



AFRL-AFOSR-JP-TR-2018-0053

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**Towards the Application of MILD Combustion to Gas Turbines**

**Paul Medwell  
THE UNIVERSITY OF ADELAIDE**

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**06/21/2018  
Final Report**

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**Air Force Research Laboratory  
AF Office Of Scientific Research (AFOSR)/ IOA  
Arlington, Virginia 22203  
Air Force Materiel Command**

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<b>REPORT DOCUMENTATION PAGE</b>			<i>Form Approved</i> <i>OMB No. 0704-0188</i>		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Executive Services, Directorate (0704-0188). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.</b></p>					
<b>1. REPORT DATE (DD-MM-YYYY)</b> 21-06-2018		<b>2. REPORT TYPE</b> Final		<b>3. DATES COVERED (From - To)</b> 25 Jun 2014 to 24 Dec 2017	
<b>4. TITLE AND SUBTITLE</b> Towards the Application of MILD Combustion to Gas Turbines				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b> FA2386-14-1-4039	
				<b>5c. PROGRAM ELEMENT NUMBER</b> 61102F	
<b>6. AUTHOR(S)</b> Paul Medwell				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> THE UNIVERSITY OF ADELAIDE 115 GRENFELL ST ADELAIDE, 5000 AU				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> AOARD UNIT 45002 APO AP 96338-5002				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> AFRL/AFOSR IOA	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> AFRL-AFOSR-JP-TR-2018-0053	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> A DISTRIBUTION UNLIMITED: PB Public Release					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> The PI was succesful in the proposed effort to develop robust methods for producing regime maps in the transition to MILD combustion. While this approach is an improved method to classify flames, the applicability of generalized regime maps at predicting the appearance of turbulent flames is limited without a-priori knowledge of the flow-field. The PI identified the importance of minor species, formaldehyde (CH <sub>2</sub> O). CH <sub>2</sub> O plays a critical role in flame stabilization under MILD combustion conditions. Additionally, equilibrium levels of OH in the oxidant stream needs to be considered in modelling of these flames. The results from calculations of simplified reactors can be applied to more complex and realistic flame conditions, providing the temporal and/or spatial effects are taken into consideration. Computational models of jet flames can reproduce experimental trends, including a-priori predictions. Finally, a new burner has been developed to facilitate future experimental campaigns of flames in a vitiated coflowincluding MILD combustionunder elevated pressure conditions (up to 10 bar). The PI was very successful with 19 publications as a direct result of the research grant.					
<b>15. SUBJECT TERMS</b> AOARD, MILD combustion, Flameless Combustion					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b> CHEN, JERMONT
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			
Standard Form 298 (Rev. 8/98) Prescribed by ANSI Std. Z39.18					

DISTRIBUTION A: Distribution approved for public release.

				<b>19b. TELEPHONE NUMBER</b> <i>(Include area code)</i> 315-227-7007
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## **FA2386-14-1-4039: Final Report**

### **Towards the application of MILD combustion to gas turbines**

March 2018

Principal Investigator: Paul Medwell (The University of Adelaide)

#### **Abstract**

MILD combustion is a relatively recently exploited unique combustion regime characterised by high thermal efficiency and low emissions, especially NO<sub>x</sub> and soot. To date, implementation of MILD combustion has been almost exclusively limited to furnace environments. There have been several recent attempts at incorporating this technology into gas turbines. In this application the almost complete elimination of soot formation and thermal NO<sub>x</sub> under MILD combustion conditions is highly desirable; however the power density has been reported as being too low for practical implementation using established techniques. An innovative approach of integrating MILD combustion into gas turbines is proposed, by exploiting the inter-turbine burner (ITB) concept previously introduced by AFRL. Through a fundamental-level study, this project addresses some of the gaps in the current understanding of combustion science relating to the proposed concept of applying MILD combustion to gas turbines. A series of nineteen publications have arisen from the work, and a new burner has been designed to enable future experimental studies of flames in a hot and vitiated coflow under elevated pressure conditions.

# 1. INTRODUCTION

## 1.1 Gas turbines

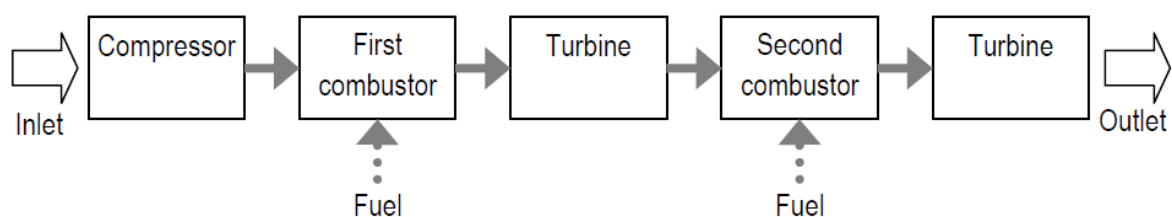
Gas turbines are a critical component for the U.S. Air Force to achieve its objectives, both for electricity generation and aerospace propulsion. For economic and operational reasons there is a continual demand for higher power output, higher efficiency and lower emissions (both environmental benefits and reduced thermoacoustic signature).

