the glow plug timed out, fuel

flow was shut down and purging gas was introduced in the whole system, to avoid any undesired deflagration or detonation.

Operating Conditions Setup

After successful ignition, due to the high-temperature rise and subsequent density drop in the hot gases, a sudden drop in air mass flow was noticed (implying choked operation of the back-pressure valve). This was accounted for by setting slightly higher air and fuel flows before ignition.

With established flames and operating conditions stabilised, the next step was to get to the targeted test point. Increasing the inlet conditions involved a stepped approach of slowly building pressure and increasing the mass flows in the system. It involved coordination between manually increasing compressor supply pressure (in the compressor house) by $0.5\text{bar} - 1\text{bar}$ intervals, bottled gases outlet pressure by $2\text{bar} - 4\text{bar}$ intervals and flow regulation for both air and fuel from the control room of the test cell. This process was done carefully and at such small intervals to avoid potential flame-out events by a sudden rush of air in the test section.

3.6.2 Data Acquisition and Repeatability

Data Sampling and Logging

The developed LabView VI interface allowed monitoring of air and fuel pressures along the system and air temperature at different points. It also allowed monitoring of air and fuel mass flows and control of the fuel. Sampling was performed continuously for both pressure and temperature at a rate of 36Hz . The refresh rate at the monitor was 4Hz (every 0.25 seconds). Since bulk flow, static pressure, temperature and mass flows were monitored, and interest in data acquisition was focused on steady-state¹ conditions for these parameters, there was no requirement for higher sampling rates. The refresh time of 0.25s was considered fast enough to monitor changes in operating conditions. The VI also allowed logging data in real-time with the same refresh rate including a timestamp. The parameters recorded were: static pressure upstream of the orifice plate, the differential pressure across the orifice plate, air static pressure upstream and downstream of the micromix burner, fuel pressures

¹These parameters are not time-invariant even at a specific operating point, yet their fluctuations are small and mainly attributed to noise or imposed by the compressed-air supply system.

across the main board of the fuel system and in the fuel chamber, air and fuel mass-flows (along with some relevant calculated parameters like Reynolds number for the airflow), temperatures, downstream of the orifice plate, upstream of the micromix burner on the air side, downstream of the burner measuring hot gas temperature, and at two points on the inlet of the heated sample line and equivalence ratio.

For NO_x emissions, as already mentioned, data monitoring and logging were done through the software supplied by the supplier of the gas analyser. The software allowed a minimum time of 15s between samples recorded. In order to retain good experimental practice but also minimise the time of operation for each testing condition, 20 samples were acquired, as a minimum requirement for statistical processing for each point, with the recording period lasting 5 minutes. NO_x emissions data were recorded in one file from the initiation of combustion till the shutdown of the rig. To extract the 20 samples for each point, the timestamps of this file and the file containing monitoring data for the specific condition were compared. It should be noted that after steady conditions were reached at a test point, the gas analyser was allowed at least 1 minute of time to settle to the new condition (the response time for the CLD sensor is 45s) and this was accounted for when selecting the samples of NO_x .

Repeatability Tests

To ensure that test results were not a product of chance but rather, have significance, test cases were repeated on separate dates. Although repeats in short time intervals would have been more appropriate to ensure the soundness of the experiment, time pressure and the need to cover as many test cases as possible during a testing day, led to conducting the test repeats at different dates. Moreover, it shall be noted that test conditions could not be reproduced on the exact values of pressure, air-inlet temperature, and equivalence ratio, due to the difficulty in regulating air pressure and mass flow.

3.7 Data Handling

3.7.1 Review and Filtering of Raw Data

NO_x emissions data gathered were reviewed after the experimental campaign was concluded. For each case on a testing day the 20 values of measured emissions, along with the rig parameters corresponding to the same time frame, were transferred to a new file to facilitate statistical processing. The monitoring parameters included in the new file were pressure upstream and downstream of the micromix burner, barometric pressure of the day (measured by a small weather station), inlet-air temperature, mass flows of fuel and air, equivalence ratio, hot gas temperatures and the temperature readings at the inlet of the heated sample line. Data that were taken on days when setup malfunctions were observed, such as condensed water appearing to block the capillary tubing of the gas analyser or unexpectedly low temperature at the inlet of the heated sample line, were discarded fully or partly, depending on the point in time that the issue presented itself.

3.7.2 Statistical Processing

Following the first step of filtering out data, for each of the remaining cases, the sampled values for NO_x and monitored parameters were averaged. For repeated cases, the samples of corresponding test points from different dates were merged and then averaged. Standard deviation values were also calculated from these extended samples. With regards to operating conditions, these averaged values of pressure, air-inlet temperature and equivalence ratio, are the ones used in the plots presented in Chapter 5. Custom scripts were developed in Python to perform the aforementioned operations.

3.7.3 Metric for the Presentation of NO_x Emissions

This section discusses the calculations and underlying assumptions applied to the averaged NO_x values, after the initial processing that was described in Section 3.7.2. Slightly different calculations are applied to the experimental and numerical results, leading in both cases to the metric that is utilised for the presentation of NO_x emissions in a subsequent chapter. This metric is the energy emission index (EEI).

3.7.3.1 Derivation of the $EEINO_x$ for Experimental Results

The metric that is utilised for the presentation of NO_x emissions is an energy-based index ($EEINO_x$ in g of NO_x /MJ) derived from the emission index ($EINO_x$), measured in g of NO_x /kg of fuel. The $EINO_x$ is currently used widely in regulatory documents and the ICAO Aircraft Engine Emissions Databank and serves the purpose of emissions comparison between different engines and operating conditions for kerosene fuels such as Jet A-1. When it comes to hydrogen, given its different density and significantly higher lower heating value (LHV) (120MJ/kg) compared to kerosene (43MJ/kg) a comparison on the basis of emissions per mass of fuel is not appropriate. A more fair basis for comparison can be given by expressing emissions per unit of energy released by the fuel, which is effectively the energy-based emissions index.

$$EEINO_x \text{ [g/MJ]} = \frac{EINO_x \text{ [g/kgfuel]}}{LHV \text{ [MJ/kgfuel]}} \quad (3.4)$$

Calculation of the energy-based index requires a number of other quantities to be calculated beforehand and for these calculations, assumptions need to be made, as outlined below.

The first step is to correct the NO_x concentration ($[NO_x]$) measured from the gas analyser on a dry basis (water vapour fully removed) and account for the window cooling air² (correction to the local Φ) to allow comparison with the numerically derived results.

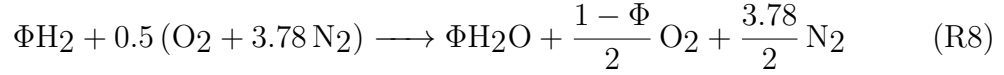
Hence, if n_{NO_x} is the number of moles of nitrogen oxides in the sample and n_{sample} is the total number of moles reaching the gas analyser,

$$[NO_x] = y_{NO_x} 10^6 = \frac{n_{NO_x}}{n_{sample}} 10^6 \Rightarrow n_{NO_x} = [NO_x] n_{sample} 10^{-6} \text{ mol} \quad (3.5)$$

where y_{NO_x} is the molar fraction of NO_x . Since the gas analyser measures total NO_x as NO , there is no problem in assuming a number of moles of NO_x (instead of separately calculating moles of NO and NO_2). For the total moles in the sample, one needs to consider that it is a mixture of gases that consists of combustion products that are partly dried (remember the drying stages of the sampling system), excess air, and the air introduced for window cooling. Here, the following assumptions are introduced:

²The cooling air for the windows is explained in the next chapter (Chapter 4)

- the number of moles of reactants and products is calculated based on the global, one-step hydrogen/air combustion reaction (R8)
- minor species, such as NO and NO_2 are considered negligible compared to the concentrations of the major species and, hence are omitted from the calculation of total moles in the sample
- although the water content after drying is unknown, it is assumed that it amounts to 4% of the water initially present in the sampling line



Taking into account the above discussion, and with the help of (R8),

$$n_b = 0.5 N_{inj} (\Phi + 4.78)$$

are the moles of the combustion products,

$$n_{H_2O} = (1 - 0.04) \Phi N_{inj}$$

are the moles of water remaining in the sample after the drying process and

$$n_c = 0.5 (N_{AG} - N_{inj}) 4.78$$

are the moles of cooling air. The total moles in the sample that goes in the gas analyser are:

$$n_{sample} = n_c + n_b - n_{H_2O} = 2.39 N_{AG} - 0.46 \Phi N_{inj} \quad (3.6)$$

where N_{AG} is the number of air gates and N_{inj} is the number of injectors for each of the configurations. From (3.6) and (3.5) the moles of NO_x are calculated. The next step is to get the molar fraction on a dry, no-cooling air basis, that is

$$y_{NO_x,corr} = \frac{n_{NO_x}}{n_b - n_w}$$

with $n_w = N_{inj} \Phi$, which yields

$$y_{NO_x,corr} = \frac{n_{NO_x}}{0.5 N_{inj} \Phi} \frac{\text{moles of } NO_x}{\text{moles of mixture}} \quad (3.7)$$

Having the corrected value of the molar fraction allows the calculation of the mass fraction of NO_x ($x_{NO_x,corr}$) and subsequently enables the calculation of the $EINO_x$

and $EEINO_x$ metrics. For the calculation of the mass fraction, the molar masses of NO_x and of the mixture are required. Here, two important assumptions come into play.

- the molar mass of NO is considered for NO_x as the gas analyser turns all NO_2 into NO before the measurement.
- minor species in the mixture, such as NO_x , are neglected and the dried mixture only consists of oxygen and nitrogen. This is a fair assumption since NO_x concentration is two to three orders of magnitude lower than that of oxygen and nitrogen.

Molar mass of NO_x is then given by

$$M_{NO_x} = M_{NO} = 30 \text{ (g/mol)}$$

. For the mixture, the molar mass is the weighted average of the contributions of oxygen and nitrogen

$$M_{mix} = 32 y_{O_2} + 28 (1 - y_{O_2}), \text{ where} \quad (3.8)$$

$$y_{O_2} = \frac{n_{O_2}}{n_{mix}}$$

From reaction R8, and neglecting the H_2O term since the calculation is on a dry basis,

$$y_{O_2} = \frac{1 - \Phi}{4.78 - \Phi}$$

The mass fraction, expressed in $\frac{g \text{ of } NO_x}{g \text{ of } mix}$ can now be calculated as

$$x_{NO_x,corr} = y_{NO_x,corr} \frac{M_{NO_x}}{M_{mix}} \quad (3.9)$$

To express the mass fraction of NO_x in the dry mixture, in terms of mass of NO_x per mass of fuel ($EINO_x$ in $\frac{g \text{ of } NO_x}{kg \text{ of } fuel}$), the mass of dry products per unit mass of fuel is required. This can be calculated based on equation 8, and yields the dry (oxygen and nitrogen only) mixture mass produced ($g \text{ of } mix$) per unit mass of hydrogen ($g \text{ of } H_2$):

$$m = \frac{4.78 - \Phi}{4\Phi} M_{mix} \quad (3.10)$$

where M_{mix} is the molar mass of the oxygen/nitrogen mixture in the products, given by the expression

$$M_{mix} = \frac{32 (1 - \Phi) + 28 \cdot 3.78}{4.78 - \Phi} = \frac{137.84 - 32 \Phi}{4.78 - \Phi} \left[\frac{g}{mol} \right]_{mix} \quad (3.11)$$

$$\text{3.10} \xrightarrow{\text{3.11}} m = \frac{34.46 - 8\Phi}{\Phi} \left(\frac{g \text{ of } mix}{g \text{ of } H_2} \right) \quad (3.12)$$

Subsequently, the emission index (EI) can be expressed in $\frac{g \text{ of } NO_x}{kg \text{ of } fuel}$ as

$$EINO_x = m \ x_{NO_x,corr} \ 1000 = \frac{4.78 - \Phi}{4\Phi} M_{mix} \ x_{NO_x,corr} \ 1000 \quad (3.13)$$

The $EEINO_x$ is then calculated from equation 3.4.

3.7.3.2 Derivation of the $EEINO_x$ for Numerical Results

Numerically derived results, produced in the context of the ENABLEH2 project, were provided as ppmv concentrations corrected to 15% O_2 content (denoted as $[NO_x]_{15\%O_2}$). A similar process was followed as with the experimental results, calculating the mole fraction on a dry-sample basis. First the mole fraction of NO_x in the products is calculated and is then corrected to dry-sample, as follows:

$$y_{NO_x} = [NO_x]_{15\%O_2} \frac{20.9 - y_{O_2} \cdot 10^2}{20.9 - 15} \ 10^{-6} \quad (3.14)$$

$$y_{NO_x,corr} = y_{NO_x} \frac{n_{mix}}{n_{mix,dry}} \text{ where} \quad (3.15)$$

$$n_{mix} = \frac{\Phi + 4.78}{2} \text{ and}$$

$$n_{mix,dry} = \frac{4.78 - \Phi}{2}$$

Similarly to the previous section, the mass fraction of NO_x in a dry mixture is given by equation 3.9 and the molar mass of the mixture by equation 3.11. $EINO_x$ and $EEINO_x$ are given by equations 3.13 and 3.4 respectively.

3.7.4 NO_x Uncertainty Estimation

3.7.4.1 Measurement Uncertainties

Uncertainties were estimated for the measured NO_x emissions in order to assess the quality of the measurements. The uncertainty analysis presented here is based on estimates of both systematic and random errors. Random errors are calculated from the acquired samples while a number of sources contribute to the systematic error. It is noted that not all of these sources could be quantified in the context of this work. The total uncertainty can be then calculated, in terms of absolute error (in ppmv) denoted U , as

$$U^2 = s_x^2 + b^2, \quad (3.16)$$

where s denotes uncertainty stemming from random errors and b denotes uncertainties from systematic error sources.

The reason for the uncertainty estimation as already stated is to provide the reader with an idea of the quality of the measurement setup in terms of quantifying emissions. In other words, it is good experimental practice. An example of uncertainty estimation on the gathered data is given in [Appendix B](#).

Random Error

The random error varies during a measurement period and is attributed to sources for which the variability limits are not known precisely, such as electronic interference or minor fluctuations of the measured quantity (when measuring steady-state phenomena). The random error from all potential sources is estimated, for a measurement point, as the standard deviation of the mean value of the sample:

$$s_{\bar{X}} = \frac{s}{\sqrt{n}} \quad (3.17)$$

where s is the sample standard deviation and n is the sample size.

Systematic Error

Errors that do not vary during the measurement period are characterised as systematic. For this setup, the sources of systematic error are as follows:

- Instrument errors (linearity, repeatability etc)
- Calibration error
- NO_2 dilution due to water condensation

Intrument Errors

Instrument errors are associated with the specifications of the measuring device. Linearity (ε_l), repeatability (ε_{rep}), zero ($\varepsilon_{z,dr}$) and span ($\varepsilon_{s,dr}$) drifts, water vapour content (ε_{vap}) and NO_2 converter efficiency (b_{con}) are the factors contributing to this error source. Instrument uncertainty as a percentage of the instrument full-scale (FS) is calculated as:

$$\varepsilon_{in} = \sqrt{\varepsilon_l^2 + \varepsilon_{rep}^2 + \varepsilon_{z,dr}^2 + \varepsilon_{s,dr}^2 + \varepsilon_{vap}^2} \quad (3.18)$$

and the error value is

$$b_{in} = \beta_{in} + \beta_{con} = \varepsilon_{in}FS + \varepsilon_{con}[NO_2] \quad (3.19)$$

ε_{con} is the error arising from the NO_2 converter efficiency being < 1 and is expressed as the efficiency percentage of the NO_2 fraction of the sample, and $[NO_2]$ is the concentration of NO_2 . This efficiency is certified by calibration to be $> 95\%$. FS is the full-scale (range) of the instrument, chosen by the experimenter.

Of instrument-related errors, the contribution of the NO_2 converter efficiency cannot be estimated as the fraction of NO_2 in the sample is not known.

Calibration Error

The calibration error arises from the uncertainty in the exact contents of the calibration gas cylinders, against which the instrument zero and span values are checked. Oxygen-free N_2 is used for the zero check and NO balanced with nitrogen for the span check. The calibration bottled gas for NO comes with a certificate regarding the concentration of its contents with a percentage uncertainty of that value, while the N_2 cylinder has a concentration of 99.998%. During the day-to-day calibration³, the instrument is checked at its zero and span values. Since the zero check is done with a high-purity, oxygen-free nitrogen bottle, the uncertainty of zero calibration

³The process is actually a check on instrument drift and corrects what is measured, to the nominal concentration value of the bottled gas. Technically calibration refers to a similar procedure where the instrument is compared against another instrument of at least an order of magnitude higher accuracy.

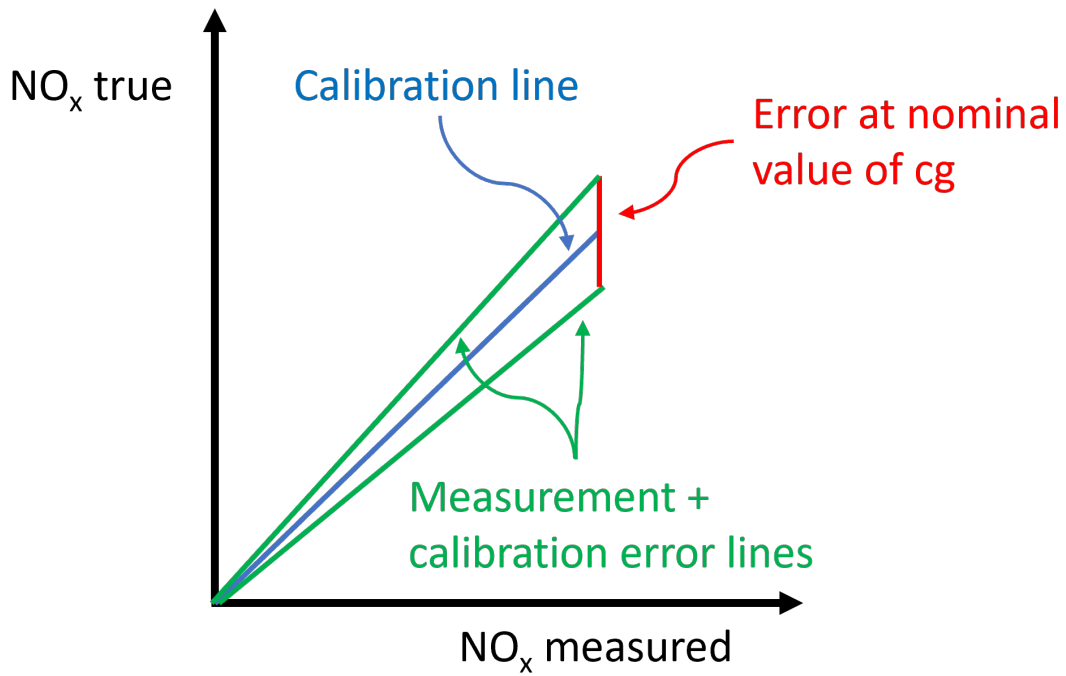


FIGURE 3.8: Quantitative graph for the derivation of error due to uncertainty of the calibration gas (cg) cylinder

is negligible. On the span value, the uncertainty is that of the gas bottle for *NO*. Thus, as can be seen in Figure 3.8 the calibration uncertainty has a linear dependence on the instrument reading, within the set range, and the slope of the line is the percentage uncertainty of the bottled *NO* gas:

$$b_{cg} = \varepsilon_{cg} Rd \quad (3.20)$$

where ε_{cg} is the percentage uncertainty of the *NO* bottled gas and Rd is the instrument reading.

*NO*₂ Dilution

Condensation of water vapour in the sample lines presents another source of error in the measurement. Condensed water dilutes *NO*₂ affecting its contribution to the measurement and biasing it towards an underestimation of the total *NO_x*. Heated components were used along the gas sampling line wherever possible along with drying stages as already described in Section 3.5.3.1, but the problem of condensation persisted. The amount of water in the sample line is not known, hence its effect on *NO*₂ and subsequently, the imposed uncertainty could not be estimated.

Estimated Systematic Error

Based on the preceding discussion, the summation of the instrument and calibration uncertainties $b = b_{in} + b_{cg}$ provides an estimate of the systematic uncertainty expressed in *ppmv*. This estimate, cannot be considered good as it neglects a potentially significant source of error, which is NO_2 dilution, as already mentioned.

Total Error

The estimation for the total error is given by equation 3.16. It shall be noted that the created error bars are bilateral, $U = \pm\sqrt{s_x^2 + b^2}$, potentially overestimating the contribution of the considered sources of error.

3.7.4.2 Uncertainty Propagation for the $EEINO_x$ Metric

The $EEINO_x$ metric is derived from measured and calculated quantities as discussed in the previous section. As such, the uncertainty estimation for it is conducted by applying the Taylor Series method for the propagation of uncertainties, as described by Coleman in [15].

The definition of the energy-based emission index is given by equation (3.4), $EEINO_x = \frac{EINO_x}{LHV}$. To allow for a calculation of the uncertainties, Eq. 3.4 needs to be brought to a form that can be useful for the analysis, i.e., a form that expresses $EEINO_x$ as a function of variables for which the uncertainties are known or can be calculated. Starting from equation 3.13:

$$\begin{aligned}
 EINO_x &= \frac{4.78 - \Phi}{4\Phi} M_{mix} x_{NO_x,corr} 1000 \\
 \stackrel{3.9}{\Rightarrow} EINO_x &= 10^3 \frac{4.78 - \Phi}{4\Phi} y_{NO_x,corr} M_{NO_x} \\
 \stackrel{3.7}{\Rightarrow} EINO_x &= 10^3 \frac{4.78 - \Phi}{4\Phi} \frac{n_{NO_x}}{\frac{N_{inj}\Phi}{2}} M_{NO_x} \\
 \stackrel{3.5}{\Rightarrow} EINO_x &= 10^3 \frac{4.78 - \Phi}{2\Phi^2 N_{inj}} [NO_x] n_{sample} 10^{-6} M_{NO_x} \\
 \stackrel{3.6}{\Rightarrow} EINO_x &= 10^{-3} \frac{(4.78 - \Phi)(2.39N_{AG} - 0.46\Phi N_{inj})[NO_x] M_{NO_x}}{2\Phi^2 N_{inj}}
 \end{aligned}$$

Given the assumption of $M_{NO_x} = 30g/mol$ we get:

$$EINO_x = 15 \cdot 10^{-3} \frac{(4.78 - \Phi)(2.39N_{AG} - 0.46\Phi N_{inj})[NO_x]}{\Phi^2 N_{inj}} \quad (3.21)$$

This expression (Eq. 3.21) combined with equation 3.4, yields:

$$EEINO_x = 15 \cdot 10^{-3} \frac{(4.78 - \Phi)(2.39N_{AG} - 0.46\Phi N_{inj})[NO_x]}{\Phi^2 N_{inj} LHV} \quad (3.22)$$

In this expression, the simplifications described for the measurement uncertainty of the previous paragraph are still valid. Namely, these are $M_{NO_x} = 30g/mol$ and the consideration of NO_x as minor species, not considered in the total moles of the sample. The number of air gates, N_{AG} , and injectors, N_{inj} , are constants that do not affect the uncertainty. The lower heating value of hydrogen (LHV) is also a constant and the uncertainty in its specification does not require consideration for this calculation. Hence, the variables that affect the uncertainty calculation are, the measured NO_x ($[NO_x]$) emissions and the equivalence ratio (Φ).