Combustion efficiency within modern gas turbines is typically already quite high [1]. It is also well-known that CO and NO<sub>x</sub> emissions can be controlled by operating lean premixed combustors. However, this approach introduces a number of challenges, including: thermoacoustic instabilities, unsteady flame stabilisation, flashback, and sensitivity with operating conditions [2]. Furthermore, increasing the thermal efficiency remains an ongoing challenge due to limitations of the turbine inlet temperature which place restrictions on the outlet of the combustor, and hence its operating conditions.

To address the needs of gas turbine development, it is widely recognised that revolutionary approaches are required. The inter-turbine burner (ITB) concept is one example that has been identified as a key research priority in the U.S. Air Force “Technology Horizons” 2010–2030 report. The ITB shares similarities with other combustion technologies, and this proposal seeks to bring together these disparate concepts into a cohesive project.

## 1.2 Current state-of-the-art

The less demanding weight requirements make advancements in ground-based gas turbines somewhat less challenging, but much of the knowledge gained from this application can generally be rolled-out to aero-engine applications. One approach to improve thermal efficiency is through the use of sequential combustion [3]. In essence, following a combustor and turbine, the exhaust gases are then fed through another combustor before the final turbines, as shown schematically in Figure 1. In the second combustor, combustion occurs in the presence of exhaust gases from the first combustor. The mode of operation in stationary gas turbines featuring sequential combustion follows the same operating principles as the ITB concept.



**Figure 1:** Schematic of the sequential combustion concept.

The ITB approach can achieve the same power output, but with lower temperatures, as indicated in Figure 2 [4]. The introduction of a secondary combustor is known to be beneficial in gas turbines [5, 6] in addition to offer other benefits for military applications [7]. Further advantages are a wide range of turn-down ratios and fuel flexibility [8]. This type of combustion system has been described as a revolutionary approach to advance engine performance [9].

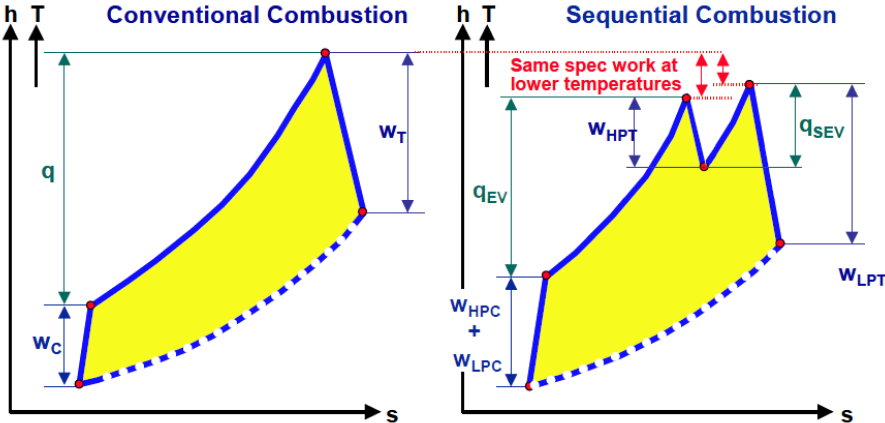


Figure 2: Sequential combustion lowers the operating temperature for the same thermal output [4].

### 1.3 MILD combustion

The combustion process in the ITB occurs in the presence of exhaust gases from the first-stage combustor. The high temperature and depleted oxygen inlet conditions of the second combustor resemble those of moderate or intense low oxygen dilution (MILD) combustion. In MILD combustion, also known as flameless / distributed / colourless combustion, the low oxygen environment creates a distributed reaction zone, thus avoiding high peak temperatures. The high inlet temperature also ensures autoignition (thus eliminating the risk of flame extinction). MILD combustion has been proven successfully in furnace environments and is typified by improved thermal efficiency, a more uniform temperature distribution and a large reduction in emissions, especially  $NO_x$  and soot.

The required conditions to achieve MILD combustion are a depleted  $O_2$  concentration and elevated temperature of the oxidant stream, as shown diagrammatically in Figure 3 [10]. The precise definition of MILD combustion is open to some interpretation, although the definition provided by Cavaliere & de Joannon [11] is most commonly used. Similarly, the location of the boundary is dependent on the fuel and operating conditions, but Figure 3 gives an indication of the conditions required to achieve MILD combustion. Of particular note is that to transition from “normal” combustion to MILD combustion it is necessary to cross either a “non-combustible zone” or one associated with lifted flames. It should be noted that flame liftoff is dependent on many factors, and so it is misleading to assert that all flames in these conditions will be lifted. Nonetheless, these operating conditions in the transition to MILD may be associated with unstable flame behaviour.