The Taylor Series Method then suggests that the uncertainty for the energy emission index is:

$$u_{EEINO_x}^2 = \left(\frac{\partial(EEINO_x)}{\partial\Phi}\right)^2 u_{\Phi}^2 + \left(\frac{\partial(EEINO_x)}{\partial[NO_x]}\right)^2 u_{NO_x}^2 \quad (3.23)$$

From 3.22, the partial derivatives of equation 3.23 are given as:

$$\frac{\partial(EEINO_x)}{\partial\Phi} = EEINO_x \cdot \frac{2.2\Phi N_{inj} + 2.39\Phi N_{AG} - 22.84N_{AG}}{\Phi(4.78 - \Phi)(2.39N_{AG} - 0.46\Phi N_{inj})} \quad (3.24)$$

$$\frac{\partial(EEINO_x)}{\partial[NO_x]} = \frac{EEINO_x}{[NO_x]} \quad (3.25)$$

The $[NO_x]$ uncertainty (u_{NO_x}) is estimated as described in the previous section. The uncertainty of the equivalence ratio (u_{Φ}) requires some further derivations and application of the Taylor Series Method, as Φ is calculated based on other measured and calculated values, which further require estimations of their uncertainties.

From the definition of equivalence ratio, and with the stoichiometric fuel-to-air ratio for hydrogen $(FAR)_{st} = 0.0293$, $\Phi = \frac{FAR}{(FAR)_{st}} = \frac{1}{0.0293} \cdot \frac{\dot{m}_{air}}{\dot{m}_f}$.

Thus, the uncertainty for the equivalence ratio is given as:

$$u_{\Phi}^2 = \left(\frac{\partial\Phi}{\partial\dot{m}_f}\right)^2 u_{\dot{m}_f}^2 + \left(\frac{\partial\Phi}{\partial\dot{m}_{air}}\right)^2 u_{\dot{m}_{air}}^2 \quad (3.26)$$

where,

$$\frac{\partial\Phi}{\partial\dot{m}_f} = \frac{1}{0.0293\dot{m}_{air}}$$

$$\frac{\partial \Phi}{\partial \dot{m}_{air}} = \frac{\dot{m}_f}{0.0293 \dot{m}_{air}^2}$$

The uncertainty of the fuel mass flow can be easily calculated by the specifications of the mass-flow controller (as given in 3.5.3.4 for the systematic error and the logged values for the random error (eq. 3.27).

$$u_{\dot{m}_f} = \sqrt{b_{\dot{m}_f}^2 + s_{\dot{m}_f}^2} \quad (3.27)$$

where, $b_{\dot{m}_f} = 0.5\%Rd + 0.1\%FS$ is the systematic error and $s_{\dot{m}_f}$ is the standard deviation of the sampled values of the fuel mass flow over the square root of the sample length, that gives the random error.

To estimate the uncertainty of the air mass flow, the guidance of BS EN5167-1:2003 and BS EN5167-2:2003 standards is followed. According to the standards:

$$\begin{aligned} \frac{u_{\dot{m}_{air}}}{\dot{m}_{air}} = & \left[\left(\frac{u_C}{C} \right)^2 + \left(\frac{u_\epsilon}{\epsilon} \right)^2 + \left(\frac{2\beta^4}{1-\beta^4} \right)^2 \cdot \left(\frac{u_D}{D} \right)^2 \right. \\ & \left. + \left(\frac{2}{1-\beta^4} \right)^2 \cdot \left(\frac{u_d}{d} \right)^2 + \frac{1}{4} \left[\left(\frac{u_{\Delta P}}{\Delta P} \right)^2 + \left(\frac{u_{\rho_1}}{\rho_1} \right)^2 \right] \right]^{\frac{1}{2}} \end{aligned} \quad (3.28)$$

where $\frac{u_C}{C} = 0.5\% + 0.9(0.75 - \beta(2.8 - \frac{D}{25.4}))\% = 0.64\%$ with $\beta = 0.55$ and $D = 50.8mm$ the inner diameter of the tube of the orifice plate. The uncertainty of the compressibility factor is also given by the standard as $\frac{u_\epsilon}{\epsilon} = 3.5 \frac{\Delta P}{\gamma P_1}$, where ΔP is the pressure drop across the orifice plate and P_1 is the value of the absolute pressure.

The uncertainty of the inner diameter of the tube of the device (u_D) was considered to be represented by the dimensional tolerance of the diameter. Since no tolerance was specified by the supplier, standard BS EN10297-2:2005 was consulted. According to the standard, for cold-finished stainless steel tubes, the following tolerances apply:

- for the outer diameter (OD = 63.5mm) $\pm 0.75\%$ or $\pm 0.3mm$, whichever is greater
- for the wall thickness ($t = 6.35mm$) $\pm 10\%$ or $\pm 0.2mm$, whichever is greater

Since $D = OD - 2t$, then applying the Taylor series Method we get:

$$u_D^2 = u_{OD}^2 + 4u_t^2 = [(0.75\%)63.5]^2 + 4[(10\%)6.35]^2 = 1.84 \Rightarrow u_D \approx 1.36mm \quad (3.29)$$

Hence, $\frac{u_D}{D} = \frac{1.36}{50.8} = 2.68\%$.

Regarding the uncertainty of the diameter of the orifice plate itself (u_d), the tolerance according to the manufacturing drawings is $\pm 0.15mm$, which leads to a value of $\frac{u_d}{d} = \frac{0.15}{28} = 0.54\%$.

Calculation of the $\frac{u_{\Delta P}}{\Delta P}$ term is based on the specifications of the differential pressure sensor and the DAQ analogue-to-digital converter (ADC), as well as the logged values of the sensor (for the random error). Specifically, $u_{\Delta P}^2 = b_{\Delta P}^2 + s_{\Delta P}^2$, where $b_{\Delta P} = \beta_{sensor} + \beta_{DAQ}$ is the systematic uncertainty and $s_{\Delta P}$ is random uncertainty, and is calculated based on the logged data. From the sensor specifications, $\beta_{sensor} = 0.08\%Rd$ and from the specifications of the ADC card (NI9205) $\beta_{DAQ} = 0.062\%FS$, with FS referring to the 10V full-scale output of the card. Since the conversion of the voltage into pressure is a proportional relationship, the β_{DAQ} can be applied to the sensor's full-scale pressure value.

The last term at the right-hand side of eq. 3.28 also requires the application of the Taylor Series Method, since density is calculated based on the measurements of pressure upstream of the orifice plate and temperature downstream of the orifice plate: $\rho_1 = \frac{P_{1a}}{RT_2}$. So, we get:

$$u_{\rho_1}^2 = \left(\frac{1}{RT_2}\right)^2 u_{P_{1a}}^2 + \left(-\frac{P_{1a}}{RT_2^2}\right)^2 u_{T_2}^2$$

The absolute pressure value is calculated by the measurements of the gauge sensor positioned upstream of the orifice plate and the ambient pressure sensor, $P_{1a} = P_{1g} + P_{atm}$, which means that the uncertainty is calculated as, $u_{P_{1a}}^2 = u_{P_{1g}}^2 + u_{P_{atm}}^2$. The systematic and random uncertainty components of $u_{P_{1g}}$, $u_{P_{atm}}$ and u_{T_2} are estimated as always based on sensor (and DAQ) specifications (see 3.5.3.4) and the logged data. Here, it should be noted that, for the ambient pressure sensor, data was not logged, so the random error can't be estimated and is not considered. This does not affect the overall uncertainty significantly. Moreover, for the temperature ADC card, the systematic error component is $\beta_{DAQ} = 0.118\%Rd$.

Having estimated all the different uncertainty terms for the air mass flow, the uncertainty of equivalence ratio can be estimated and finally, the overall uncertainty for the $EEINO_x$ results, using equation 3.23.

CHAPTER 4

Design and Development of the Hydrogen Combustion Rig

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4.1 Introduction

This chapter presents the design and development of critical systems and components of the combustion rig including the micromix burner. The main aim is to outline the challenges associated with the effort of developing a small-scale combustion rig for hydrogen and the considerations to be taken into account during such a process. These are presented in the form of a discussion around design choices for critical components, the implementation of safety features, improvements in the setup and its current limitations. In that context, the successful application of a hybrid manufacturing process for the creation of the micromix burner is also detailed.

4.2 Facility Overview

The experimental setup consists of three main systems. The air supply, the fuel supply and the test section (Figure 4.1) along with its instrumentation. High-temperature inlet air for combustion is provided by the Pebble Bed (PB) heater. The PB is a regenerative heat exchanger and is described in Appendix A. The fuel system enables control and safe delivery of fuel towards the rig and implements safety-related characteristics as described in the following section (4.3). The main test section, briefly presented in section 3.2, consists of components that bear instrumentation upstream and downstream of the flames. In this chapter, the focus is placed on the critical components which are the combustion chamber and micromix burner.

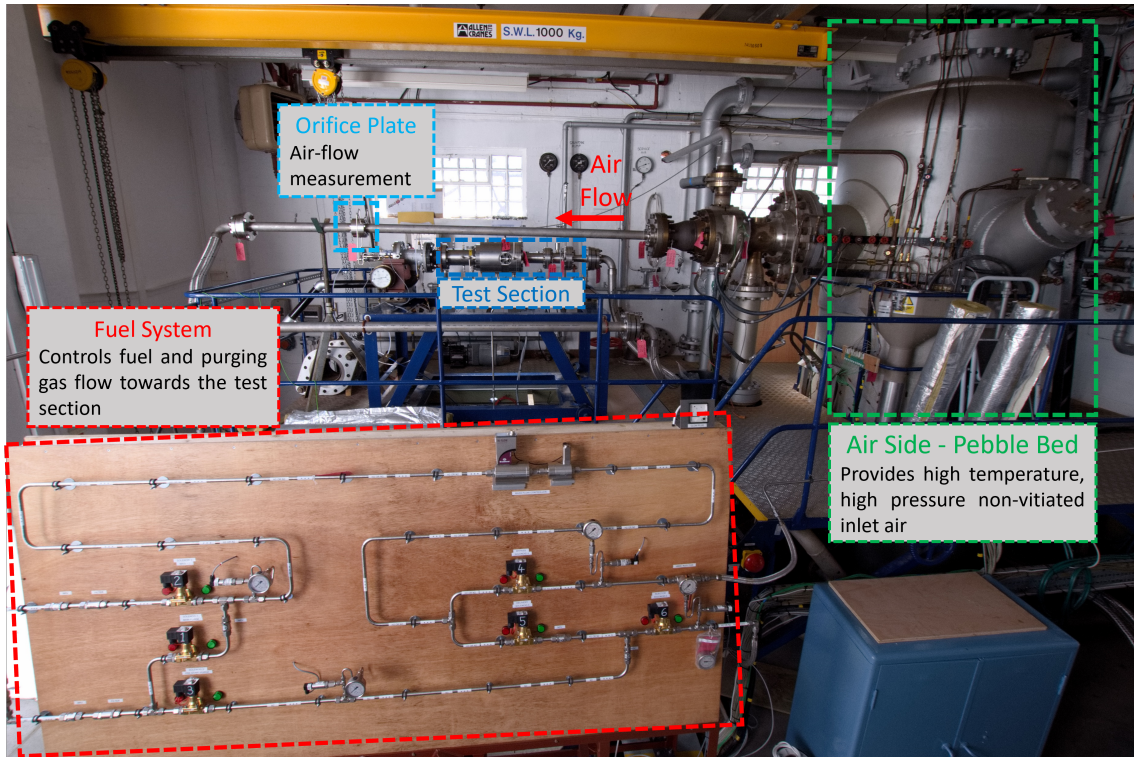


FIGURE 4.1: Overview of the main systems of the micromix combustion experimental apparatus

4.3 Key Systems and Components

Handling hydrogen can be a challenging task, due to its wide flammability limits (4% to 74% volumetric in air), and low energy required for ignition. It calls for a design approach where safety requirements and rig performance requirements sometimes contradict and need to be bridged. In this section, the design and development of the fuel delivery system, the combustion chamber, and the micromix burner, are discussed.

4.3.1 Fuel Supply System

Hydrogen was stored in a pallet of compressed-gas cylinders connected with a manifold, at a pressure of 175bar and positioned outside of the Test House. The fuel supply system was tasked with safely delivering hydrogen from the cylinders to the fuel chamber of the test section. A schematic of it can be seen in Figure 4.2. Stainless steel 316 is used for all the tubing, fittings, filters and non-return valves. The solenoid valves are made of brass with PTFE seals. Stainless Steel 316 and brass

are compatible for operation with hydrogen and show good embrittlement behaviour [7].

Swagelok stainless steel 316 fittings are used for tube and pressure sensor connections as according to their specification they are tested for leaks at high pressure with helium. Particulate filters ($90\mu m$) are used at the inlet of each of the lines to remove potential impurities from the bottled gases (Figure 4.2). To ensure the safety of operation, nitrogen gas is used to purge the system of any leftover hydrogen and air, before and after the operation of the rig. Non-return valves are employed to prevent the back-flow of hot gases, air and any potential flashback event. The hydrogen mass-flow controller (MFC) is positioned along the main hydrogen line and allows regulation of the fuel flow. Since nitrogen is used only for purging flow metering and control were not necessary.

The system comprises two inlet and three outlet lines and is operated in five distinct modes, briefly described below (S2 to S6 denote the solenoid valves - see Fig. 4.2):

- Standby: S2 (Figure 4.2) is only open and fuel flows up to the MFC. This is the initial mode to prepare the system for operation.
- Bypass: S2 and S4 are open. Hydrogen flows through a mimic injector, used to simulate pressure losses of the system in the main line. This mode helps the MFC stabilise to the requested mass flow. Fuel through this line is vented in the atmosphere outside the Test House.

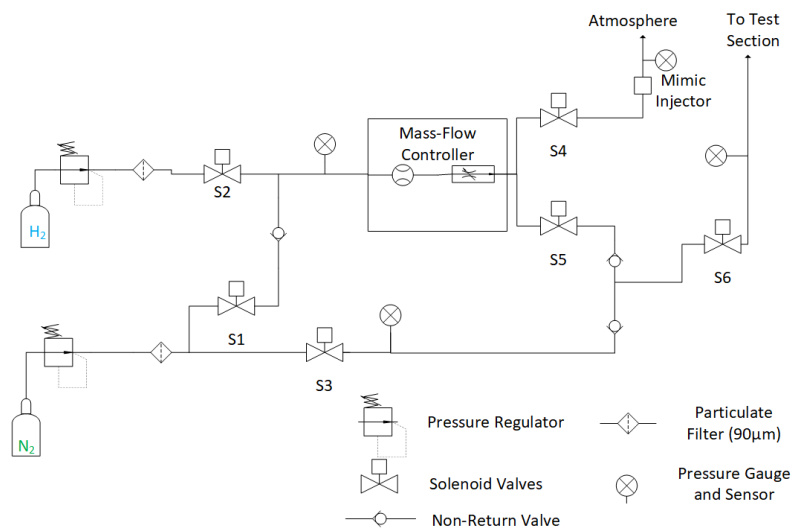
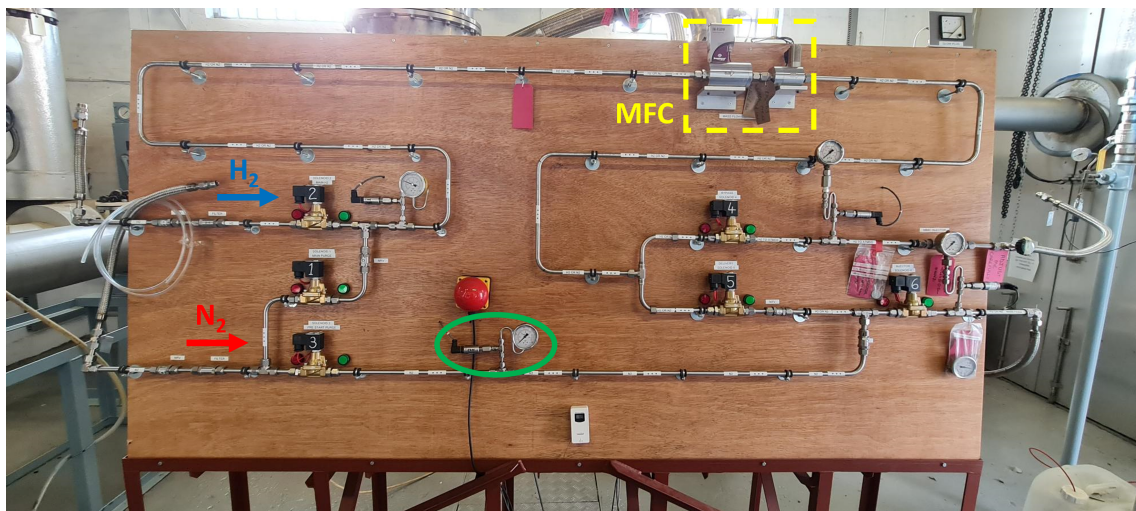


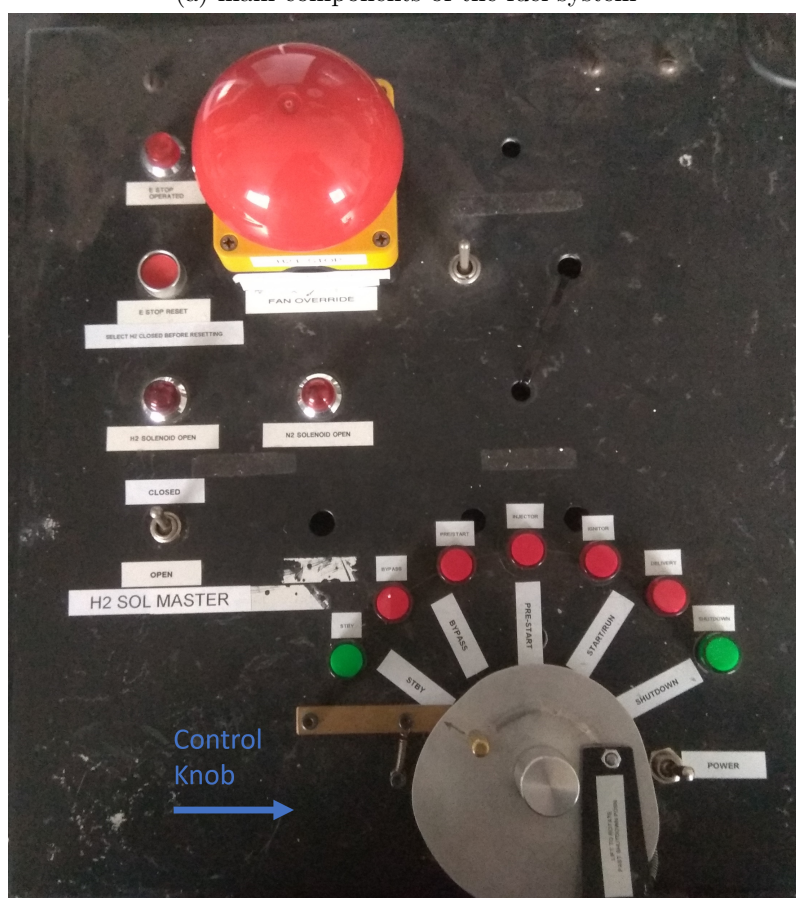
FIGURE 4.2: Schematic of the fuel supply system

- Pre-start/Purge: As in Bypass, with S3 and S6 also open. In this mode, nitrogen flows through the main line and the test section, purging it, to ensure safe fuel delivery when this is requested.
- Start/Run: S3 and S4 close and S5 opens. The flow of nitrogen through the rig stops and hydrogen switches from the venting line, to the test section. The ignitor runs for 30 seconds.
- Shutdown: S2 closes while the other solenoids and the MFC are open. Nitrogen flows through all the lines and the test section to purge any remaining or pooling hydrogen to remove any risk of undesirable ignition.

The different modes are selected by the use of an electromechanical system controlling the solenoid-operated valves through a distinct-position knob (Figure 4.3b). The solenoid valves isolate the different lines and enable the control of the system in different modes. Pressure measurement served monitoring purposes, as well as safety reasons: an unexpected pressure drop between subsequent sensors could indicate a fuel leak along the lines. As a form of redundancy in case the digital monitoring interface (in LabView) stopped working, the pressure was monitored both with transducers and analogue gauges (Figure 4.3a - in green ellipse).



(a) main components of the fuel system



(b) Fuel system control interface

FIGURE 4.3: The main board and mode controller of the fuel system

4.3.2 Combustion Chamber

Requirements and Criteria

The starting point for the design of the test section was the combustion chamber as it is the main component of interest: it carries the micromix burner and facilitates the combustion process. It is a component that is subjected to high mechanical and thermal stresses and is required to facilitate measurement and diagnostics equipment. The rest of the components were designed around it. The requirements for the combustion chamber were as follows:

- safe ignition and operation at high pressures and temperatures
- dome geometry to allow micromix representative flame patterns
- facilitation of different micromix burner designs
- provisions for ignition device, optical access and instrumentation

The design criteria applied were simplicity of the geometry and ease of manufacturing in an effort to minimise cost and turnaround times by retaining the manufacturing process in-house.

Design Challenges and Choices

Finding the best solution between a simple, cost-effective design, and safety, presented the main challenge and entailed the following aspects:

- enhanced protection against the potential effects of undesirable detonation.
Due to the peak thermal power of $\approx 150kW$, in an enclosed space at high pressure, the possibility of a potential deflagration to detonation event had to be dealt with, with a robust combustion chamber, which meant more complexity in machining.
- safe fuel supply towards the micromix burner.
Close to the micromix burner, inside the combustion chamber component, the main risks were:
 - that of hydrogen leaking towards the combustion compartment through routes other than the micromix injectors

- hot gases from the combustion compartment leaking backwards towards the fuel delivery system, which could lead to undesirable effects
- the design of optical access.

Positioning the optical material close to the inner wall so as not to compromise the representative micromix flame patterns meant high thermal stresses for the material. Moreover, for a given small domain size, a large field of view can impact the structural integrity of the component and complicate sealing.

Initial concepts of different domain sizes and cross-section geometries with and without cooling configurations were modelled via computer-aided design (CAD) tools. CFD studies were also carried out by the ENABLEH2 team and provided information on the flow and flame characteristics of the different concepts.

Cooled configuration suggestions implemented a double-wall layout with cooling and combustion air supplied from the same source. Coupled with a test section of rectangular cross-section, these appeared to be the most promising in terms of flow and flame characteristics. In such a configuration, thermal and mechanical loads are decoupled, which benefits the optical material. Double wall, rectangular rig designs were discarded due to higher complexity in facilitating instrumentation, the limitation of in-house manufacturing and increased associated costs. A single wall, cylindrical geometry of 42mm dome (internal) diameter, with no active cooling, was decided. In order to cool the optical material of the windows, part of the air sent in the combustion compartment served as a form of cooling for the windows. The material selected for the combustion chamber was stainless steel 316L, a low-carbon grade of stainless steel that can cope with the high mechanical and thermal loads expected.

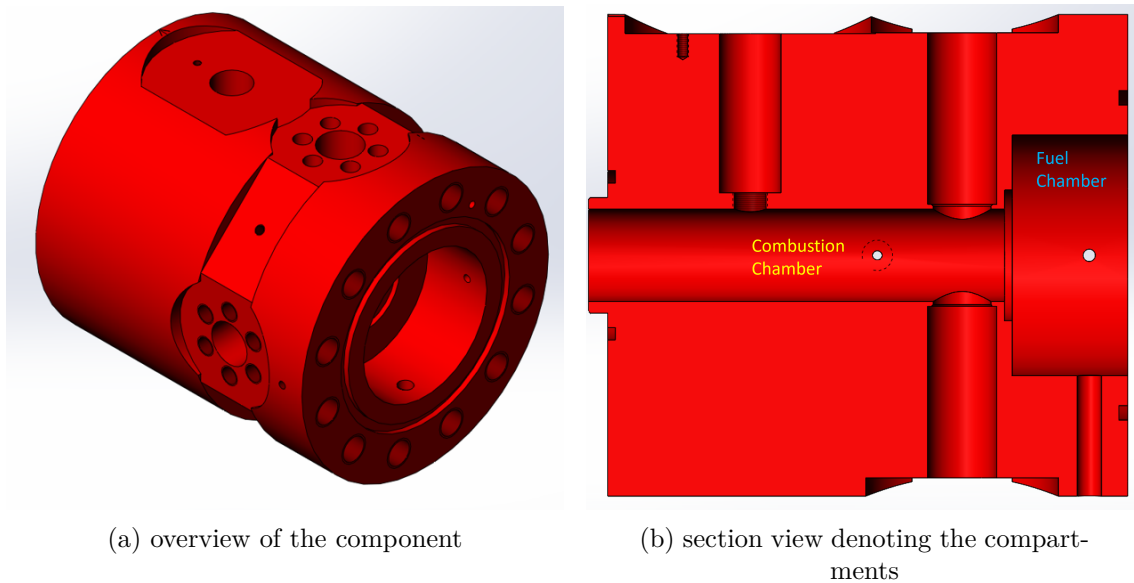


FIGURE 4.4: The combustion chamber

The designed component featured two compartments (Figure 4.4b), with the upstream compartment serving as a fuel chamber, and the downstream one facilitating combustion. The two compartments were separated by the micromix burner and a metal bellows expansion joint (Figure 4.5). The combustion compartment wall thickness was 100mm and its weak points were the circular windows where fused silica glass was installed. The large wall-thickness of the combustion compartment was considered enough to contain a possible small-scale detonation, although no such scenario was simulated. Potential damage to the combustion compartment's inner wall posed a risk of rendering it useless and requiring re-machining the whole combustion chamber component, thus delaying the experimental campaign significantly. To avoid such a scenario, a liner insert made of the same material was used as a sacrificial component (Figure 4.5).

Air and fuel flowed through the upstream compartment but were kept separate by the use of the bellows. Moreover, appropriate sealing was required between the combustion and fuel compartments. The metal bellows expansion joint, connected on one side to the micromix burner, and on the other side to the outer flange of the combustion chamber, served both purposes of keeping the fluids separate and compartment sealing (Figure 4.5). Air followed the axial direction coming from the upstream piping and flowed through the bellows, while fuel entered the fuel chamber radially and flowed around the bellows. The fuel flow path from the chamber to the injectors can be seen in Figure 4.8. More details for the fuel path are provided in section 4.3.3.

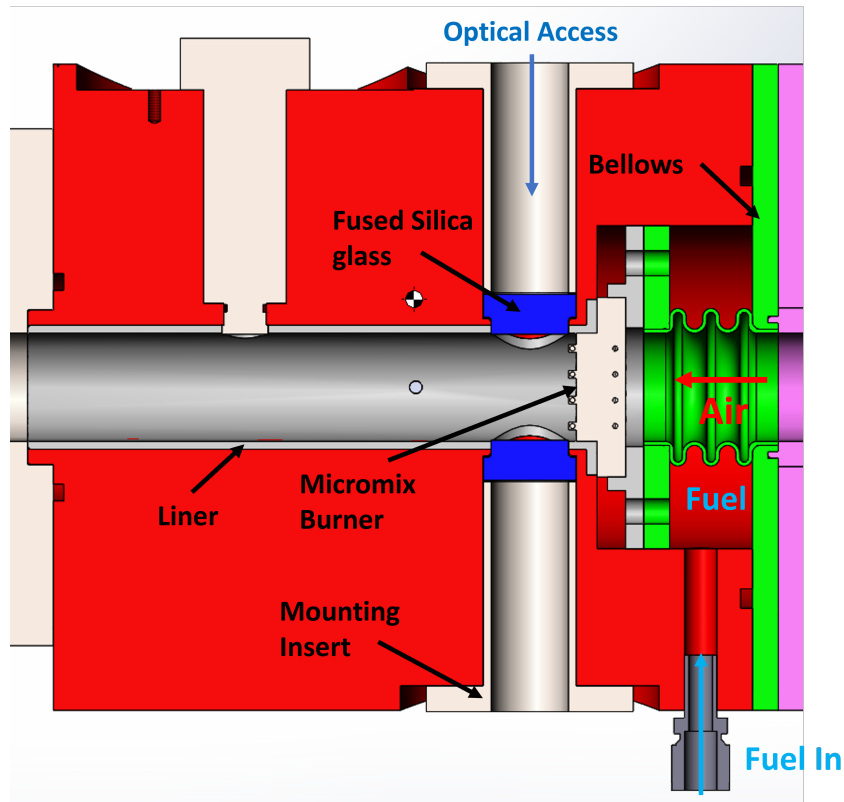


FIGURE 4.5: Section view of the combustion chamber. The liner, micromix burner, bellows and windows are denoted

The high thermal gradients between the hot combustion compartment and the cooler fuel chamber were expected to produce an axial expansion of the hotter part (Figure 4.6) that could compromise sealing between compartments. Simplified transient thermal and static structural analyses were performed with ANSYS Workbench (within the ENABLEH2 team) to provide information on the expected temperature distribution in the component and its deformation. For the thermal analysis convective heat transfer was used, with a temperature of $600K$ in the fuel chamber and a ramped profile from $600K$ up to $1350K$ in the combustion chamber and simulated operation for 40 minutes. The static structural simulation took into account a pressure of $15bar_a$ inside the two compartments of the chamber, remote forces of the support of the rig and utilised the results of the thermal analysis. The axial expansion of the sealing face was calculated to be about $1.5mm$ (Figure 4.7). Thus, the bellows were installed in a compressed state (by $3mm$ of their normal length) that allows retention of sealing at all conditions during operation.

For optical measurements, three circular windows, at 90° angles to each other, provided access to the flame front. Such a configuration allows the application of flame imaging techniques such as OH^* -Chemiluminescence and $OH - PLIF$. Figure 4.9

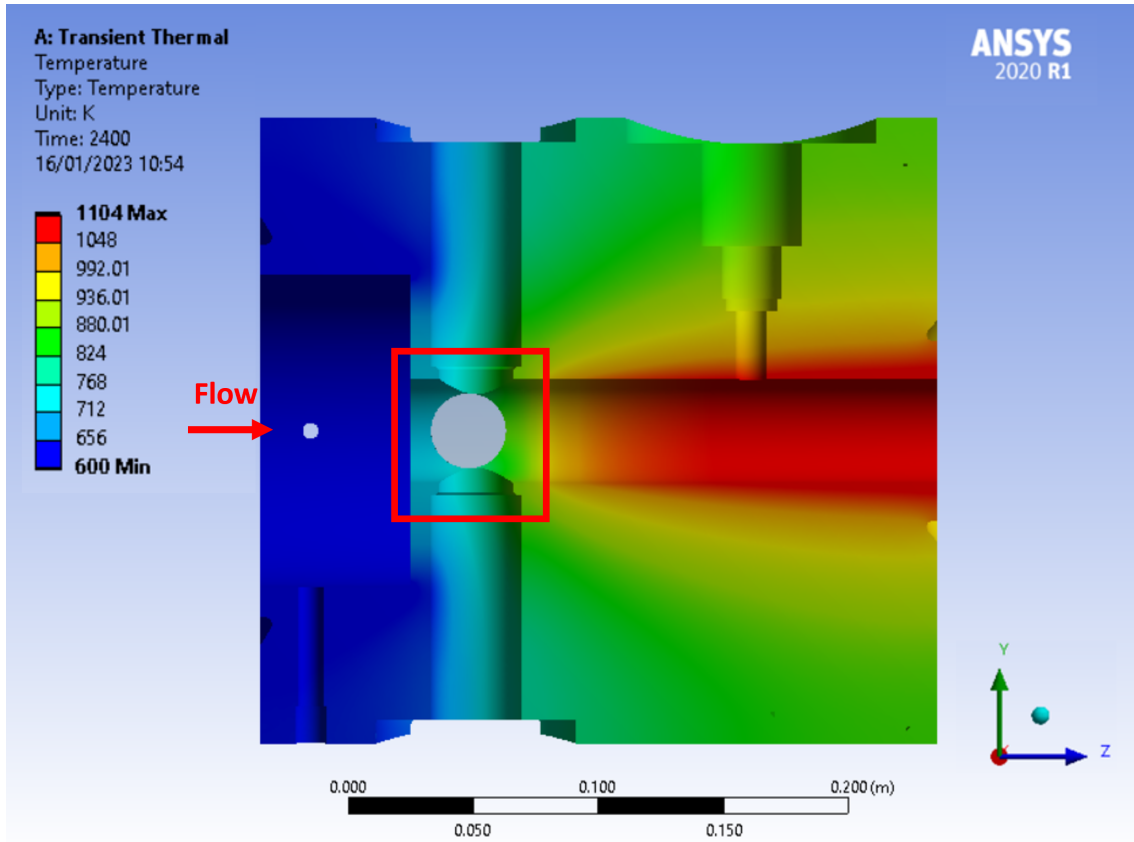


FIGURE 4.6: Temperature distribution of the combustion chamber from a transient thermal analysis on ANSYS Workbench. The red rectangle denotes the area of the optical access. *Note:* The direction of flow is opposite to what is presented in other figures to provide a view of all 3 windows.

shows aspects of the window assembly and its position relative to the injectors so that the flame stabilisation position can be visible. The optical material was positioned in such a way that the inner face of the glass and the inner wall of the chamber liner were at the same level. Fused Silica glass was the choice for the optical material. Its high chemical purity makes it ideal for imaging applications at a broad range of wavelengths, from ultraviolet (UV) all the way to infrared (IR). Moreover, it displays great mechanical strength at elevated temperatures, with continuous operation limits in the range of 1000°C .

Based on the results of the thermal analysis, the expected metal temperature in the region of the windows was between $700\text{K} - 900\text{K}$ in an axial gradient (Figure 4.6) at the most extreme condition of the rig and after 40 minutes of operation. Given that fused silica has a specific heat capacity (C_p) that is higher compared to that of stainless steel, the optical material was not expected to reach such high temperatures.

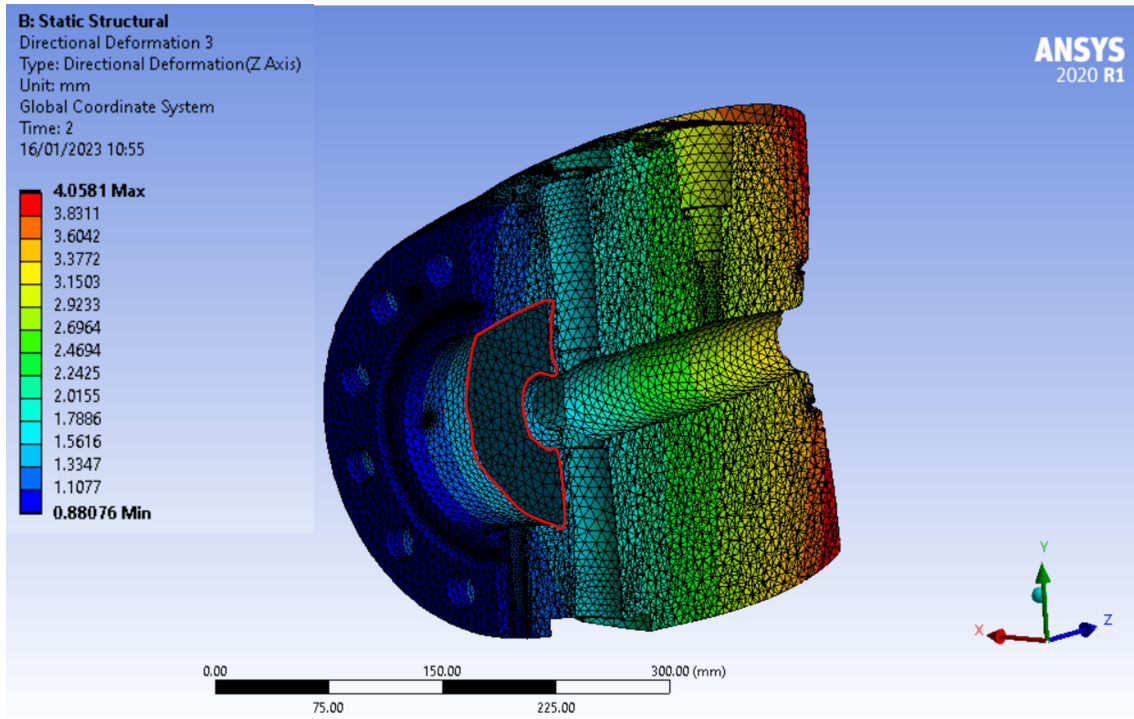


FIGURE 4.7: Deformation in the axial (z-axis) direction for the combustion chamber (half section). The sealing face is highlighted in the red curve.

With regard to the structural integrity of the optical material, some simplified calculations were performed in order to ensure that loads did not exceed the material limits. In the direction of its thickness, the glass is in compression and the compressive strength of fused silica is approximately 1150MPa . The maximum mechanical load (that of pressure difference if the mounting load is ignored) is 1.5MPa (see Table 3.1). The thermal stress in that direction, assuming a flat plate with uniform temperatures across the inner and outer faces, and a temperature difference between

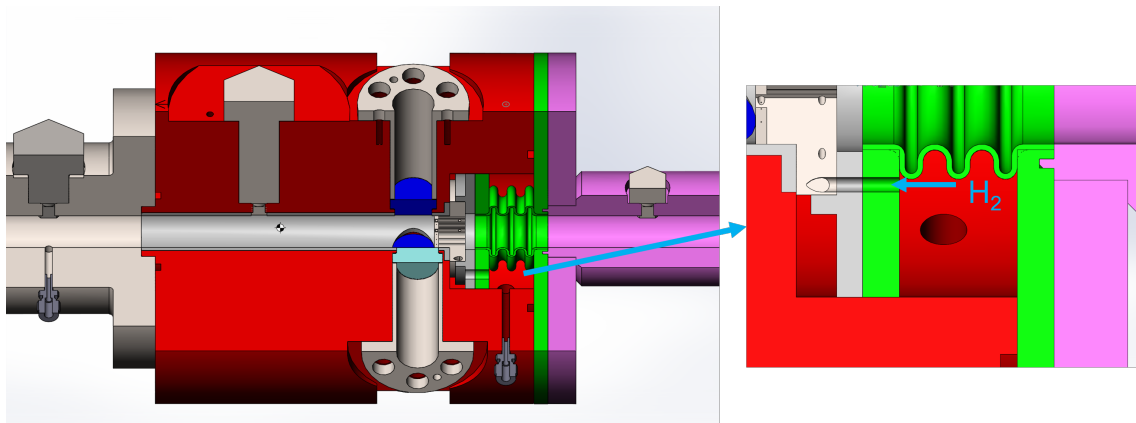


FIGURE 4.8: Fuel flow path from the compartment towards the injectors

the faces of $800K$ (extreme case) can be approximated by [56]:

$$\sigma_{th} = \frac{1}{2(1-\nu)} E \alpha \Delta T \quad (4.1)$$

with Young's modulus $E = 72.5MPa$, coefficient of thermal expansion $\alpha = 4.8 \cdot 10^{-7} K^{-1}$ and $\nu = 0.17$ Poisson's ratio for fused silica. Equation 4.1 yields a stress of approximately $16.8MPa$. The combined stresses in the direction of thickness are far from the material strength. It must be noted though that the assumptions for the calculation, such as uniform temperature across the faces of the glass do not hold true for this case (see Figure 4.6), and the calculation is a rough approximation. In the axial direction, where tensile stresses could occur, a temperature difference could be assumed to be roughly $300K$, in accordance with the thermal analysis on the metal chamber (red rectangle in Figure 4.6), according to [56]

$$\sigma_{th} = \frac{1}{(1-\nu)} E \alpha \Delta T \approx 13MPa \quad (4.2)$$

a value which is lower than the tensile strength of $42MPa$ of fused silica. A calculation for the minimum thickness of the optical material, able to sustain tensile stresses was performed, taking into account only mechanical loads [35] as follows:

$$t_{min} = \left(\frac{1}{2}D_0\right) \left[\frac{K_w SF \Delta P}{\sigma_{des}}\right]^{1/2} \quad (4.3)$$

where t_{min} is the minimum thickness for the supported part of the optical material, D_0 is the aperture of the glass ($30mm$ for our field of view), K_w is a constant regarding the mounting situation of the glass, SF is a safety factor and $\sigma_{des} = 25MPa$ is the allowable design stress, taken as half of the tensile strength of fused silica in this case. This calculation, with a safety factor $SF = 2$, yielded $t_{min} = 4.5mm$. Since the calculation did not account for thermal stresses, the calculated supported thickness was doubled to $9mm$ for safety.

In order to avoid disturbance in the flame shapes and characteristic micromix patterns, the total thickness of the material was $15mm$, bringing the inner face of the optical material almost flush with the inner wall of the liner, as already discussed (Figure 4.9b). In an effort to protect the inner surfaces of the optical material, the air channels at the circumference of the micromix burner (Figure 4.10) do not bear fuel injectors, creating a film of inlet air on the inner side of the windows. A chamfered step, machined on the inner wall of the combustion compartment supported the optical material. On the outer side, a thin-walled insert bolted on the outer surface of the chamber kept the glass in place (Figures 4.5 and 4.9a). Careful

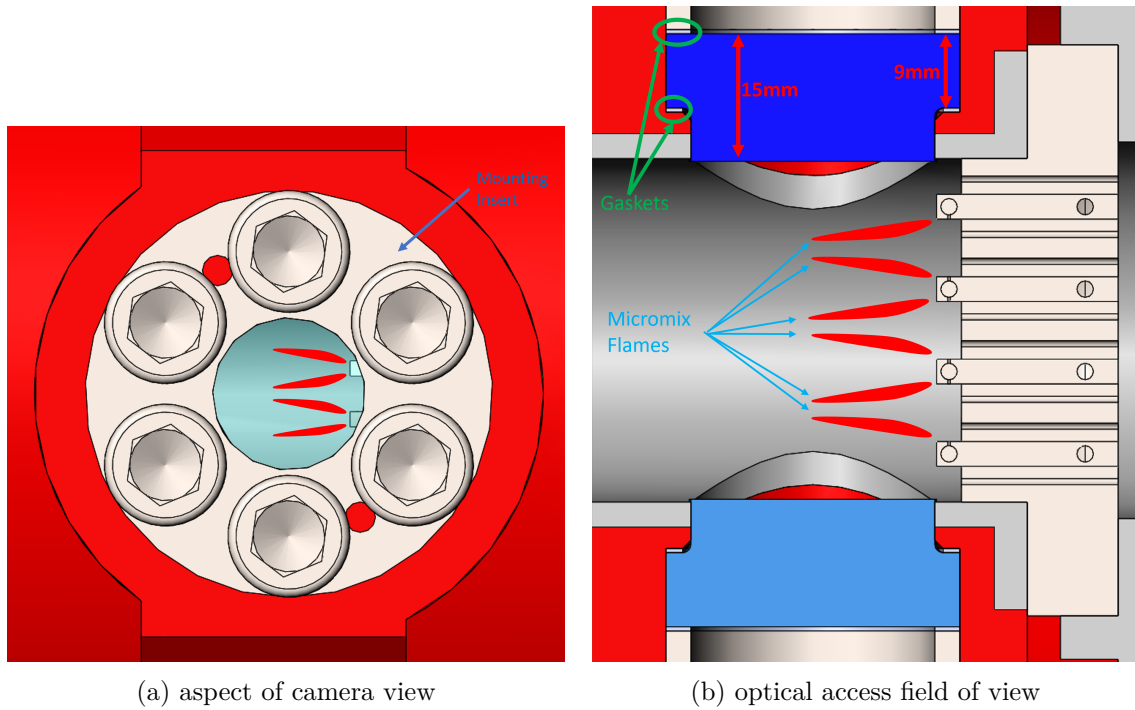


FIGURE 4.9: cAD representation of the window assembly with micromix flames depicted.

consideration was required in the choice of gasket material. Glass-to-metal contact must be avoided and adequate sealing is critical to avoid hot gas leaks. The gasket used closer to the flame, on the bottom side of the glass, was made of Thermiculite[®] 870 sealing material. Although it showed great sealing characteristics and stability at high temperatures, its brittleness requires careful handling. Between the glass and the top insert, Thermiculite[®] 815 was used, as a less expensive, temperature resistant and easier-to-handle alternative. The reason the 815 was not used in both cases, is that when positioned closer to the flame, hot gas leaked and scorching marks were observed on the gasket.

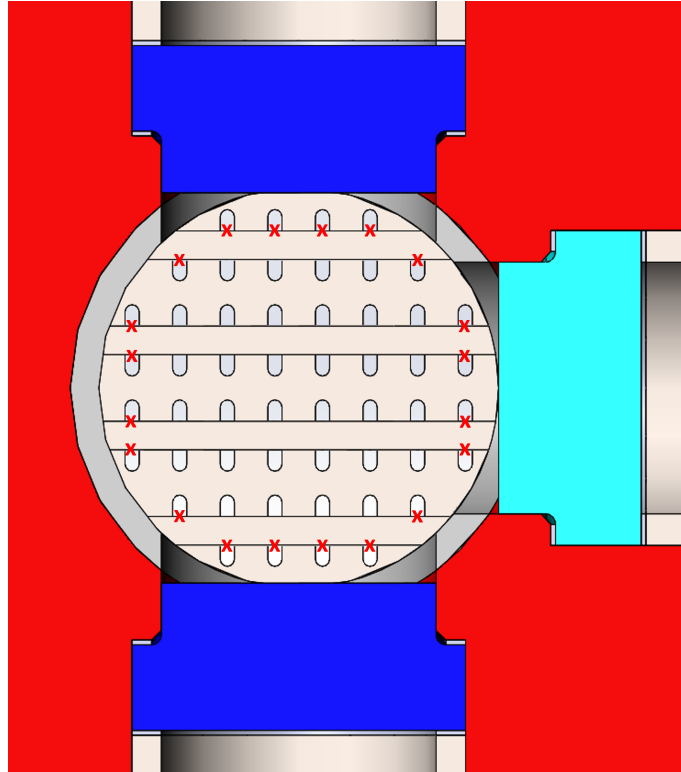


FIGURE 4.10: Front view of the combustion chamber in section. The micromix burner is visible. Red "X" symbols denote the no-fuel supply channels.