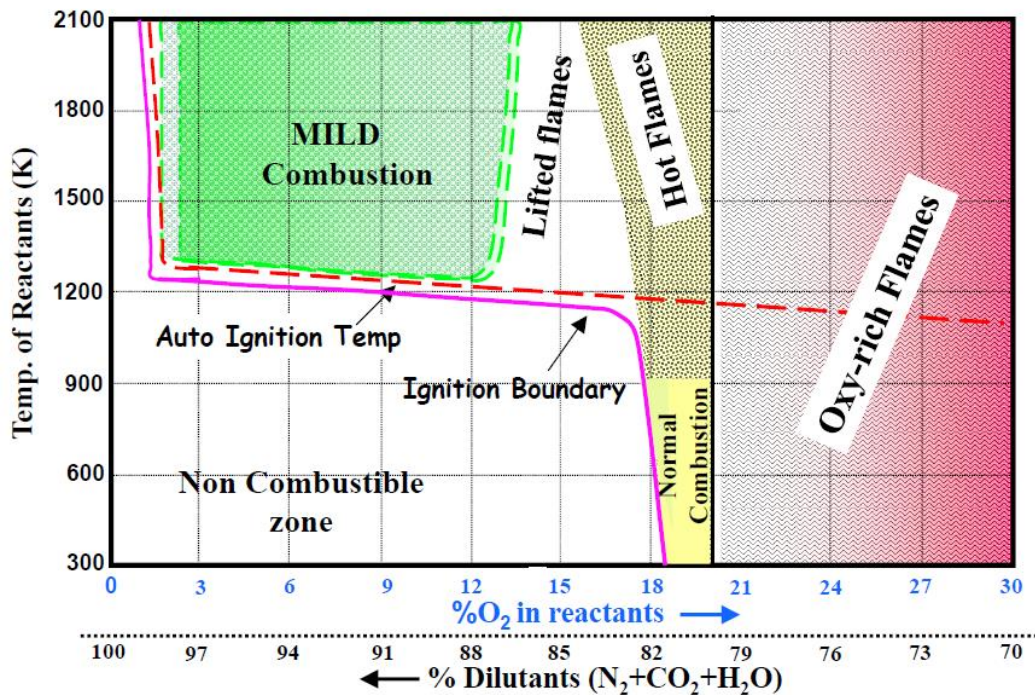


Figure 3: Combustion regime diagram [10].

With regard to the ITB concept, the level of  $O_2$  in the oxidant stream will govern the overall flame behaviour. For the *Alstom* sequential combustor the  $O_2$  concentration is of the order of 13% at the ITB [12]. Consistent with Figure 3 and lifted flame experiments, an  $O_2$  concentration in this range is likely to be within an unstable region which seems to occur between conventional combustion and stable MILD combustion [13]. Therefore, there appears to be a significant advantage in operating at lower  $O_2$  levels, entirely within the MILD regime, to avoid any potential issues with stability.

The unstable flame behaviour encountered in the transition from conventional to MILD combustion condition is poorly understood. Pressure, fuel composition, oxidant composition (both oxygen concentration, and major/minor species), oxidant temperature, flow-field and turbulence intensity are all known to have important effects on flame behaviour. However, a comprehensive understanding of the effects of these parameters on the flame stabilisation mechanisms governing jet flames in a heated and vitiated coflow remains elusive.

## 1.4 MILD combustion in gas turbines

To date, practical application of MILD combustion has been predominately limited to furnace environments. There has been recent interest in applying MILD combustion to gas turbine applications. Operating in the MILD combustion regime offers many advantages to gas turbine applications, including: lower operating temperatures, avoidance of thermoacoustic instabilities, fuel flexibility, no lean flammability limit (enabling very wide range of turn-down ratios), low  $NO_x$  emissions and an almost complete elimination of soot.

The development of MILD combustion has almost exclusively concentrated on atmospheric pressure systems. The behaviour of MILD combustion under high pressure conditions is poorly understood, yet will be critical for practical ITB applications. The role of pressure is of particular importance in the identification of different combustion regimes. Interestingly, despite much research into the MILD regime, the transition from conventional air combustion to MILD combustion still remains poorly understood for atmospheric pressure. It is known from experience with furnaces and experimental burners that an unstable regime exists between conventional and MILD conditions; however, little is known about the factors responsible for this instability, let alone this transition regime under elevated pressure.