4.3.3 Micromix Burners

The main challenges presented for the micromix burner design were the following:

- safe fuel delivery to the injectors

The small size of the combustion dome and the restricted space inside the fuel compartment made installation and ease of assembly/disassembly of fuel delivery equipment to the burner difficult.

- machining of sub-millimetre features

As already mentioned, the fuel injection points for the tested burners were 0.3mm in diameter. From a manufacturing point of view, machining holes of 0.3mm in diameter, with consistent dimensional and positional tolerances, is a challenge in itself.

Two approaches were considered for the micromix burner design: that of a modular, multi-piece part and the alternative of a one-piece component. A modular design (Figure 4.11), allowed for traditional, material-removal methods to be applied and had the potential of keeping the cost low. The design featured a split between the

air channels and the fuel injectors into two panels (Figure 4.11), where the hydrogen panel was also made up of smaller welded components. A modularised hydrogen panel had the benefit of accommodating the application of electrical discharge machining (EDM) for the sub-millimetre injectors with no specific problems.

Although it appears to be a simple solution, the modular design involves several machining processes including welding in areas of the part with limited accessibility (Figure 4.11). The presence of weld beads would affect the flow characteristics and moreover, potential imperfections on the bead could create leak paths for hydrogen. Residual stresses from welding could also create shape distortions on the thin-wall sections. An alternative to welding was bolting the injector component to the air-channel component at 4 points, but again the risk of hydrogen leaks was high as bolt pressure distribution along the interface between components would not be smooth.

Fuel delivery to the injection points was complicated too, as homogeneous fuel distribution was required for all injectors. In order to achieve that a fuel line would be necessary from each side. Moreover, leak-free and easy-to-assemble connections were required, but as already mentioned, space constraints did not allow for a neat solution.

A similar alternative was that of a one-piece hydrogen panel not requiring the welding of small bits together with EDM applied for the micromix injectors. This solution was applied to create a test piece injector plate. The main issue observed was that the EDM tool needed to perform line-of-sight machining through the full length of the part. Such a thin tool can break when going through the metal, or deviate from the straight-line axis, and produce hole sizes different to the desirable (Table 4.1 - EDM case), as was the case for the created test piece.

A one-piece design for the full burner implementing metal additive manufacturing (AM), avoids many of the issues mentioned above, with regard to the different machining processes and sealing issues. More importantly, by implementing channels internal to the body of the component, fuel delivery is simplified and potential fuel leak paths are significantly reduced. The flow of cooler fuel on the inner side of the wall close to the flames (injector-side channels-Figure 4.12a) also assists with cooling the component. On the downside, the design needs to be adapted for AM and this can have implications for the flow characteristics of both the fuel and air. Surface roughness is high in as-printed components and post-processing of the part is required to smooth external faces, especially when it comes to wetted surfaces. Finally, the cost of AM-produced parts can be significantly higher compared to traditionally machined components. On the side of the fuel injection points, such

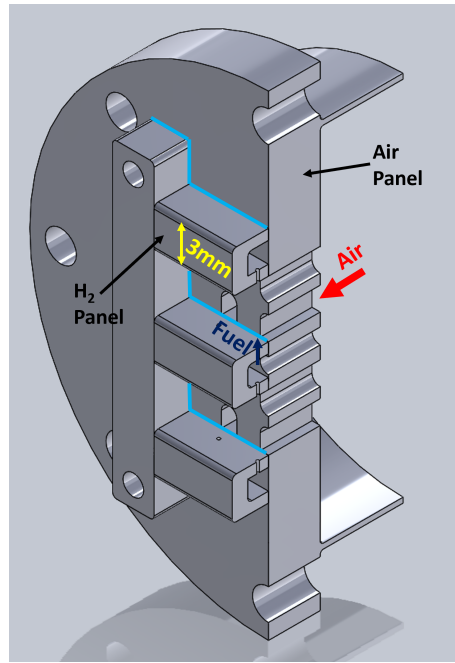


FIGURE 4.11: CAD section of a modular version for the micromix burner. The blue lines denote weld beads.

features are on the limits of the capabilities of AM machines and dimensional quality is not guaranteed.

In order to identify the possibility of creating a complete (with air channels and fuel injectors) one-piece burner with additive manufacturing, test plates with through-holes of different sizes (from 0.3mm to 1mm) were created. Two additive manufacturing techniques were applied, and the results can be seen in Table 4.1). It is evident in pictures taken with the help of an optical microscope of the features of interest that AM produces unacceptable dimensional and geometric tolerances for 0.3mm features. The big dimensional deviations of AM-produced holes may be attributed to the building orientation of the components and further research would be required on that aspect.

A potential solution for the injectors was micro-EDM, an EDM technique by which very small features can be created by the use of miniaturised electrodes that allow machining without line-of-sight, a characteristic which was crucial for this design. Test pieces with the featured holes provided the best results (Table 4.1) with dimensional tolerances of $\pm 10\mu\text{m}$. These tolerances were considered acceptable for the micromix concept at this stage of development. The cost associated with the application of micro-EDM though is high, especially when a small number of parts is produced.

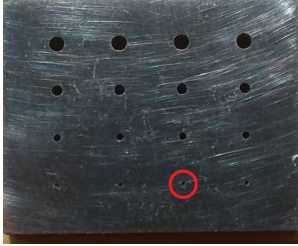
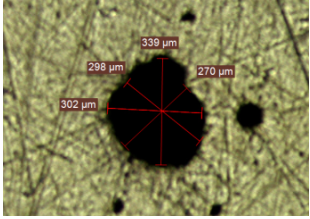
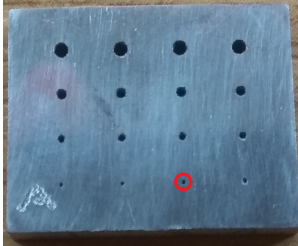
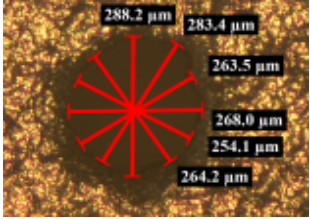
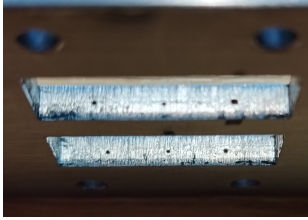
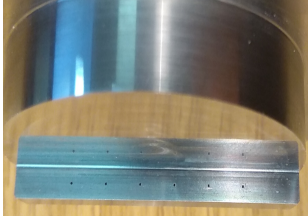
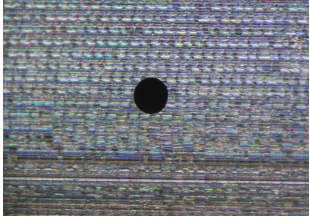
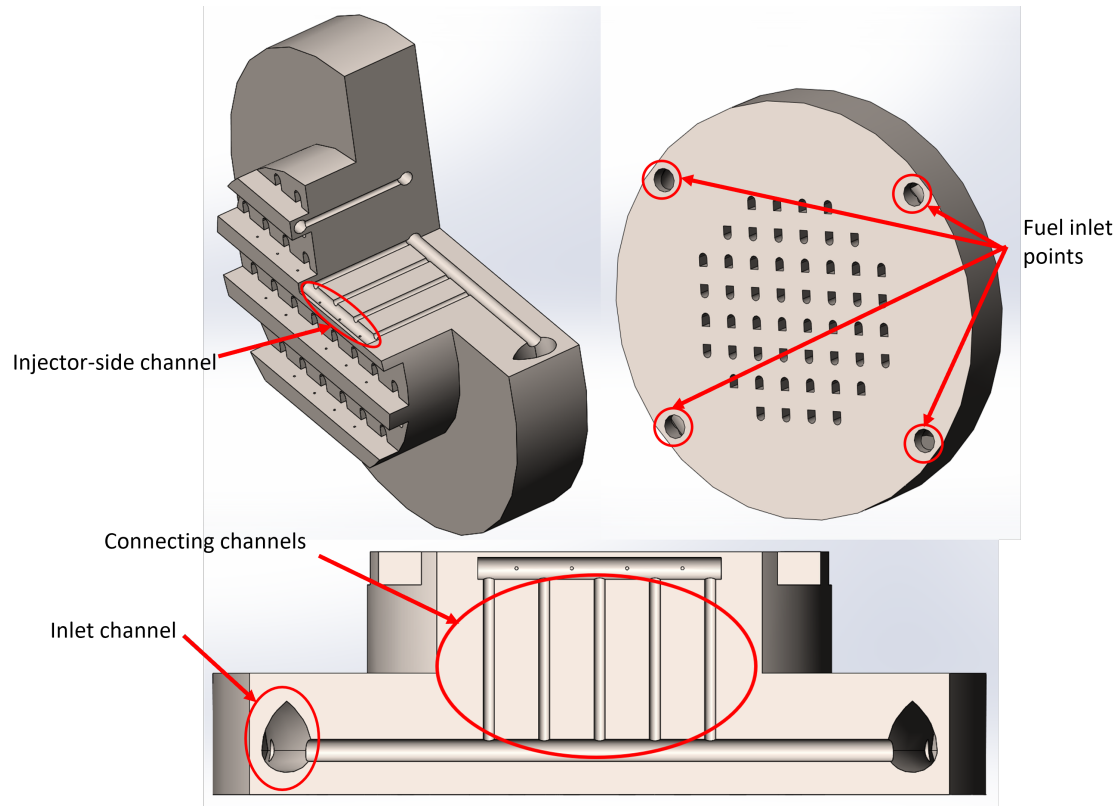
Material	Technique	Test Piece	Representative Image of inspected nominal 0.3mm hole	Tolerances on nominal diameter
Alloy 625	DMLS			-30 μm to 39 μm
Stainless Steel 316L	BJT			-46 μm to -12 μm
Stainless Steel 316L	EDM		N/A	N/A
Stainless Steel 316L	Micro-EDM			-10 μm to 10 μm

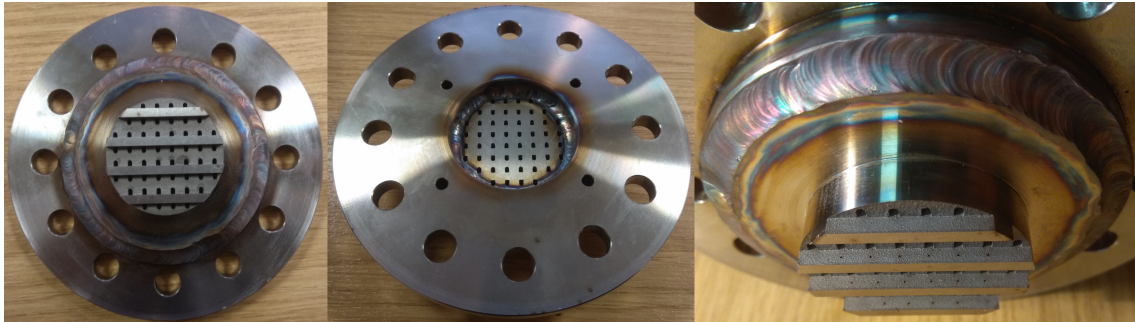
TABLE 4.1: Comparison of 0.3mm diameter holes, fabricated with different processes. *DMLS=Direct Metal Laser Sintering*, *BJT=Binder Jetting Technology*, *EDM = Electrical Discharge Machining*

The one-piece approach was adopted, in a hybrid manufacturing process combining AM and material removal machining and the selected material was Stainless Steel 316L. The main body of the burner was produced by Direct Metal Laser Sintering, an AM technique and excluded the 0.3mm holes from the process. The sub-millimetre features were produced by micro-EDM. The result was a compact design with reduced potential paths of leakage (Figure 4.12).

The suggested design and manufacturing strategy also have drawbacks. The total



(a) details of the one-piece micromix burner (CAD model)



(b) aspects of the manufactured micromix burner welded on a flange

FIGURE 4.12: Prototype micromix burner

thickness of the component results in lengthy air gates that yield increased pressure loss along the burner. This was a compromise between retaining easy fuel access (through the inlet channels - Figure 4.12a) and avoiding complex support structures during the additive manufacturing process. Moreover, the internal channel structure complicates powder removal (necessary after the AM process) from the injector side channels (Figure 4.12a) since the only exit points are the fuel inlets (Figure 4.12a). The latter was not an issue in the low and medium momentum flux ratio (MFR) designs. For the high MFR design though, because the injector-side channels were smaller in diameter, these were left open on their sides (Figure 4.14) for easier powder removal and were welded with filler material afterwards. Further to that,

a number of fuel injectors could not be opened by the micro-EDM process. It is suggested that the internal channel was not printed properly, or partly collapsed. This theory should be checked by non-destructive-method testing, such as X-ray imaging. Subsequently, this configuration was tested with 27 out of 32 fuel injectors (Figure 4.13).

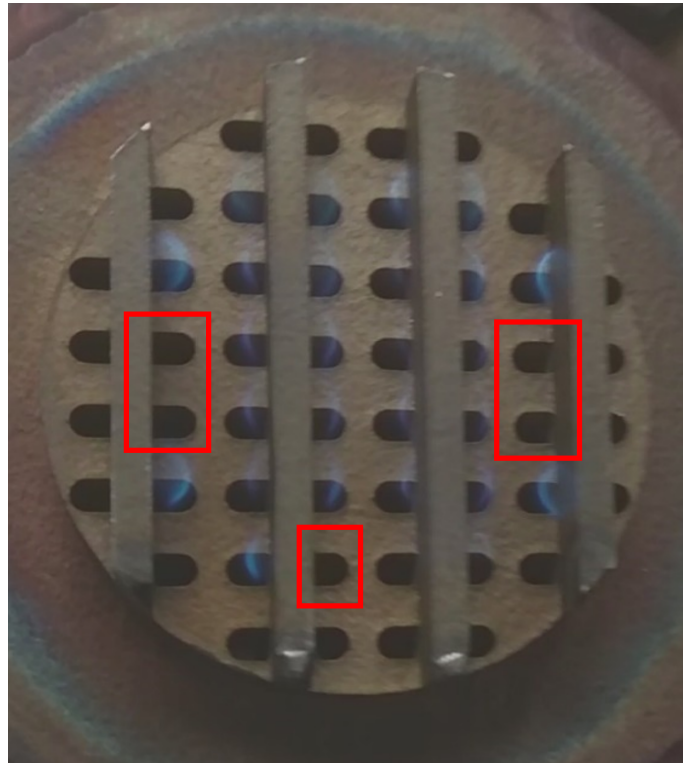


FIGURE 4.13: Propane test for the high MFR design. Red rectangles point out the blocked fuel injectors

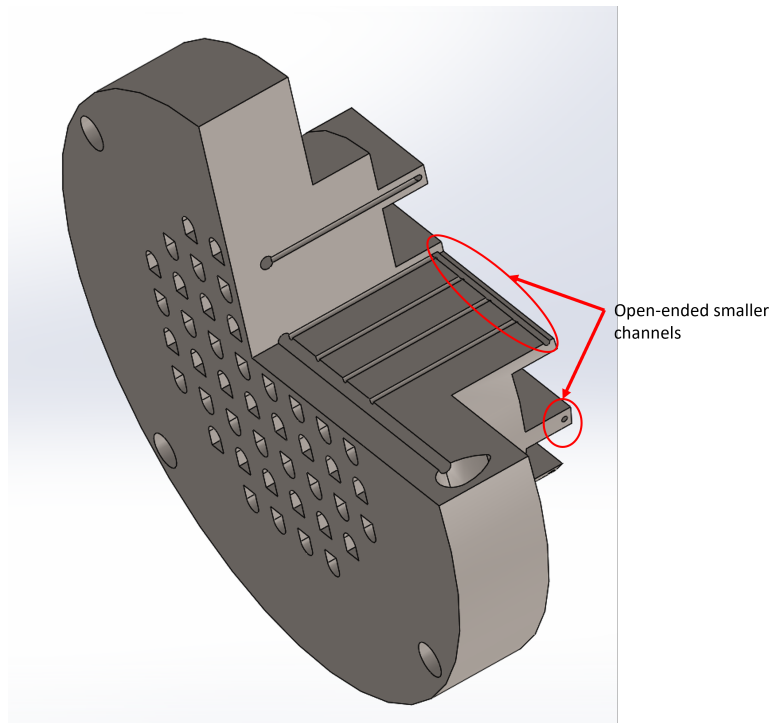


FIGURE 4.14: Detail of open-ended channels for powder removal of high MFR design

4.4 Health and Safety Considerations

4.4.1 Approach to Health and Safety

The main risk posed by hydrogen is that of undesirable deflagration, which can occur at a very wide range of concentrations in air. In combination with the high diffusivity of the molecule, and the ease with which it escapes through the tiniest available paths, the risk of creating flammable concentrations in the atmosphere can be high if appropriate measures are not taken. In a laboratory installation where storage and transfer are necessary, creating a safe environment can be challenging. Some safety measures have already been presented in the sections describing the fuel supply system (4.3.1), the combustion chamber (4.3.2) and the micromix burner (4.3.3). A broader view of the approach around hydrogen safety is presented here. This approach was based on the implementation of safety features on three different levels:

1. prevention of undesirable leakage
2. early detection and action in case of leakage

3. prevention of build-up of dangerous concentrations

Measures to avoid a potentially dangerous occurrence start with preventing fuel leakage. The selection of appropriate materials and components and installation by experienced personnel can guarantee a leak-free setup. Due to the elevated pressure at which hydrogen was stored and transferred in this application, stainless steel 316 and brass were selected for the components in contact with hydrogen. Moreover, the one-piece, compact burner design minimised potential leak paths and undesirable fuel/air mixing before the combustion compartment.

On the second level, in case a hydrogen leak occurs, one needs to keep in mind the low value of the lower flammability limit of hydrogen (4%vol. in air). In such a scenario it is very important to be able to detect it early and act fast to prevent the buildup of flammable hydrogen mixtures. For the experiments described in this thesis, detection relied on two hydrogen leak detectors installed in the test house. These were positioned high on a side wall nearest the rig and set off an alarm if concentrations of hydrogen at 25% of the lower flammability limit were detected. In such an event, quick action meant a cut-off of the fuel flow and a purge of the system with nitrogen. Fuel cut-off and nitrogen purging were achieved by the normal operation of the fuel system control, switching to a shut-down mode or two emergency stop buttons, one of which was installed close to the rig and one inside the control room. It should be noted that the stop buttons only shut down the fuel but did not activate the purge line. Thus, the preferred route was to perform a normal shutdown.

As a third level of protection, in case of a fuel leak that wasn't detected early on or continued (e.g. ruptured fuel-line tube) build-up of flammable atmospheres was avoided. This was necessary, particularly for restricted spaces where hydrogen could pool on a low ceiling. Prevention of flammable concentrations was achieved through natural and forced ventilation of the test house. Natural ventilation meant that the doors of the test house were kept open at all times during testing. Forced ventilation was achieved by the use of fans circulating the air, forcing it away from the ceiling of the building, or certain enclosed spaces inside the test house (Figure 4.15). Operationally, the procedure instructed that staff were to assume the potential existence of an invisible flame. The approach to the test cell should be done with caution and it was advised that a wooden stick (or similar object) be held in front of the person approaching, to allow the detection of a potential flame.

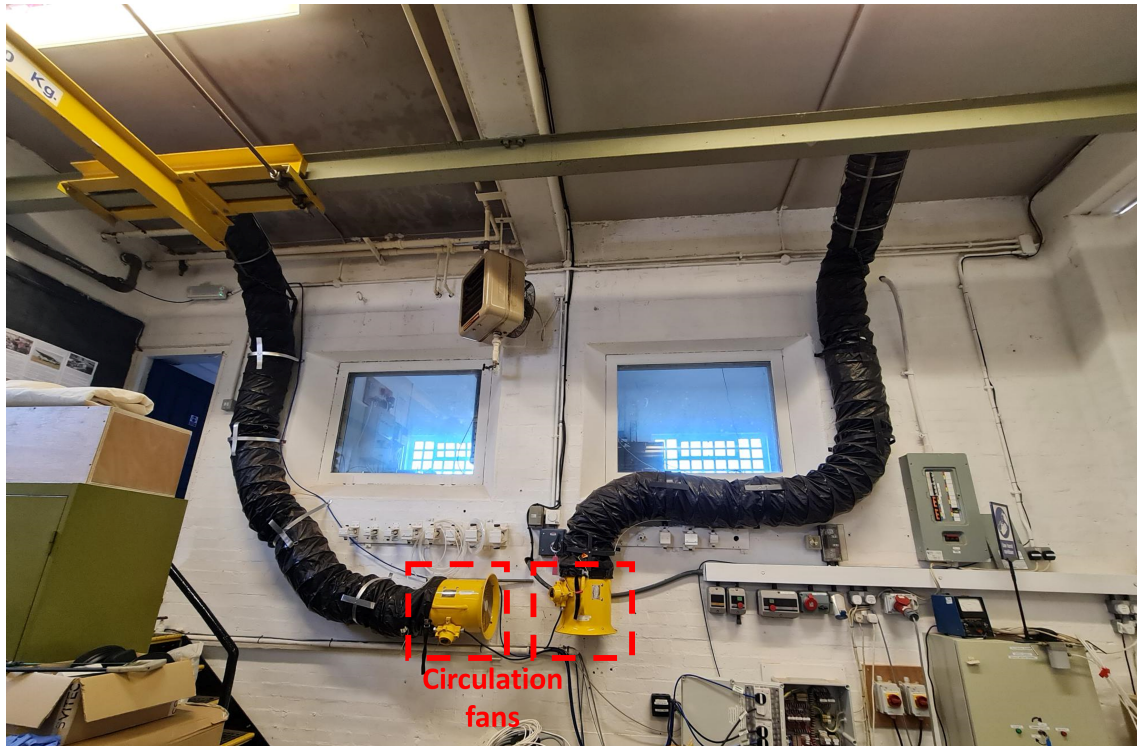


FIGURE 4.15: Fan-forced ventilation of the area close to the ceiling

4.4.2 Lessons Learned

The experience of working with high-pressure gaseous hydrogen teaches some valuable lessons, to be considered in further experimental studies. Safety for hydrogen shall be considered in all aspects of an experiment, from component design and material selection to operational procedures, and human factors.

Overall, in terms of health and safety, some of the key takeaway lessons are:

- design-wise, the minimisation of potential leak paths is crucial. This refers to the design and manufacture of rig components (e.g. one-piece designs for critical components), as well as the fuel supply system design (e.g. minimising the use of tube-connecting components). Material selection is also crucial for hydrogen-related components, as these need to be resistant to embrittlement, as well as able to operate at extreme temperatures (in the case of a combustion rig)
- standard operating and emergency procedures need to be adapted to the use of hydrogen
 - Under normal operation, hydrogen needs to be introduced to the rig gradually and the process must be monitored for stable ignition

- The time required to ignite varies for different inlet conditions. Failure to ignite shall lead to a cut-off of the fuel supply and purging of the whole system before ignition is re-attempted. An attempt to re-ignite without purging bears the hazard of an undesirable detonation
 - in an emergency, stopping the fuel supply is not enough and again, purging the whole system is advised
 - in terms of human factors, operators should always proceed with caution after an emergency stop/leakage occurrence as there may be flames present that are invisible
- development of appropriate standard operating procedures and familiarisation of the personnel with such procedures can significantly lower the risk of a hazardous event happening
- commencement of the operation of a new rig should start with the lower risks possible. Without combustion and at low pressures and temperatures initially, and then gradually increasing the testing complexity. Such a process reduces the chances of dangerous situations occurring and allows time for the operating procedures to also be tested and be improved
- leakage occurrences at high fuel supply pressure, during testing, showcased the successful operation of the safety system and procedures but also highlighted the fact that even some of the most trustworthy, commercially available components (tubing, fittings etc.) may not be suitable for operation with gaseous hydrogen at high pressures. In such applications, close collaboration with the supplier of such components is required
- safety requirements for hydrogen and desirable measurements (along with their safety aspects) can sometimes contradict each other and lead to compromises. For example, the requirement to keep open the test cell doors for natural ventilation, clashes with the requirement to isolate and interlock the test cell when applying laser-based measurements with high-power lasers. Of course, there are solutions to such issues, but one needs to keep in mind such potential compromises.

4.5 Preliminary Testing and Setup Improvements

Prior to commencing the main experimental campaign, a period of rigorous testing is always necessary. Starting with low intensity, at atmospheric inlet conditions, without combustion the behaviour of the rig was observed. A gradual increase in pressures and temperatures and the introduction of combustion provided a smooth and low-risk process of ensuring the safe operation of the rig. Moreover, it allowed the operators to understand the complexity of the system, familiarise themselves with the procedures in place, and make improvements to these procedures. Preliminary testing also allowed the detection of flaws and omissions in the original setup at an early stage and provided an opportunity for improvements.

In the case of this rig, the preliminary testing campaign revealed several issues regarding the emissions measuring setup and the optical access equipment. In the case of the emissions measurements, some improvements were applied but further changes are still required to achieve the desired measurement accuracy. For the optical access, the issues could not be solved in the available time frame.

4.5.1 Emissions Setup

The emissions setup during early combustion tests proved insufficient for measurements. It consisted of a 3-hole (2mm diameter each) sampling probe, the heated sample line, a venting needle valve, the drain separator, and the electronic cooler unit and gas analyser. This setup presented issues with:

1. the position of the original sampling probe and sample dilution The proximity of the sampling probe to the back-pressure valve cooling configuration had an effect on the measurement, consistently yielding very low NO_x values. It was discovered that the closeness of the probe to the back-pressure valve cooling configuration affected the measurements although it was not completely understood in what ways.
2. sample quantity and pressure regulation At lower pressure cases, the pumps of the gas analyser and electronic cooler unit could not draw enough sample quantity for the analyser to measure. At higher pressure tests, the venting valve was used to regulate sampling line pressure to levels acceptable by the gas analyser. The venting of part of the sample caused an increase in flow through the heated sample line, leading to its overheating.

3. the high concentrations of water vapour and lack of heated equipment led to condensation being formed in the tubing and to the water removal devices (drain separator and electronic cooler unit) being unable to remove all the amount of water.

The first issue was tackled by a $1m$ tube section that was introduced between the probe and the back-pressure valve.

The pressure and sample quantity issue was dealt with by replacing the 3-hole probe with a new, 1-hole probe and introducing a pump downstream of the heated sample line. The revised probe, bearing only one hole of $0.5mm$ in diameter choked the flow at the inlet, regulating the pressure at that point. Since the pressure drop occurred inside the probe, the subsequent sample temperature drop which could lead to water condensation was compensated by the heat of the surrounding gases. Downstream of the probe, sample suction and pressure regulation were achieved by the installed pump. This configuration significantly reduced overheating incidents of the heated sample line.

Avoidance of water condensation was attempted by introducing an extra drying stage (membrane dryer) right downstream of the pump. The dryer assisted the other two water removal devices in an effort to reduce the condensation in the tubing, by removing an amount of water vapour right after the pump. This setup was adequate for lower pressure and inlet temperature cases, but at higher inlet conditions, condensation was still evident in the tubing between the non-heated components. Time restrictions and high lead times on components required did not allow for further improvements, and this setup was used during the main experimental campaign as already mentioned in Chapter 3.

4.5.2 Optical Access

The configuration of the optical access, along with the cooling provisions has already been described in a previous section. Despite the existence of a form of cooling for the windows, the lifespan of the fused silica glasses proved to be short. Small surface cracks appearing after a few hours of operation, were the first sign which eventually led to the removal of layers of the material and subsequent loss of transparency and visual access to the flames (Figure 4.16).



(a) inner view of glass. Layers of the material have broken off

(b) outer view of damaged glass

FIGURE 4.16: Damaged windows in the installation position. Removal of layers is evident.

It is believed that the cooling configuration was not as effective as had been expected and extreme gas temperatures developed near the optical material. Moreover, thermal cycling attributed to the operating procedure in place is believed to have significantly reduced the life expectancy of the fused silica glasses and is believed to have been the main reason for their failure. The operating procedure dictated immediate shutdown and nitrogen purging of the rig at the end of a day's tests or for safety reasons leading to abrupt cooling and, in cases of shut-down and re-ignition, reheating. The temperature differences in small time intervals must have been extreme.

A suggested and temporarily applied solution was to move the optical material at a distance from the flames to reduce the cyclic thermal loading. This though created recirculations within the empty space left by retracting the glasses. These recirculations destabilised the flames and created distorted patterns not representative of micromix.

A more appropriate solution is to redesign the window assembly and hence the combustion chamber to include active cooling, as well as improve the operating procedure. A redesign and manufacture of the whole combustion chamber were not feasible within the available time frame and are left for future work.

4.6 Limitations of the Experimental Setup and Suggestions for Improvement

4.6.1 Control of Inlet Conditions

Precise control of the air pressure, mass flow and inlet temperature was a challenge, due to fluctuations in the supply, caused by the compressor. The control of these parameters relies on the compressor pressure setting and the position of a control valve in the air-line primarily, and to a lesser degree on the position of the back-pressure valve. Hence, they all depend on each other and a change in supply pressure for constant valve positions leads to mass flow and temperature changes. Compressor operation, as already stated causes small, low-frequency pressure fluctuations around the set value, which translate to mass-flow fluctuations. These fluctuations can be neglected when the compressor supplies at 2kg/s . But when by regulating the valves, the supply is limited to flows of the order of 0.1kg/s , these fluctuations become important. This imposes a limitation on how accurately the inlet conditions can be controlled and the effect is apparent when repeats of a case need to be performed.

Potentially, the introduction of a flow settling chamber right upstream of the test section could reduce the magnitude of such fluctuations and improve control of the inlet parameters. A more appropriate, lower flow capacity air supply system could also help alleviate the problem, although that is a much more costly solution.

4.6.2 Design Imposed Limitations

Fuel Temperature Monitoring

One of the limits of the current setup is that fuel injection temperature cannot be measured. Although no fuel preheating was part of the experiment, the design configurations of the fuel chamber and the micromix burner certainly led to increases in fuel temperature. The feature of fuel flowing around the bellows expansion joint that carries the inlet air leads to an increase in fuel temperature when the inlet air is hot, due to heat transfer through the bellows. Moreover, the internal channels of the burner that distribute fuel along the injectors are separated by the flames through a thin metal wall. Given the high flame temperatures, it is believed that heat transfer rates from the flames to the hydrogen channels were high, and fuel temperature increased even further. In many cases the operation of the rig was

transient, meaning that the fuel temperature potentially fluctuated throughout the experiment even at a certain operating point. This may imply an effect of changing fuel temperature on NO_x , and further research is required to assess such a scenario.

The current design of the burner for fuel delivery does not allow easy measurement of the fuel temperature. A potential estimation could be provided by incorporating thermocouples on the wall of the hydrogen segments from the side of the flame and estimating the fuel temperature through heat transfer calculations. Positioning thermocouples in extreme-temperature regions though carries the risk of damaging them and not getting measurements. It also adds design complexity in terms of instrumentation installation in the combustion chamber.

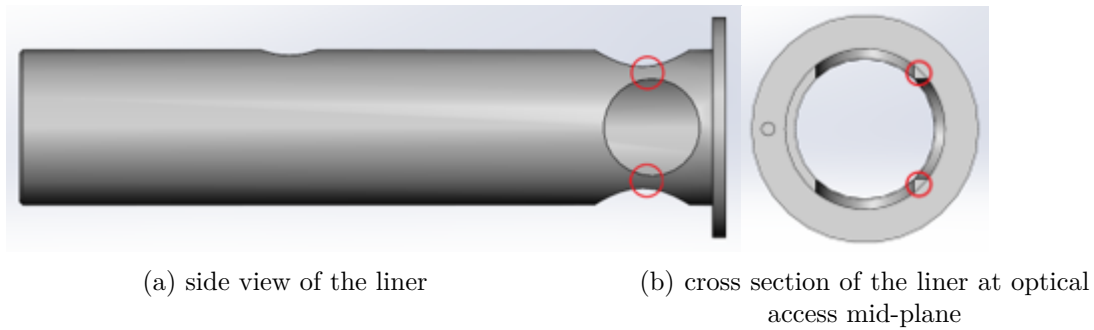


FIGURE 4.17: Limitations on the field of view. Red circles denote the weak points on the liner.

4.6.3 Flame Imaging

Flame imaging data collection was significantly limited, due to the optical access issues described in section 4.5.2. This meant that OH^* -Chemiluminescence could only be applied in a small number of cases at the lower end of inlet conditions (atmospheric pressure and inlet temperature) that are not presented in this thesis.

From a design aspect, the field-of-view was limited to $30mm$ in diameter, although at certain low-pressure conditions, flames of approximately $50mm$ of length were expected. This limitation is related to the shape of the optical access and the size of the combustion domain. Circular windows, compared to rectangular, allow for lower stress concentration and are easier to machine. Given that the inner wall of the liner is $42mm$ in diameter, 3 consecutive openings of $30mm$ create thin-walled areas between them (Figure 4.17) that can compromise structural integrity. Anything larger than $30mm$ would create one large open space, and disturb the flow field.

A redesign of the combustion chamber would be required, with a cooled configuration for the optical access material, in order to improve the chances of survival of the optical access and enable the applications of diagnostics such as flame imaging. Further to that, a change in operating procedures can have a significant positive impact on the life of the windows: A smooth heating procedure of the rig till a steady state is achieved, before initiating combustion, and a smooth cool down before shutdown, to avoid extreme thermal cycling. The latter suggestion though will require a significant amount of time and may restrict the number of tests performed in a day. Moreover, rectangular windows could be designed with rounded edges, a small height and extended length, to improve the field of view without compromising the structural integrity.

4.6.4 NO_x Emissions Measurements

The limitations of the gas analysis setup in terms of hardware are associated with the high degree of customisation of the setup and the inability to acquire more suitable components on time. Specifically,

- the custom one-hole sampling probe could not guarantee a representative sample since the hot gases may not be fully mixed out and NO_x may be distributed in the chamber cross-section. Instead, a *multi-hole* probe with appropriate cooling is suggested, as discussed in [54]. Care would need to be taken in the design of a new probe with regard to its dimensions, as the available space in the rig is limited and a big probe could impose significant blockage to the flow
- the use of unheated components, such as the pump, and long lengths of unheated tubing allowed further condensation of water vapour which is known to affect the measured NO_x
- the use of a membrane dryer is not suggested as with this type of dryer NO_2 may be removed from the sample. Instead, an appropriate water removal device shall be used. Another solution is that of a gas analyser that can perform the measurement with the gases at high temperatures, although drying the sample is still suggested.
- the main gas analyser unit is outdated and technical support and maintenance were difficult. Moreover, as a portable instrument, it facilitates all sensors for the different gases in a single unit. Hence, the sample needs to be dry and at a low temperature, which is associated with the limitations discussed already.

To that end, Cranfield University is in the process of acquiring a new emissions measurement system.

In terms of measurement quality, high measurement uncertainties¹ are the limiting factor in the gas analysis setup. The implication of such high uncertainties is that a quantitative assessment of the performance of hydrogen micromix combustion becomes difficult. Moreover, careful consideration is required before utilising the data for the validation or calibration of numerical models.

The high uncertainties were a result of the incorrect selection of calibration gas and instrument range. The initial estimation of expected NO_x emissions from micromix was of the order of a few hundred ppm for the higher end of testing conditions (high pressure, high inlet temperature and high equivalence ratio). A range of 500ppmv was selected on the instrument and a NO calibration gas cylinder with a nominal concentration of 400ppmv and an uncertainty of $\pm 5\%$ as it was the one closest to the chosen range. Preliminary testing revealed that even for these conditions the NO_x produced were significantly lower. For the lower end of test conditions, emissions were one, and in some cases two orders of magnitude lower. An effort to obtain a more appropriate calibration gas cylinder of lower concentration and lower uncertainty was unsuccessful due to the high lead times in the delivery of the gas. To achieve lower uncertainties, the calibration gases need to be selected in the appropriate nominal concentrations followed by suitable instrument range selection, depending on the expected emissions values of different test conditions.

Another disadvantage of the setup was water condensation, which also had an effect on the measurement uncertainty. The effect of water condensation though could not be quantified (see Section 3.7.4). The alleviation of the water condensation issue has already been discussed.

4.7 Chapter Summary

This chapter discussed important aspects of the development process of a hydrogen combustion rig by presenting the experimental apparatus that was recently developed at Cranfield University. Focus was placed on critical systems and components and the challenges of their design, implementation and operation. In the context of the work, a hybrid strategy for manufacturing micromix burners was successfully applied and the findings related to manufacturing are presented in detail.

¹The method for uncertainty estimation was described in section 3.7.4.

The most important points can be summarised in the following:

1. fuel systems for hydrogen require a careful selection of materials and equipment, not susceptible to hydrogen embrittlement
2. the hot (combustion) sections of the rig should be designed for safety, which may imply compromises with rig performance or design simplicity
3. the suggested fabrication route for micromix burners presents limitations. Further research is required as to reliable and safe fuel supply to the injectors, sub-millimetre injector manufacturing and the value of additive manufacturing in future micromix burners
4. preliminary testing is a very important procedure, that in this case highlighted design and operational issues
5. a number of further changes are still required in terms of components and system setup in order to achieve the full capability of the rig with reliable measurements of emissions, thermoacoustics and diagnostics.

CHAPTER 5

Hydrogen Combustion Tests

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5.1 Introduction

This chapter presents the outcomes of the main experimental campaign. The tested micromix configurations and realised test cases are presented initially followed by a short discussion on the pressure drop characteristics of the different designs. NO_x emissions are subsequently presented in an energy emission index ($EEINO_x$) metric, and trends of their change with operating conditions are compared with large-eddy simulation (LES) derived results. The CFD simulations were conducted by Dr. X. Sun in the context of the ENABLEH2 project.

5.2 Overview of Tested Configurations and Test Conditions

5.2.1 Micromix Injector Configurations

Three micromix configurations with different geometric parameters were tested (Figure 5.1 and Table 5.1). These configurations cover a range of values of the momentum flux ratio (MFR) as described in Section 3.4.2. The penetration depth of hydrogen depends on the hydrogen injection diameter (d_{H_2}) and momentum flux ratio (MFR - J) as given in [22]:

$$y_{H_2} \propto d_{H_2} \cdot \sqrt{J} \quad (5.1)$$

The medium MFR design was used as a baseline and was the first design to be implemented and tested, while the other two designs were produced at a later stage. Due to manufacturing complexities explained in section 4.3.3, for the high MFR design only 27 fuel injection points were open out of 32.

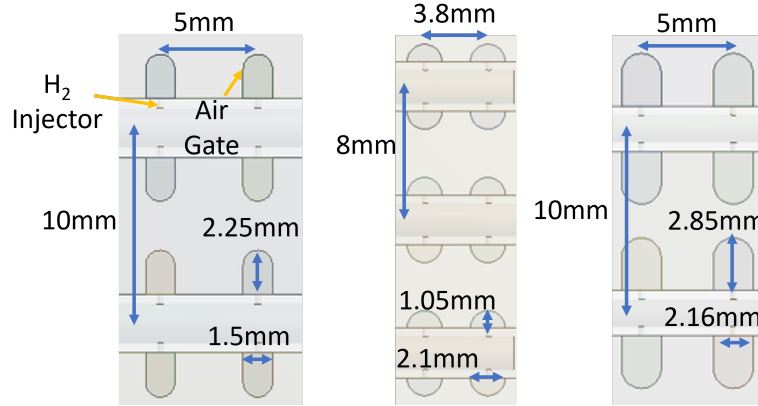


FIGURE 5.1: Geometries of the tested configurations. Medium (left), low (middle) and high (right) MFR

Design	Hydrogen Offset Distance (mm)	Hydrogen Mixing Distance (mm)	Aspect Ratio	Typical J	No of H_2 Injectors
Low MFR	2.50	1.00	0.5	0.64	52
Medium MFR	1.50	1.50	1.5	2.06	32
High MFR	4.75	0.86	1.33	6.34	32(27)

TABLE 5.1: Hydrogen offset and mixing distances for the three micromix configurations.

It should be noted that the typical values of J in Table 5.1 are taken for conditions at 10bar_a pressure, 600K air-inlet temperature and $\Phi = 0.4$. Calculation based on fuel temperature of 300K . Aspect Ratio refers to the ratio of air-gate height to air-gate width as given in Figure 5.1.

5.2.2 Realised Test Cases

Tables 5.2, 5.3 and 5.4 show the test cases realised for each of the three designs. Technical issues did not allow for the realisation of the full ideal test matrix presented in Section 3.4.

Specifically, test conditions for the low momentum flux ratio (J) could not fully replicate those of the other two designs. For the 10bar_a and 600K case, equivalence ratio of 0.5 was not tested as components downstream of the combustion chamber were operating at extreme temperatures (glowing red) after several hours of continuous combustion. At the 10bar_a and 450K case a leak from the side of the optical access and a subsequent alarm from the hydrogen leak detectors did not allow testing at Φ of 0.4 and 0.5. In both cases, the rig was shut down safely. A miscalculation in the expected residual heat of the Pebble Bed led to testing at 315K air inlet temperature at 5bar_a instead of 450K . The pressure of time did not allow an attempt to repeat the missing test points. For the high J design, although tests were performed at 5bar_a and 450K , the results are not presented here as the gas analyser operation was deemed unreliable, due to the high concentration of condensed water in the instrument.

Finally, tests at 15bar_a and 600K were planned originally for all the configurations, as more representative operating conditions of a modern turbofan engine at cruise. These tests were not realised as attempts to reach these points led the rig to overheat or hydrogen to leak from the supply line.

Although the test cases refer to pressure and temperature conditions that are round numbers, e.g. $P = 5\text{bar}_a$ and $T_{air,in} = 600\text{K}$, the actual conditions achieved always differ to a degree. This is a consequence of fluctuations in the air supply (see 4.6.1). Specifically, the deviation of pressure from the targeted value was between -5% to $+3.8\%$, in inlet temperature between -6.4% to $+5.3\%$ and in equivalence ratio between -3.5% to $+4.7\%$. It should be noted that the values quoted here are not directly related to measurement accuracy. They are derived as percentage deviations of the averaged sample values of each quantity from the targeted value.

Low MFR Design			
$P(\text{bar}_a)$	T_{in} (K)	Φ	$\frac{\Delta P}{P}$
5.07	316	0.297	9.8%
5.02	315	0.401	9.9%
5.02	314	0.490	10.4%
4.92	590	0.308	7.5%
5.12	585	0.398	7.7%%
5.00	595	0.506	8.1%
10.0	457	0.302	8.4%
9.79	595	0.299	8.2%
10.0	576	0.407	7.8%

TABLE 5.2: Realised test cases and measured pressure drop for the low MFR micromix configuration.

Medium MFR Design (Baseline)			
$P(\text{bar}_a)$	$T_{air,in}$ (K)	Φ	$\frac{\Delta P}{P}$
4.90	447	0.304	3.7%
4.90	446	0.403	3.9%
4.90	446	0.514	4.5%
4.78	574	0.304	4.0%
5.04	579	0.385	3.8%
5.12	584	0.496	3.8%
9.74	439	0.307	4.8%
9.87	442	0.402	4.7%
9.87	440	0.490	4.7%
9.71	572	0.300	3.7%
9.72	572	0.403	3.7%
9.60	574	0.511	3.8%

TABLE 5.3: Realised test cases and measured pressure drop for the medium MFR micromix configuration

High MFR Design			
$P(\text{bar}_a)$	$T_{air,in}$ (K)	Φ	$\frac{\Delta P}{P}$
5.00	582	0.303	1.2%
5.10	577	0.408	1.2%
5.06	581	0.517	1.2%
10.03	446	0.302	0.9%
10.03	442	0.406	1.0%
9.91	450	0.498	1.2%
10.1	580	0.302	1.1%
10.1	584	0.396	1.2%
10.0	589	0.507	1.2%

TABLE 5.4: Realised test cases and measured pressure drop for the high MFR micromix configuration

5.3 Outcome of the Experimental Campaign

The analysis presented in this section is a collaborative effort between Dr. X. Sun, Dr. V. Sethi and the author of this thesis, and was done as part of a deliverable report for the ENABLEH2 project [67].

The main testing campaign provided data on pressure drop and NO_x emissions for each design at all operating conditions. Results showed that the configuration yielding the lowest NO_x also had the largest pressure drop, while the one with the highest NO_x presented the lowest pressure drop. These results are presented in the following sections.

5.3.1 Pressure Losses Across the Micromix Burners

The pressure values given in Tables 5.2, 5.3 and 5.4 refer to combustor pressure, while the $\frac{\Delta P}{P}$ values represent pressure drop across the micromix burner

$$\frac{\Delta P}{P} = \frac{P_{up} - P_{dn}}{P_{up}} \quad (5.2)$$

where P_{up} is the air pressure upstream of the burner and P_{dn} is the pressure in the combustion chamber. The high momentum flux ratio (MFR- J) design shows the lowest pressure drop of about 1%, while the low momentum flux ratio design presents the highest drop, ranging from 8% to 10%. This can be explained by the size of the air gates for the different designs. The low MFR design has air passages with the lowest cross-sectional area, while the high MFR design has air passages with the highest cross-sectional area (Figure 5.1). Given that current combustors do not exceed 3 – 4% in pressure drop, only the high MFR design abides by this requirement, while the medium MFR burner is on the threshold. Yet, as will be seen in the following section (5.3.2) the low MFR design yields the lowest NO_x , with the high MFR design giving the highest NO_x . This points out a potential trade-off between NO_x levels and pressure drop that can be achieved. Further quantification of this trade-off requires a design-space exploration.

In order to facilitate the AM process, without complicated support structures for the component, the air passage length (5.2) had to be extended from 5mm to 19mm. This likely resulted in much higher pressure losses within the air passage. The potential of minimising the length to 5mm through a different design philosophy or application of other manufacturing techniques should be explored.

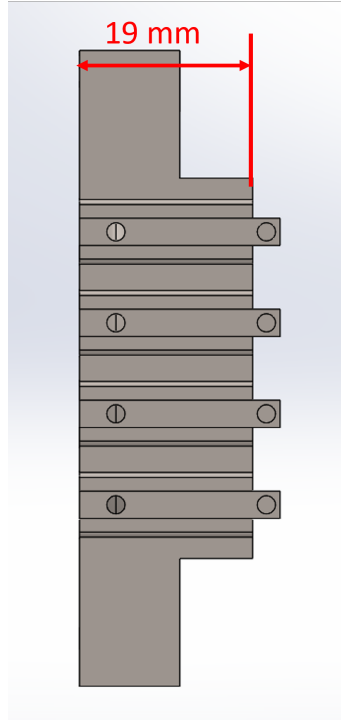


FIGURE 5.2: Length of the air passages of the micromix burners

5.3.2 NO_x Emissions Results

This section presents the results of NO_x measurements for the cases and injector configurations shown in Tables 5.2, 5.3 and 5.4, along with the estimated uncertainties, which are presented and commented upon. The effects of equivalence ratio (Φ), combustor inlet pressure and temperature are discussed, and the NO_x emissions of the three designs are compared. For each design, a comparison with results produced by CFD using large-eddy simulations (LES) is provided, in an attempt to explain the trends and the discrepancies between numerically and experimentally derived values. With regard to the metrics presented here, it is noted that NO_x emissions for different engines and different operating conditions are currently compared on the basis of:

1. mass of NO_x per unit thrust ($Dp/F_{oo} - \text{g/kN}$)(used to quantify NO_x in the Landing and Take-Off (LTO) cycle for engine certification)
2. emissions index ($EINO_x - \text{g/kg of fuel}$)

These metrics are used by current legislation and by the ICAO Engine Emissions Databank. Since all current engines use Jet A-1 as fuel, these metrics are a fair basis for comparison. However, when changing to an alternative fuel such as hydrogen,

the comparison is not fair anymore, due to the difference in the lower heating value (LHV) between the two fuels: 43MJ/kg of kerosene compared to 120MJ/kg of hydrogen. Thus, a more appropriate metric for presentation and comparison would be an energy-based emission index ($EEINO_x - \text{g/MJ}$).

$EINO_x$ for a specific fuel can be converted to $EEINO_x$ by 3.4. The procedure of turning the NO_x values measured by the gas analysis system, into $EEINO_x$ is described in section 3.7.3.1. $EEINO_x$ is used here for the presentation of the results of both the experimental campaign and the numerical simulations to allow a fair basis of comparison of the NO_x produced by Jet A-1 and H_2 fuelled aircraft.

In the following section, these results are discussed. It is important to note that the lack of reaction zone imaging data limited the calibration of the LES. Notwithstanding this limitation, the results from the CFD simulations are still able to provide some qualitative insights into the flow physics and combustion phenomena, thereby helping to interpret the experimental results. To quantify the discrepancies, flame visualisation data is essential and is highly recommended for future work.

In section 1.1 the importance of temperature on NO_x formation was emphasised. Thus, the temperature of the flame and post-flame zones, in conjunction with residence time are the most important factors affecting the production of thermal NO_x which is the only route considered here. Referring to Figure 1.2, it can be seen that increasing equivalence ratio theoretically leads to increased flame temperature¹, until close to stoichiometric mixtures ($\Phi = 1$). Combustion at the fuel-lean side, as already discussed, means lower flame temperatures, hence lower NO_x . In predominantly diffusion flames, such as micromix, although a global equivalence ratio may be assumed based on a total fuel-to-air flow ratio, there is a limited premixing process and this leads to a distribution of equivalence ratios, with regions of stoichiometric mixture creating hot spots of high NO_x production. Thus, mixing quality is a dominating factor in flame and product temperatures and subsequently in NO_x formation. The three injector configurations tested in this experimental campaign represented different momentum flux ratios. Figure 5.3 - repeated here as it is important for the analysis of the results - shows, in a qualitative way, the expected NO_x emissions levels and different flame patterns for different momentum flux ratio values (J). The low and medium MFR designs are in the region of the red rectangle. As will be seen in the CFD results presented below, the low MFR configuration was expected to produce flames stabilised in the inner recirculation zone (IRZ) and close to the metal wall of the injectors, while the medium momentum flux ratio design was expected to generate flames that stabilise in the same region, but further away from

¹At constant pressure and inlet temperature

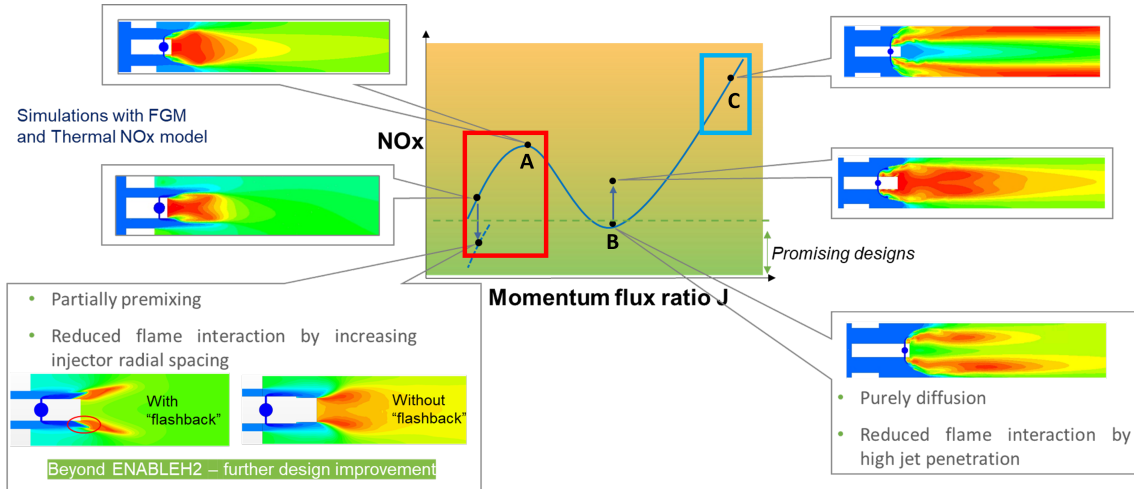


FIGURE 5.3: Expected behaviour of NO_x emissions with momentum flux ratio. The qualitative graph is based on LES simulations. ([67])

the wall. The high MFR design is in the region of the blue rectangle. Due to the high jet penetration, there is more interaction between the flames of neighbouring injectors, which results in long flames merging downstream of the outer recirculation zone (ORZ). This results in higher residence time and therefore higher NO_x .

5.3.2.1 Estimated Uncertainties

The uncertainties of the energy-based emission index ($EEINO_x$) are presented in this subsection in tubular form, instead of being shown as error bars in the results plots. The reason for this is the high level of uncertainties that would lead to large error bars and would make the plots unclear and difficult to interpret. Instead, the plots of the experimentally derived $EEINO_x$ including error bars are shown in Appendix C. These plots also include the error bars for the equivalence ratio.

A look at tables 5.5, 5.6 and 5.7 reveals the large magnitude of the uncertainties. As discussed in section 4.6.4, a number of factors contributed to the extremely high measurement uncertainties, the most important of which was the selected range of the instrument, followed by the calibration gas concentration uncertainty. The estimated uncertainty levels for the energy-based metric remain high since the dependence of the index on the measured NO_x values is directly proportional (see equation 3.22).

Low MFR Design					
$P(\text{bar}_a)$	$T_{air,in}(K)$	Φ	$EEINO_x(g/MJ)$	$u_{EEINO_x}(g/MJ)$	$\frac{u_{EEINO_x}}{EEINO_x}$
5	315	0.3	0.0043	0.0175	393%
		0.4	0.0042	0.0130	291%
		0.5	0.0046	0.0108	221%
	600	0.3	0.0053	0.0169	308%
		0.4	0.0069	0.0133	184%
		0.5	0.0124	0.0109	82%
10	600	0.3	0.0208	0.0182	85%
		0.4	0.0273	0.0141	49%

TABLE 5.5: Case for case $EEINO_x$ values and their uncertainties for the low momentum flux ratio design

Medium MFR Design (Baseline)					
$P(\text{bar}_a)$	$T_{air,in}(K)$	Φ	$EEINO_x(g/MJ)$	$u_{EEINO_x}(g/MJ)$	$\frac{u_{EEINO_x}}{EEINO_x}$
5	450	0.3	0.0086	0.0191	215%
		0.4	0.0093	0.0146	150%
		0.5	0.0116	0.0117	95%
	600	0.3	0.0086	0.0191	218%
		0.4	0.0115	0.0154	129%
		0.5	0.0149	0.0123	78%
10	450	0.3	0.0121	0.0191	153%
		0.4	0.0123	0.0148	116%
		0.5	0.0132	0.0124	89%
	600	0.3	0.0195	0.0200	99%
		0.4	0.0257	0.0155	57%
		0.5	0.0274	0.0126	43%

TABLE 5.6: Case for case $EEINO_x$ values and their uncertainties for the medium momentum flux ratio design

High MFR Design					
$P(bar_a)$	$T_{air,in}(K)$	Φ	$EEINO_x(g/MJ)$	$u_{EEINO_x}(g/MJ)$	$\frac{u_{EEINO_x}}{EEINO_x}$
5	600	0.3	0.0255	0.0233	112%
		0.4	0.0532	0.0178	70%
		0.5	0.182	0.0149	42%
10	450	0.3	0.0276	0.0238	77%
		0.4	0.0754	0.0187	51%
		0.5	0.145	0.0169	38%
	600	0.3	0.0340	0.0246	85%
		0.4	0.0661	0.0196	56%
		0.5	0.218	0.0163	49%

TABLE 5.7: Case for case $EEINO_x$ values and their uncertainties for the high momentum flux ratio design

Regarding the uncertainty on the value of the equivalence ratio, this ranges in all the tested cases between 1% and 2% of the logged, averaged value of Φ .

5.3.2.2 Low Momentum Flux Ratio Design

The low momentum flux ratio (MFR) design presents a relatively mild or insignificant increase in NO_x with the rise in equivalence ratio (Φ), both for experimental and numerical results. As expected, NO_x increases with an increase in inlet temperature and pressure.

According to the CFD predictions, in all cases for this design, the reaction zones are positioned towards the shear layer, in the vicinity or within the IRZ. The flames are surrounded by a cooler air/fuel mixture which reduces the temperature of the flame and post-flame zones. For this design, it is believed that this cooling effect dominates the increase of equivalence ratio and expected increased adiabatic flame temperatures despite also the increased length of hot regions ($T > 2200K$). Therefore, for 5bar conditions, NO_x emissions do not increase significantly with an increase in equivalence ratio from 0.3 to 0.5. This may not be the case for the designs with higher momentum flux ratios, as illustrated in Figures 5.5, 5.6. However, at 10bar conditions, it can be seen from Figure 5.4 that the impact of flame separation (i.e. less flame-flame interaction) is more dominant as the equivalence ratio changes from 0.3 to 0.4. Therefore, LES predicts a decrease in NO_x .

Figure 5.3 shows that NO_x first increases to a local maximum (point A) as a function of MFR. It then decreases to a local minimum (point B) before significantly increasing to point C. There exist uncertainties between the predicted position (i.e. the MFR) for the transition points A and B by CFD and the corresponding experimental values. For the low MFR case, LES predicts a decreasing trend at high-pressure conditions due to the dominant effect of flame separation, which corresponds to the right side of point A, whereas for the experiment it is more likely that the corresponding MFR is still on the left side of point A. However, as the local peak A is situated in a region with relatively low NO_x , the measured and predicted values are similar even though they may be on different sides of point A. This requires further validation beyond the scope of this thesis.

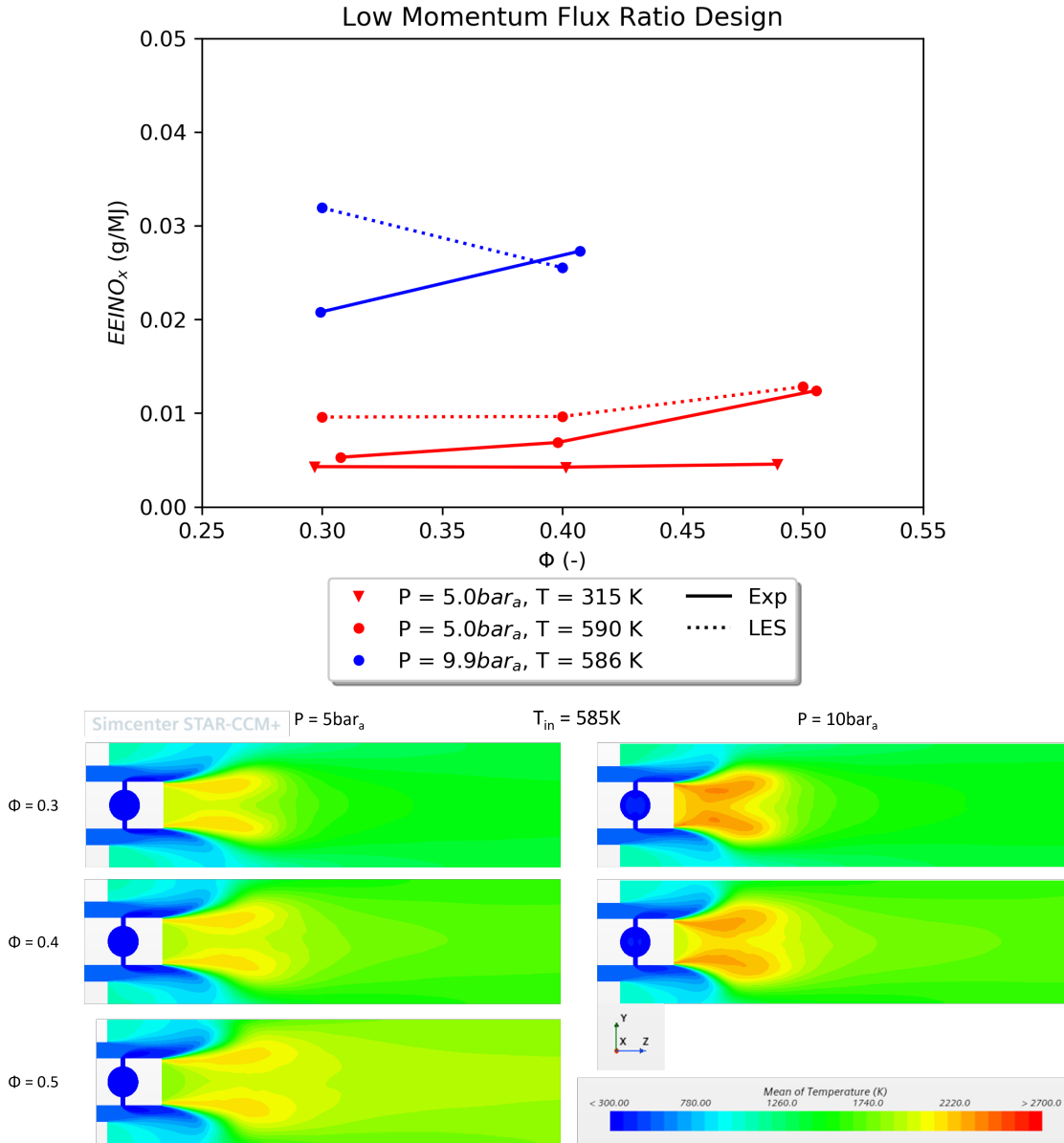


FIGURE 5.4: NO_x against Φ - experimental and numerical data (top). Temperature contours from LES (bottom) for the low MFR configuration

5.3.2.3 Medium Momentum Flux Ratio Design

At 450 K air-inlet temperature both at 5 bar_a and 10 bar_a , for the medium MFR design, the impact of the equivalence ratio on NO_x seems relatively small. LES and experimental results agree well on trends (Figure 5.5 - top). This could be attributed to the fact that the inlet temperature is not sufficiently high to generate notably high NO_x production. Both LES and experimental results show relatively low levels of NO_x . This can also be explained by interpreting the temperature contours predicted by LES. For all 450 K cases, the high-temperature flame zones

(“hot cores”) are relatively separated by the inner recirculation zone flow. The hot products are rapidly mixed and cooled down with the unburnt flow. This becomes more evident as the equivalence ratio increases, due to higher MFR leading to higher jet penetration. It is expected that there will be less flame-flame interaction, as well as more hot-cold gas mixing, which partially offsets the effect of increasing equivalence ratio (i.e. extended flame length and slightly higher flame temperature). Therefore, this limits the amount of NO_x produced.

At an air inlet temperature of $585K$, both experiments and LES show a similar increasing trend with increases in pressure and equivalence ratio (Figure 5.5). However, there is a considerable difference between LES and experimental results for the $5bar$ cases with increasing equivalence ratio, especially at $\Phi = 0.5$.

The LES temperature contours suggest that the average peak temperature increases significantly compared to the 0.3 and 0.4 cases. Compared to $450K$ cases, as the inlet air temperature increases, its cooling potential is reduced and the mixed gas temperature in the inner recirculation zone therefore also increases. As the distance between the flames remains similar, the size of the high-temperature ($> 2200K$) region increases significantly, which results in the sudden NO_x increase at $\Phi = 0.5$.

The possible reasons for the NO_x discrepancies between the LES and experimental results are as follows:

1. As discussed for the low momentum flux ratio design, for $\Phi = 0.5$ there may be discrepancies between the predicted position (i.e. the MFR) for transition points B by CFD and the corresponding experimental values (refer to Figure 5.3). These discrepancies could arise e.g., due to inaccurate predictions in jet penetration height, heat release rate or simplified assumptions such as constant fuel temperature.
2. Since LES does not capture any heat transfer between the hot gas to the surrounding test section, it predicts higher values of flame temperatures and consequently NO_x emissions.

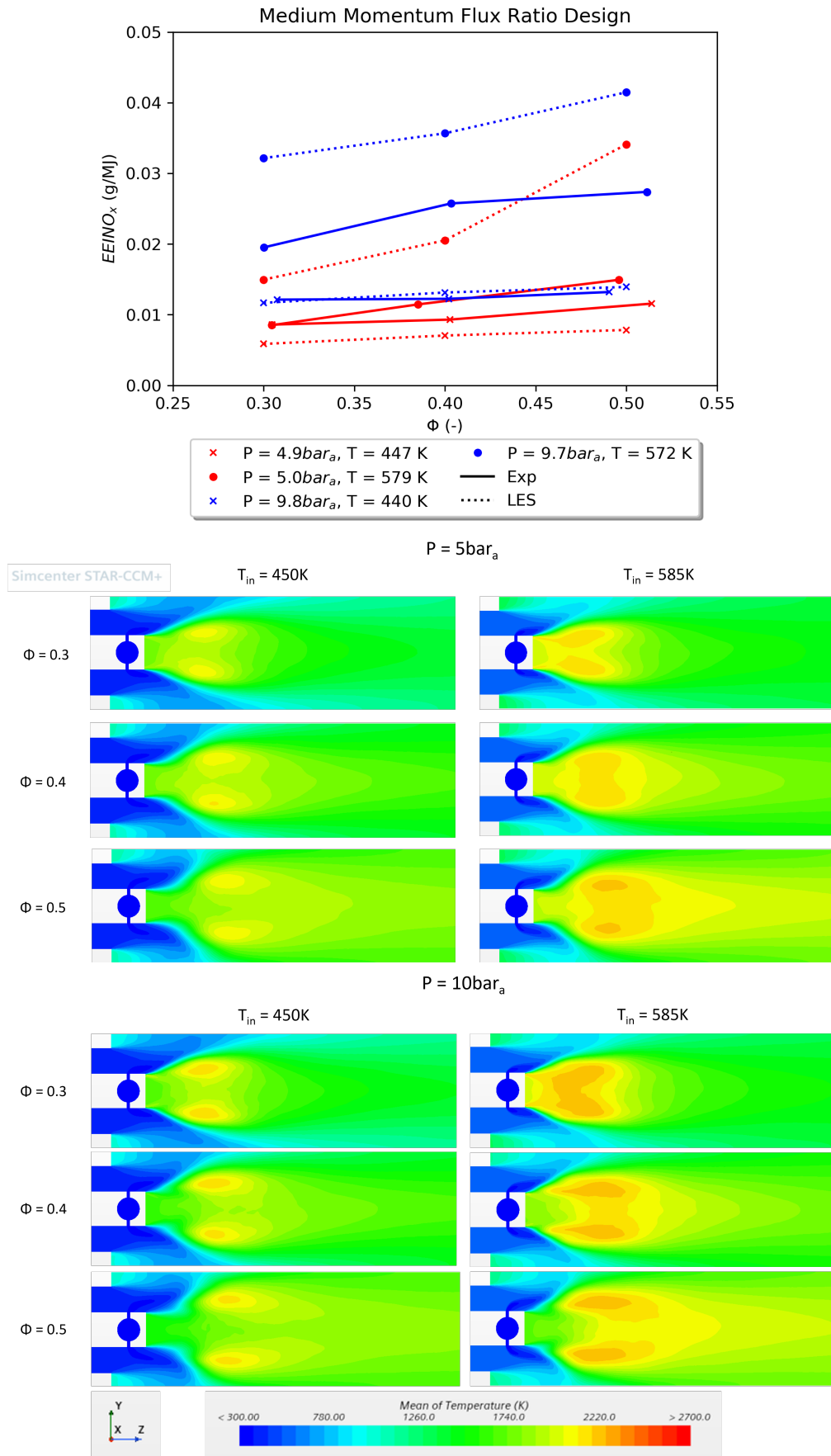


FIGURE 5.5: NO_x against Φ - experimental and numerical data (top). Temperature contours from LES (middle and bottom) for the medium MFR configuration

5.3.2.4 High Momentum Flux Ratio Design

Experiments show consistent trends in NO_x with equivalence ratio (Figure 5.6) for the high momentum flux ratio design. The trend is similar for all the pressure and temperature cases with a modest increase in NO_x with Φ . LES on the other hand predicts a much steeper increase of NO_x with increasing Φ , and the slope becomes steeper between $\Phi = 0.4$ and $\Phi = 0.5$. Observing the temperature fields produced by CFD², the increasing equivalence ratio leads to longer flames with higher peak temperatures. Compared to previous designs, there is a significant change in the size of regions $> 2300K$ even between $\Phi = 0.3$ and $\Phi = 0.4$, which may explain the steep change in NO_x . Increasing jet penetration depth (with equivalence ratio) moves the reaction zone towards the side downstream of the outer recirculation zone (ORZ). The size of the ORZ is compressed with increasing penetration whereas the flames downstream grow lengthwise. Eventually, the flames between neighbouring injectors (represented by periodic boundary conditions) merge in the radial direction, leading to excessively high NO_x formation.

The significant discrepancies between the experimental NO_x results and those produced by the LES, especially at $\Phi = 0.4$ and $\Phi = 0.5$ are because, for the experiments, the air gates on the outer circumference were designed without fuel injection for rig cooling purposes. The “cooling flow” changes the shape of neighbouring flames. There is much less flame interaction and merging effects than those predicted by LES, where all flames are assumed to have a neighbouring flame. The NO_x is significantly lower due to lower downstream temperatures. These effects are less evident for the low and medium MFR design. This is because, for these two designs, the flames are positioned mainly in the inner recirculation zone and the shear layer. Therefore the flame-flame interaction is less influenced by this “cooling flow”, which primarily affects the outer recirculation zone.

In order to provide an idea of how hydrogen compares to kerosene at similar operating conditions, the experimental results presented below are compared to the $EEINO_x$ produced by a LEAP1A35A engine (currently in service) at 7% Landing and Take-Off (LTO) Thrust. The 7% LTO thrust point is chosen because the combustor inlet pressure (P3) and air-inlet temperature (T3) are approximately $8bar_a$ and 550K respectively. The condition is close to those of the experimental tests performed for hydrogen micromix combustion. The $EINO_x$ value was extracted

²For the high MFR LES, only one injector was simulated due to high jet instabilities occurred for the 2-injector configuration. Details of this effect and explanations can be found in [64].

from the ICAO emissions databank and the $EEINO_x$ was then calculated, which is approximately 0.11.

For all the designs, the measured NO_x from hydrogen micromix is lower than the presented value for kerosene (the only exception is the LES-derived points at $\Phi = 0.5$ for the high MFR design). This is true even for combustor pressures and air inlet temperatures higher than those of the kerosene case. For all the designs, yielded NO_x at all operating points is well below the kerosene threshold by at least 50% less.

The main challenge in numerical modelling, even with LES, is to predict more accurately the locations of transition points, such as those identified in Figure 5.3, which are essential in determining low NO_x designs. The NO_x trend predictions are also highly sensitive to these locations. Tuning numerical models for hydrogen combustion will require good calibration for physical properties such as diffusivity, as well as capturing temperature distributions and heat losses that are representative of the experimental set-up. Flame imaging is essential in providing detailed information for this procedure, therefore, despite its high cost and challenges when implemented in a high-pressure high-temperature combustion rig, it should still be strongly recommended for any future experiments.

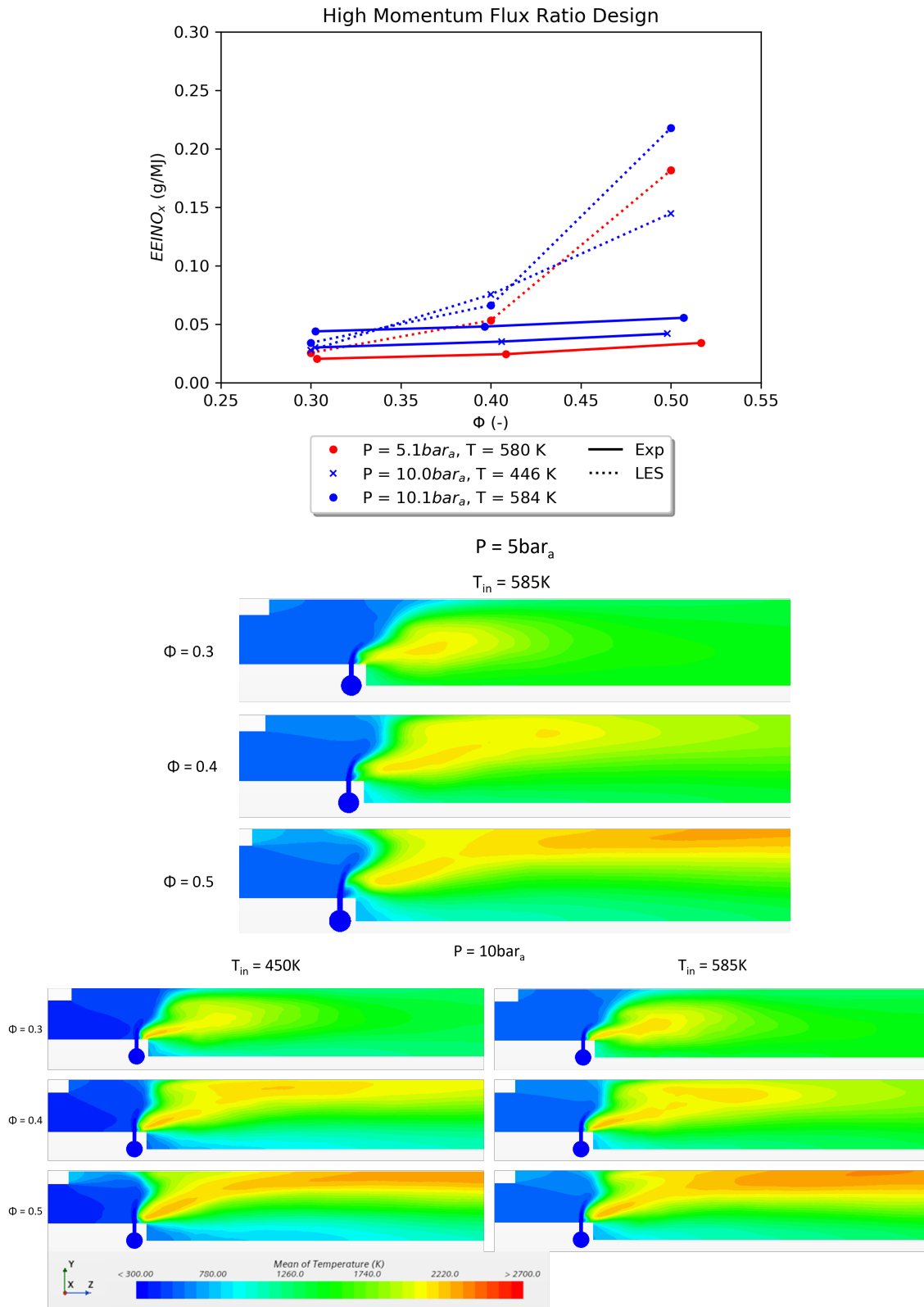


FIGURE 5.6: NO_x against Φ - experimental and numerical data (top). Temperature contours from LES (middle and bottom) for the high MFR configuration

5.4 Chapter Summary

In this chapter, the geometries of the three tested micromix configurations were presented along with the matrix of test cases and the limitations imposed on testing conditions. The experiments showed that the configuration with the lowest NO_x emissions produced the highest pressure losses, significantly higher than those of state-of-the-art combustors. Further research is required and a trade-off may be necessary between NO_x and pressure drop.

The high MFR design produced the highest NO_x denoting the importance of geometric parameters on micromix burner performance. Air-inlet temperature, pressure and equivalence ratio increase NO_x emissions, although according to experimental results equivalence ratio gives a milder increase compared to the other parameters. This, for the low and medium MFR designs, can be attributed to reduced flame-to-flame interaction and the flow of cool gas in the region of the inner recirculation zone. For the high MFR though, where flames are positioned towards the outer recirculation zone, it is attributed to heat transfer towards the "cooling air" of the outer air gates. For the high MFR configuration, this is suggested to be the reason for the large discrepancy between experimental and numerical results.

Although the experimental results are associated with high uncertainties, it is suggested that hydrogen micromix can offer significant reductions in NO_x compared to state-of-the-art kerosene burners at similar conditions.

CHAPTER 6

Conclusions and Future Work

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6.1 Conclusions

A new, high-pressure, high-temperature experimental combustion rig was designed and built at Cranfield University to test hydrogen micromix burners. This rig can measure NO_x emissions at elevated operating conditions and has provisions for thermoacoustics and optical access for diagnostics applications.

6.1.1 NO_x Emissions of Micromix Burners

- NO_x emissions production appears to be highly sensitive to momentum flux ratio changes. Comparisons of experimental and LES data of NO_x emissions lead to the suggestion that the numerical tools mispredict the position of peaks

and troughs of NO_x on the MFR axis. This can have significant implications when numerical tools are utilised to explore a design space in search of an optimal low- NO_x injector geometry.

- Discrepancies between experimental and numerical NO_x emissions occur also due to the inaccurate representation of momentum flux ratio in the numerical models. In the experimental tests, due to the design of the micromix burner, hydrogen before injection flows in channels that are right upstream of high-temperature flame regions. Consequently, the temperature of the fuel increases, leading to a change in density and injection velocity, which results in a different momentum flux ratio than the one calculated for ambient fuel temperature. This phenomenon is not captured by the LES simulations.
- Comparisons of measured NO_x from hydrogen micromix with state-of-the-art kerosene combustor at similar pressure and temperature showed potential reductions of at least 50% for hydrogen micromix. Specifically, the kerosene combustor at an inlet pressure of $8bar$ and air-inlet temperature of $550K$ produced levels of $EEINO_x = 0.11g/MJ$, while the high MFR hydrogen micromix burner that yielded the highest levels of NO_x , produced at $10.1bar_a$ and $584K$ levels of $EEINO_x = 0.05g/MJ$.
- Careful consideration is required for the design of micromix injectors as a potential trade-off exists between pressure loss and NO_x emissions.

6.1.2 Combustion Rig Design and Development Challenges - Lessons Learned

The research contribution of the design and development work presented in this thesis is found in the presentation of challenges and common blunders that can arise during the development process of a hydrogen combustion experimental rig, as well as recommendations of good practices and suggestions towards building a sound experimental setup.

- The high diffusivity and the flammability characteristics of hydrogen in conjunction with safety requirements, increase the complexity of the rig and systems design. The design philosophy for components and systems of a hydrogen rig implements safety practices on three levels:
 1. Hydrogen leakage avoidance

- Careful selection of the equipment of the fuel delivery system and installation by trained personnel to ensure leak-tight connections in the fuel supply lines
 - Materials with good embrittlement characteristics need to be chosen
 - Events of back-flow of air towards the fuel system and flashback must be avoided by the use of appropriate equipment (e.g. non-return valves) and design practices (sealing arrangements and materials)
- 2. Early detection and action in case of leakage

Quick cut-off of fuel and purging with inert gas is necessary for normal operation and emergency conditions
- 3. prevention of flammable concentrations from forming

Natural and forced ventilation is required to avoid hydrogen from pooling and building dangerous concentrations
- The design of optical access for a pressurised combustion chamber requires careful consideration between achieving the desired flow and flame characteristics and the life span of the optical material. Close proximity of the glass to the flames combined with cyclic thermal loading and rapid cooling significantly reduces the expected life of the glass.
- The design of a single-wall combustion chamber with no external cooling should be avoided where optical access is necessary. The combined, high thermal and mechanical loads on the glass, led the material to fail in only a few hours of operation. Instead, double-wall configurations with the cooling flow in between walls should be preferred. The inner wall takes the thermal load and the outer wall the pressure load in such configurations.
- The high water content produced by hydrogen combustion presents a challenge for the emissions measuring setup. Drying equipment needs to be selected, such that it removes the water vapour, before any condensation happens and without affecting the NO_2 content in the sample. Heated components are required upstream of the dryer and short lengths of line from the dryer to the measuring device. A dry sample is also important as water vapour can have an effect on the measurement inside the CLD cell (see [3.5.2.1](#)). In cases of incomplete water vapour removal, measuring the original water content in the sample and the efficiency of the drying stage, are important. It is recommended that guideline documents such as the Aerospace Recommended Practice (ARP) 1256D [55] are closely followed.

6.1.3 Micromix Burner Fabrication

- Additive manufacturing (AM) combined with micro-EDM can be utilised for the fabrication of micromix burners, although the process presents limitations. AM offers the advantage of creating one-piece components eliminating potential leakage paths for the burner, thus contributing to the safety aspect of the design.
- The limitations of AM are related to the sizes of features that can be produced through such techniques. Geometric features with sizes $< 1mm$ challenge the capabilities of AM machines. Regarding the application of AM for micromix burners, sub-millimetre sizes are encountered in the fuel injection points ($0.3mm$ in diameter) and the internal fuel delivery channels of the high momentum flux ratio (MFR) design. In the case of the latter, the produced high MFR burner appeared to have some of its internal channels blocked.
- Four different techniques were compared regarding the creation of $0.3mm$ -sized holes: Direct Metal Laser Sintering (DMLS), Binder Jetting Technology (BJT) both of which are AM techniques, Electrical Discharge Machining (EDM) and micro-EDM. Micro-EDM offered the best results in terms of tolerances of the nominal size ($\pm 10\mu m$) and the added advantage of machining without line-of-sight. This technique presents its own limitations as care needs to be taken when setting up the machining strategy, so as not to damage the component.

6.2 Suggestions for Further Work

6.2.1 Improvements to the Experimental Setup

In terms of the physical setup, the following work is suggested, in order to improve the capabilities and reliability of the rig:

- Control of the airflow supply requires improvement. Due to the difference between the supply capability of the compressor used (order of $1kg/s$) and the required flows (order of $0.1kg/s$) the fluctuations imposed by the compressor operation impacted the supplied airflow. The use of a settling chamber prior to the flow measurement device is suggested as a potential solution. A costlier option is to use a different compressed air supply for the same pressures but

lower mass flows, which currently does not exist within the Gas Turbine Testing laboratory of Cranfield University.

- Failure of the optical material of the windows is partly attributed to the lack of cooling for the designed configuration. An easy solution here is not evident and it is suggested that the combustion chamber has to be redesigned. In such a case, it is strongly suggested that a double-wall configuration is implemented with inlet air utilised for active cooling of the components bearing high thermal loads. Moreover, a larger field of view can be achieved if rectangular windows are implemented, increasing the observed field in the axial direction.
- Improvement of the NO_x emissions measurement setup is necessary in order to improve the quality of the measurements and reduce uncertainties.
 1. A new, multi-hole probe should be designed or supplied externally for a more representative gas sample.
 2. Heated components (e.g. pump and valves if necessary) need to be used along the sampling line and the unheated lengths of tube shall be minimised, to avoid condensation of water vapour
 3. A drying stage that removes water vapour without affecting the NO_2 concentration should be used downstream of the heated components and before the inlet of the gas analyser. Water vapour removal is strongly recommended to reduce interference with the measurement.
 4. NO calibration gas concentration values for span calibration of the gas analyser shall be chosen according to the expected emissions from the tested burners at different operating conditions. Preliminary testing can provide some insight into such expectations. For micromix burners, more than one cylinder of different concentrations may be required

Removal of water vapour and more accurate calibration will significantly reduce measurement uncertainties. Cranfield University has already started the process for the acquisition of a new gas analysis system and sampling-line components, according to these suggestions.

6.2.2 Suggestions for Future Research

Understanding the mixing in micromix

Since mixing quality appears to have the highest significance in the resultant temperature of micromix flames, and subsequently, in the production of NO_x emissions, it is highly important to gain an understanding of the mixing characteristics of micromix burners. These studies can also provide insights into how mixing is affected by operating parameters such as pressure and inlet temperature, as well as momentum flux ratio. Gaining such an understanding can also inform future designs that offer improved mixing quality and even lower NO_x emissions. Hence, the following studies are suggested as future work necessary for the development of the technology:

- Further experiments, similar to those described in this thesis are suggested, with the inclusion of flame imaging techniques. The application of techniques such as OH^* -Chemiluminescence and OH-PLIF are of high importance. Reaction zone visualisation can provide insights into the mixing quality achieved by different micromix configurations at different operating conditions. If such diagnostics are time-resolved, the evolution of chemical and flow phenomena can be captured and can assist in the understanding of turbulence-chemistry interaction and help improve the predictive capabilities of numerical models.
- Dedicated mixing studies (cold flow) can give an indication of the fuel distribution in the flow field of micromix configurations, by applying a PLIF technique, where a substance such as acetone, mixed with hydrogen, is used as a fluorescent tracer. It is understood though that such an application runs the risk of undesirable deflagration of the mixture. Moreover, acetone is heavier than hydrogen and thus its molecular diffusivity is different to that of hydrogen. Hence, the captured fuel distribution may not represent that of hydrogen micromix.

Parameters that affect NO_x

- The presence of the flames very close to the burner wall from which fuel is injected increases the fuel temperature and affects the true momentum flux ratio in experiments. As already discussed this causes a significant discrepancy with the predictions of numerical tools that do not capture this effect. Parametric studies with different fuel injection temperatures can be performed and reaction zone contours could be compared with experimental flame imaging

results. The closest match between images could provide an indication of the fuel injection temperature and subsequent momentum flux ratio. Another suggested route is that of performing heat transfer studies from the burner metal wall to the fuel, using estimates of the metal wall temperature. The resulting fuel temperature could be utilised as a boundary condition for subsequent combustion simulations.

- Experimentally, fuel temperature can be estimated by attaching thermocouples to the front face of the hydrogen segment of a burner to provide an estimate of the temperature of the metal, although this idea is complicated in implementation for the current setup. If metal temperature measurements can be acquired, a heat transfer analysis can be performed to estimate the temperature at the injection point, as described above.

Micromix Burner Manufacturing

The one-piece AM and micro-EDM design, although successfully applied in two out of three configurations presented in this work, requires deeper investigation into the following aspects:

- Exploration of the use of additive manufacturing for larger burners with a compact, leak-free design.
- the potential effects of as-printed roughness on the flows of fuel and air, both for internal surfaces (fuel channels) and external faces (air gates, mixing surface and flame attachment surfaces).
- design optimisation for additive manufacturing that:
 1. avoids complex support structures
 2. accommodates the simplified fuel delivery of internal channels
 3. has an optimal length of the air gates with reduced pressure losses
- dimensional tolerances of micro-EDM for the fuel injectors and the potential effect on fuel flow distribution between injectors. Cold flow experimental work will be useful for this. PIV testing could reveal discrepancies in the velocity field of injectors that ideally have the same velocity patterns.
- the reasons behind the inability to open all the fuel injection points by micro-EDM for the high MFR design. Non-destructive testing, such as X-ray imaging could shed light on this.

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APPENDIX A

The Pebble Bed Heater

The Pebble Bed (PB) is a regenerative heater, built in the 1960s for the testing facilities of the, then, Cranfield College of Aeronautics. It was originally designed to provide high enthalpy air for supersonic combustion tests. It consists of a pressure vessel made of carbon steel, with three layers of refractory lining for insulation and a large portion of its internal volume is occupied by a bed of $\approx 2\text{tons}$ of alumina pebbles supported by an Inconel grid [16].

A kerosene burner sitting at the top of the PB (Figure A.1) is the source that deposits heat on the pebbles. The hot gases pass through the pebbles and are exhausted outside of the facility through the bottom of the bed. When sufficient heat has accumulated on the pebbles, the kerosene burner stops. Temperature measurements at the Inconel grid are used to estimate when heating needs to stop. Moreover, there is provision for an infrared thermometry sensor to be installed, measuring pebble temperature, although until now, this opening serves as an eye-hole (Figures A.1 and A.2). A valve isolates the exhaust, and air from the compressor facilities is supplied, entering the PB from the bottom. This air is heated as it passes through the pebbles and exits towards the test section (Figure A.1).

According to the original report, tests denoted that the facility can provide air at 8.27bar , 0.8kg/s of mass flow and 1850K [16]. The same report also suggests that temperatures of 2050K , at 17bar and 0.9kg/s could be achieved. The temperature and mass flow values given refer to the air passing through the bed. The mixing tee (Figure A.1) provides compressed air that bypasses the PB and allows for significantly higher mass flows (up to 4kg/s) to be supplied to the test section and better control of the inlet-air temperature.

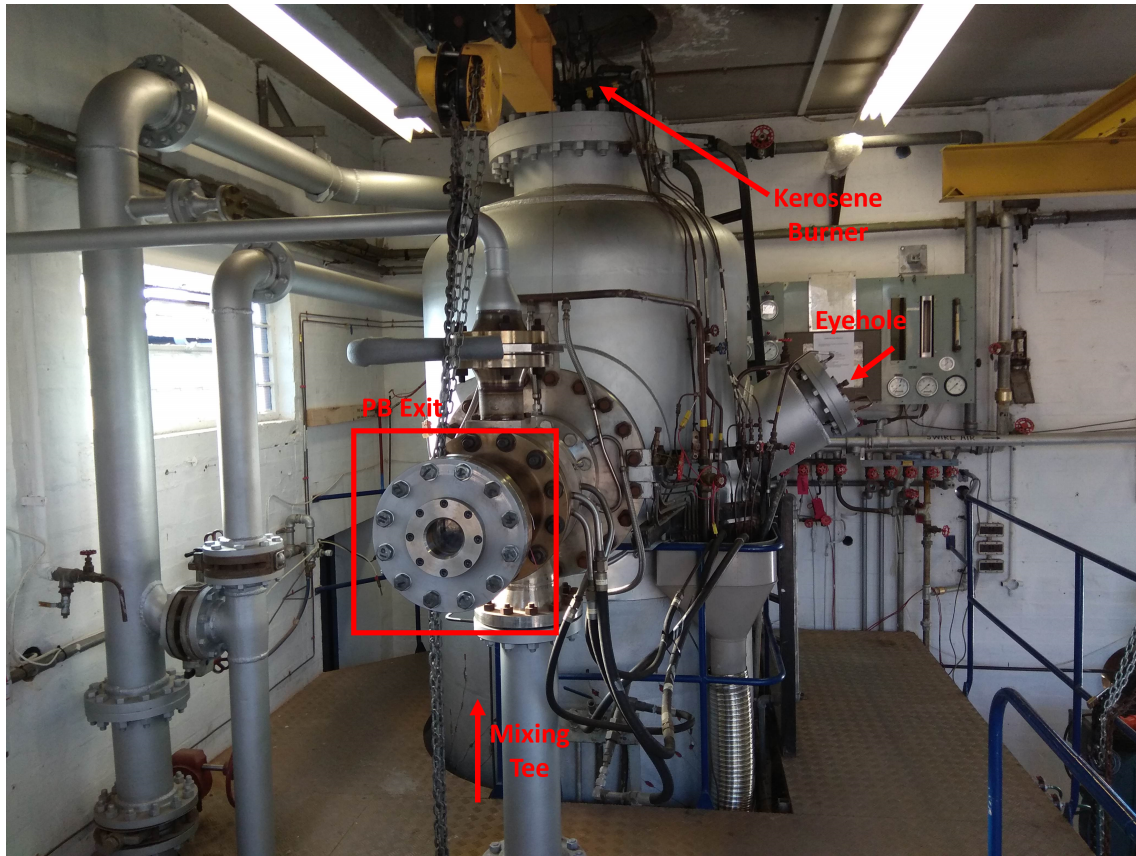


FIGURE A.1: The Pebble Bed heater

More recently, for safety reasons and in order to get clearance for recommissioning, 48 thermocouples were installed on the skin of the Pebble Bed to monitor its external temperature at four zones along its height. Moreover, an operating procedure was developed for safely heating the facility over the course of three days [12]. This is done in order to reduce the risk of quick and extreme thermal gradients that could introduce damage to the internal lining or the frame of the PB.

Control and monitoring of the facility are done remotely from a separate control room. Auxiliary air is used for the regulation of pneumatic valves that control the supply of air towards the Pebble Bed and towards the mixing tee. Pressure is monitored through gauges and temperature through digital displays positioned on a board in the control room (Figure A.3).

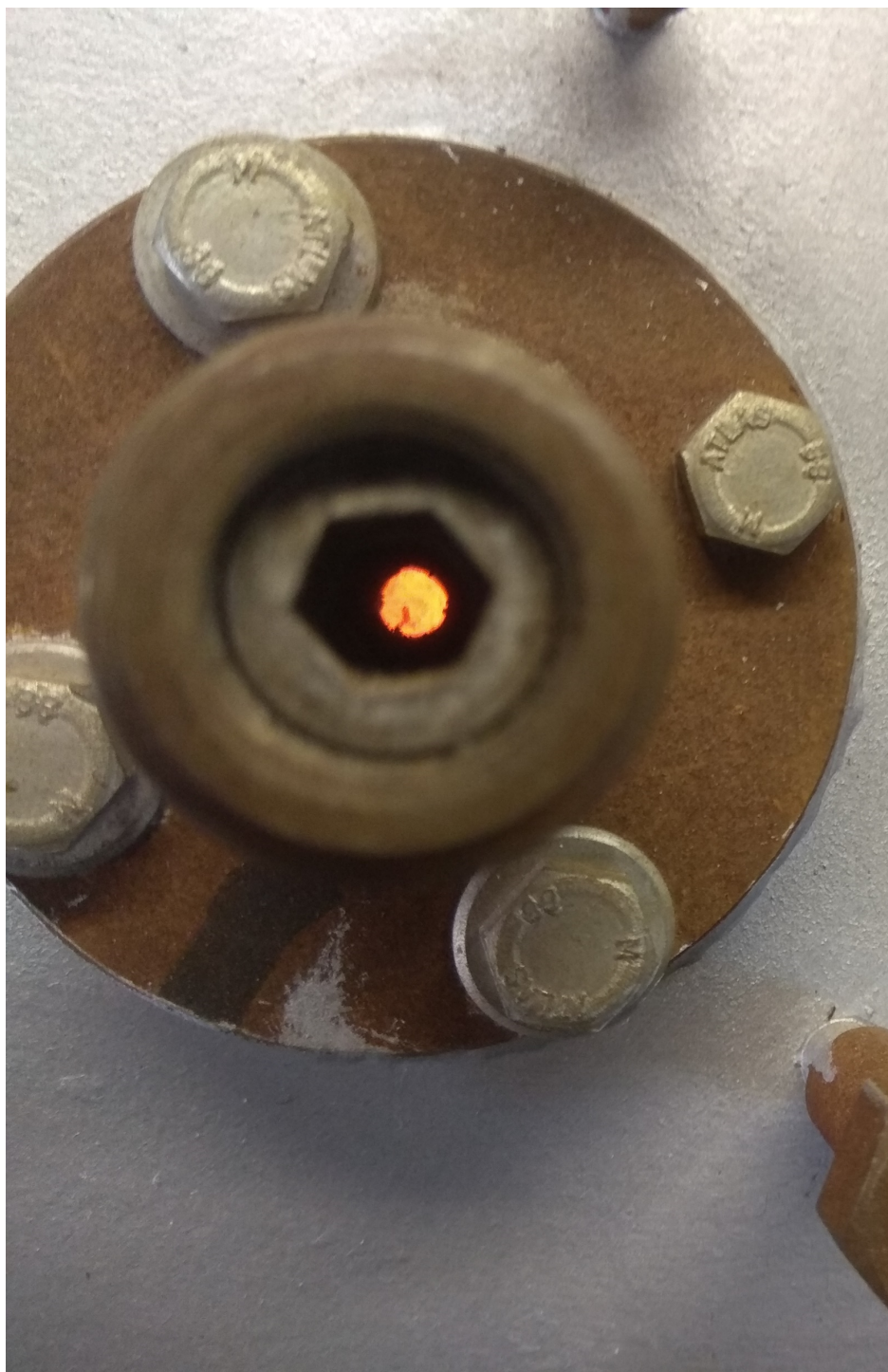


FIGURE A.2: Eye-hole that provides optical access to the pebbles. The pebbles can be seen glowing hot (orange) at the centre of the picture

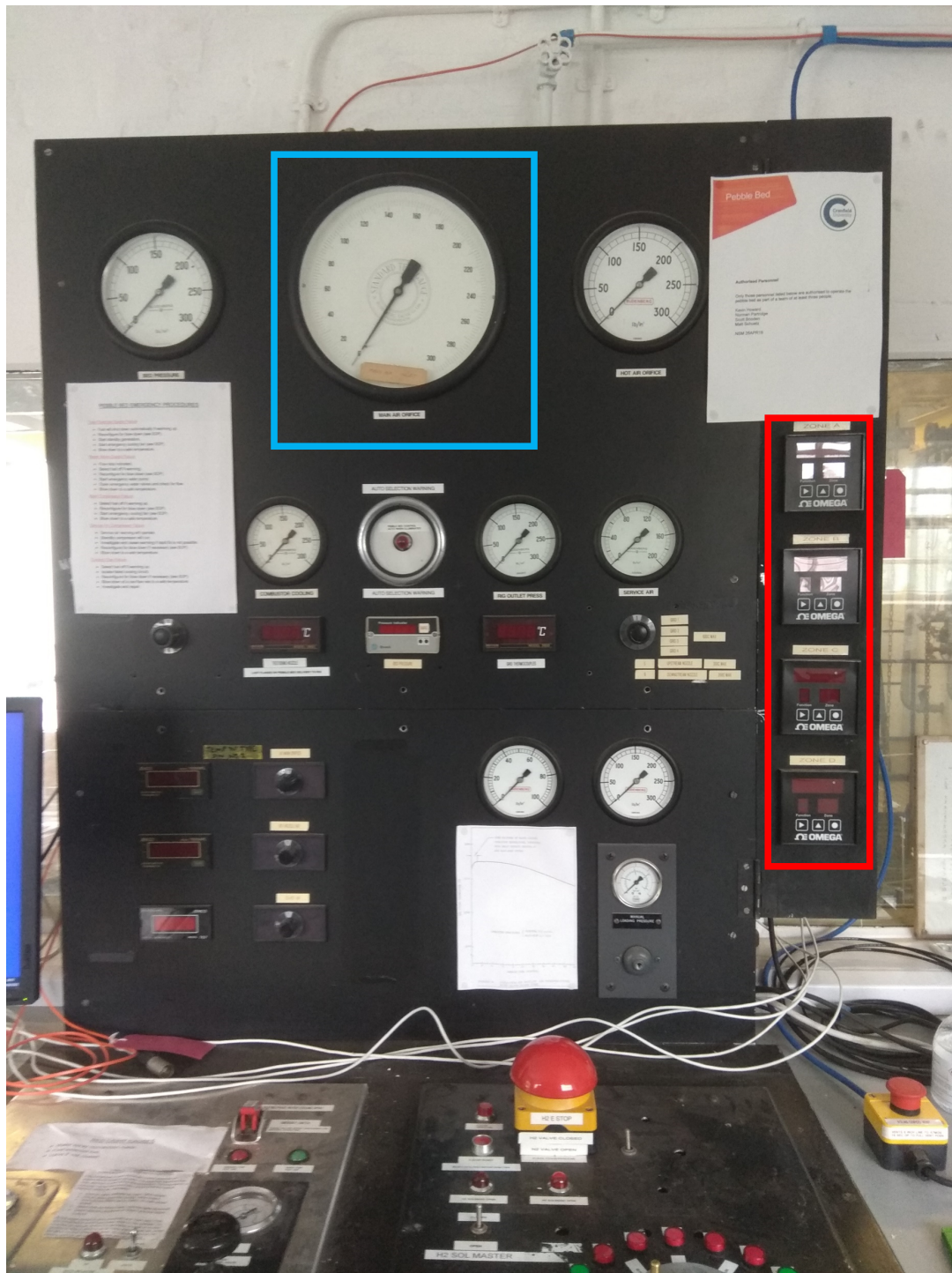


FIGURE A.3: View of the main board monitoring the pebble bed. The red rectangle highlights the displays of the 48 thermocouples and the blue rectangle highlights the gauge of the air supply pressure.

APPENDIX B

Example of Uncertainty Estimation

Based on the procedure described in section 3.7.4, this Appendix presents an example calculation of uncertainty for measured NO_x emissions of the high momentum flux ratio (MFR) burner at $10.1bar_a$ at $585K$ and $\Phi = 0.51$. The reason this point was chosen is that the high MFR design at these conditions produced the highest NO_x value and hence has the lowest relative uncertainties.

The averaged value from the sample at this condition is $[NO_x] = 51.5ppmv$. Random error is calculated from the sample values as given by equation (3.17) and for this case is $s_{\bar{x}} = \pm 0.06ppmv$.

For the systematic error, first, the uncertainty of the instrument is calculated. The values of Table 3.2 are placed in equation (3.18) and give $\varepsilon_{in} = \pm 2.36\%FS$. Hence the error arising from the instrument, for a full-scale (FS) value of $500ppmv$ is $b_{in} = \pm 0.0236 \cdot 500 = \pm 11.8ppmv$.

The error from the calibration cylinder as given by equation 3.20, with $\varepsilon_{cg} = \pm 5\%$ and the instrument reading being the averaged NO_x value of $51.5ppmv$, is $b_{cg} = \pm 2.58ppmv$.

The systematic error is the sum of the instrument and calibration errors, $b = \pm 14.38ppmv$ and the total error is $U = \pm \sqrt{b^2 + s^2} \approx \pm 14.38ppmv$.

It shall be noted here that the random error is negligible compared to the systematic and could have been omitted.

As a relative uncertainty, this total error value is approximately 28% of the reading, which highlights the unacceptably high measurement uncertainties. The highest relative uncertainty for the high momentum flux ratio design is for the $10bar_a$, $446K$

at $\Phi = 0.3$ case and is 81% of the reading. Figure B.1 is plotted to provide an idea of the magnitude of the error bars.

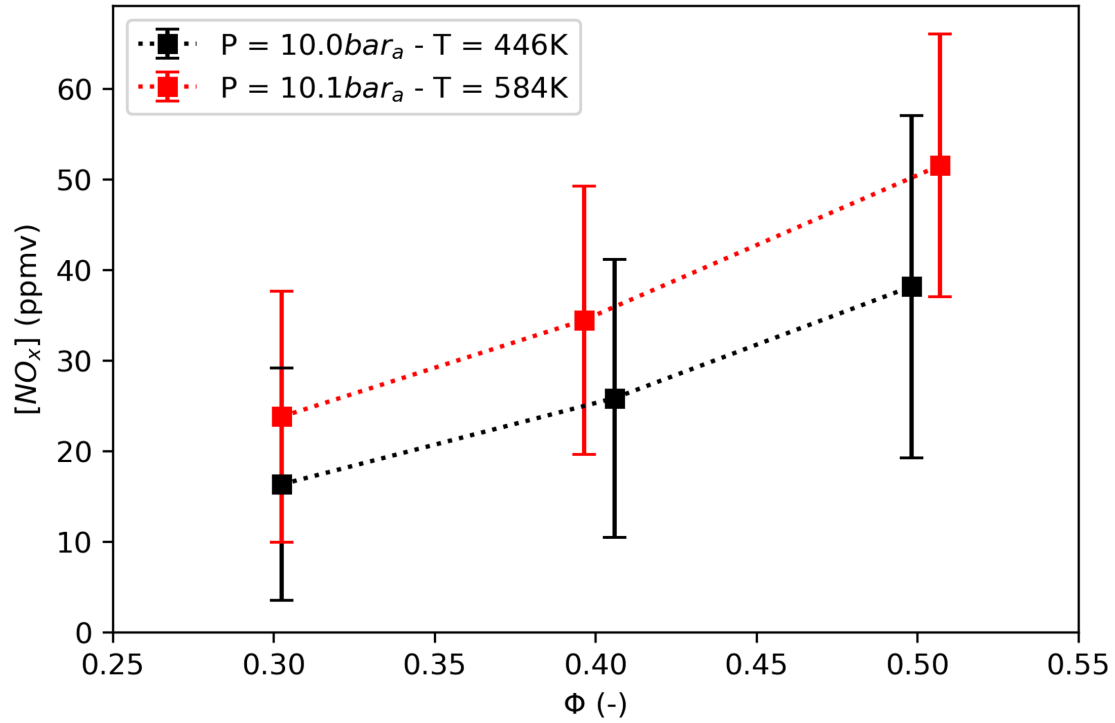


FIGURE B.1: NO_x against Φ . As measured emissions for the high MFR injector configuration including error bars based on the estimated uncertainties.

APPENDIX C

Energy Emission Index Plots with Uncertainties

This appendix shows the $EEINO_x$ plots of the experimental measurements, including the uncertainty estimations for both the emission index and the equivalence ratio.

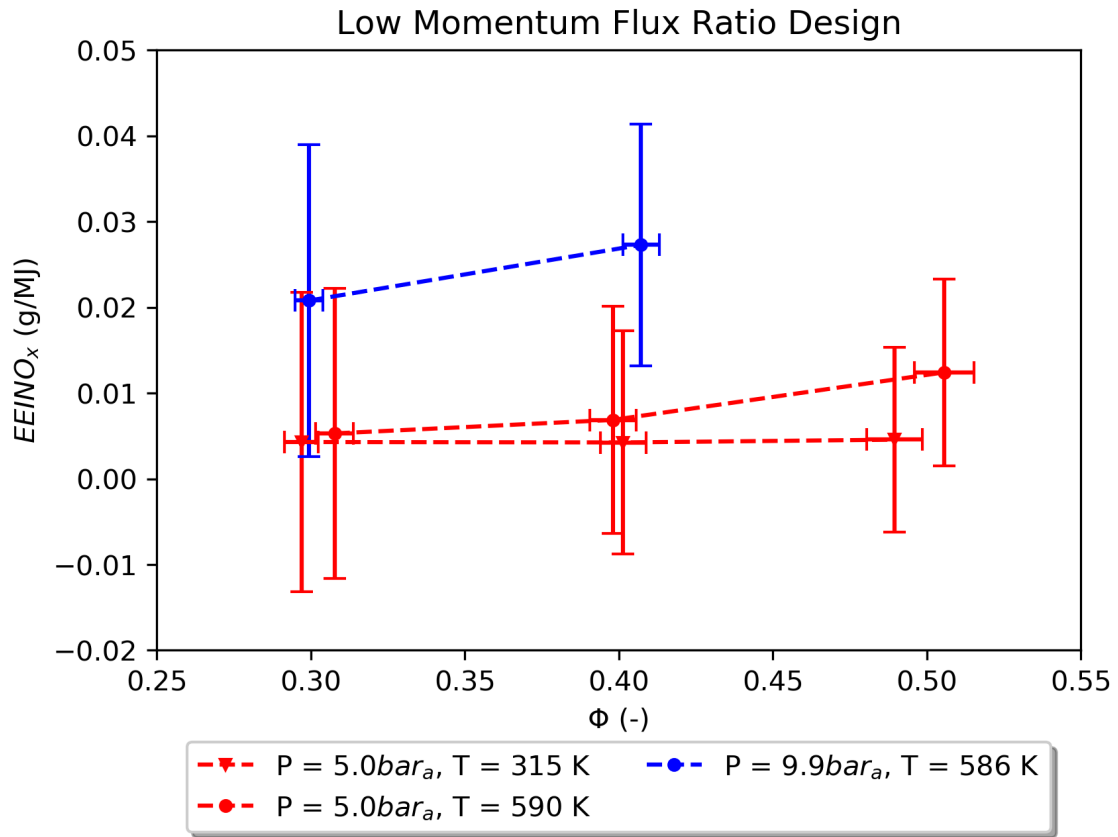


FIGURE C.1: $EEINO_x$ vs Φ for the low momentum flux ratio design

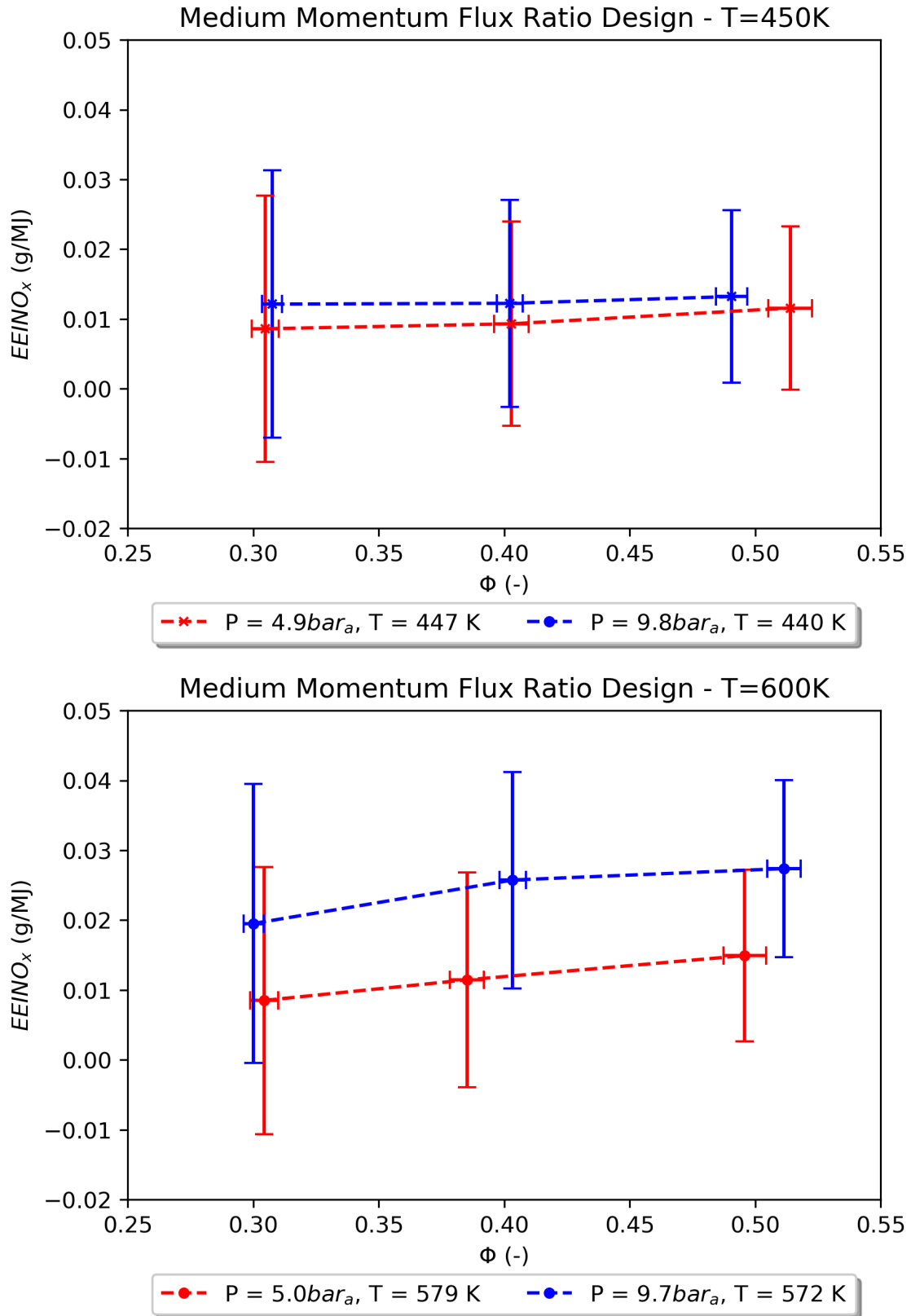
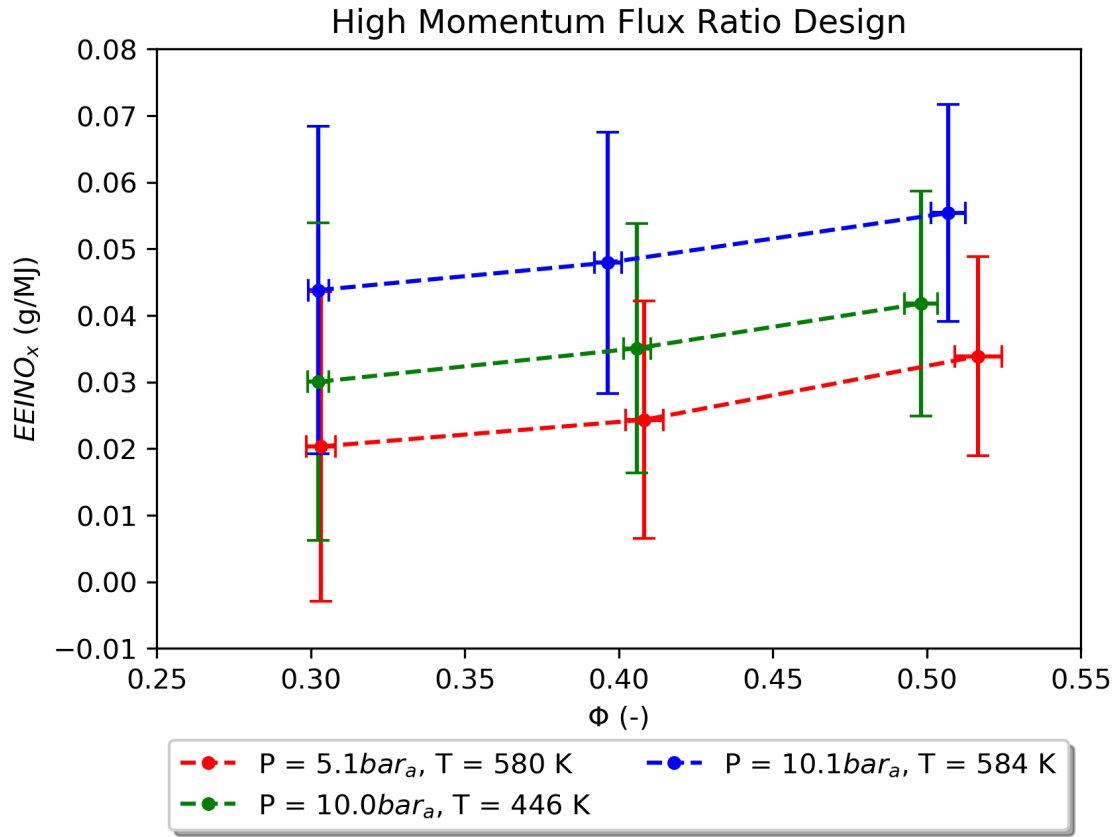


FIGURE C.2: $EEINO_x$ vs Φ for the medium momentum flux ratio design. Cases for $T_{in} = 450K$ (top) and $T_{in} = 600K$ bottom are shown separately for better clarity.

FIGURE C.3: $EEINO_x$ vs Φ for the high momentum flux ratio design

Of course, it should be noted that the extension of the $EEINO_x$ error bars to negative values in all 3 plots, has no physical meaning. Yet, the author decided to retain this aspect in the plots in order to highlight the fact that the uncertainty, especially in lower emission values, is orders of magnitude larger than the $EEINO_x$ value itself.