Given the many advantages of MILD combustion, there have been many attempts at implementing a MILD combustor for gas turbine applications. This is a non-trivial task [14]. One of the most significant impediments limiting MILD combustion in gas turbine applications is the relatively low power density, due to the requirement of mixing large quantities of exhaust gases with the fuel stream [15]. The increased level of inert gases also suggests that there will be a higher total mass-flow of gas, resulting in the need for a larger engine. Moreover, due to the low oxygen concentration conditions, MILD combustion is expected to be associated with longer chemical time-scales. Despite these challenges, a European Commission project has been initiated aimed at incorporating flameless oxidation (FLOX<sup>®</sup>) in a gas turbine combustor [16]. This project takes an established FLOX<sup>®</sup> burner designed for furnaces and operates it under gas turbine conditions. Modelling [17] and optical diagnostics were applied to experimentally study the operational behaviour of this combustor at 475 kW and a pressure of 20 bar [2, 18]. Levy et al. introduced a FLOXCOM combustor to achieve MILD combustion conditions operating in a reverse-flow mode for a gas turbine combustor [19]. Other reports of MILD combustion in a gas turbine combustor using well-established swirl techniques have also been made, further demonstrating the suitability of a wide range of fuels [20]. All of these attempts, however, have reported that the emissions are heavily dependent on the operating conditions. This is primarily a result of insufficient knowledge of the optimal conditions required to achieve MILD combustion in gas turbine environments.

## 1.5 Proposed configuration

Achieving the exhaust gas recirculation required for MILD combustion in a practical gas turbine requires different approaches to the techniques that have been established in furnaces. One of the key limitations is the power density. In contrast to explicitly recirculating exhaust gases (which requires additional space), an alternative approach is the use of sequential combustion (as previously introduced in Section 1.2). Rather than “recirculating” exhaust gases, the products from one combustion process may be used as the inlet for a second combustor. This approach has previously been demonstrated on a fundamental-level to establish MILD combustion conditions [21]. Despite the introduction of a second combustor, the added benefits may not impose a significant penalty on the overall power density of the engine [22].



The current proposal seeks to integrate MILD combustion into the proven sequential combustion system. The key difference is the operating conditions of the ITB. With further insight into flame stabilisation mechanisms under the heated and diluted oxidant conditions it may be possible to design a burner which operates under MILD combustion conditions for use in the secondary combustor. In addition to providing high efficiency, the ITB would also provide a post-combustion cleaning stage to reduce CO, NO<sub>x</sub> and soot from the conventional primary combustor [23, 24]. This would enable the first combustor to operate under conditions that may be more efficient, without particular concern of the emissions (as they may be cleaned in the second combustor). Furthermore, thermoacoustic instabilities, which can be problematic in gas turbines, are avoided under MILD combustion conditions; further enhanced by eliminating high temperatures that hasten material deterioration.

## 1.6 Objectives

The aim of the proposed work is to identify the key combustion regimes in depleted oxygen environments spanning MILD to conventional combustion over a range of operating conditions relevant to ITB applications. To realise this aim, it is necessary to further develop fundamental understanding of the factors governing flame stabilisation under these operating conditions. Notwithstanding some efforts of incorporating MILD combustion into gas turbine combustors, previous work on fundamental flame stabilisation mechanisms has focussed on atmospheric pressure unconfined flames with simple fuels. Clearly, to be of interest to the gas turbine community there needs to be a trend towards studies at high pressure, confined flames with complex and liquid fuels. In particular, the combustion behaviour in the transition between air and MILD conditions is particularly critical for engine applications to guarantee stable combustion across a wide operating range. This is the focus of the proposed work.

The motivation of the project is the application of MILD combustion into gas turbines, within the conceptual framework of an ITB / sequential combustion system. Some practical challenges are expected with the implementation of this combustion concept. Nevertheless, this project seeks to address the fundamental issues related to the combustion science. The specific aim is the development of understanding of flame stabilisation mechanisms in the transition to MILD combustion and across the range of conditions of relevance to sequential combustors.

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## 2. APPROACH

### 2.1 Goals

The over-arching goal of this research is to assess the influence of; oxygen concentration, inlet temperature, operating pressure, fuel type (especially complex and/or liquid fuels) and the role of turbulence on flame behaviour. To address the aims, four streams of tasks are proposed, as outlined in Section 2.2. The proposed tasks do not directly link to engine development incorporating the ITB concept but will develop improved understanding of the important aspects of the combustion science.

### 2.2 Tasks

**Task 1:** *Develop chemistry-dominated regime diagram from simulations.*

Combustion regime diagrams exist for some experimental configurations, but these are not comprehensive across a wide range of operating conditions and do not enable the salient chemistry effects to be isolated. To address this goal the following sub-tasks have been identified:

- 1.1) Compare ignition delay for flames at 1 atm and with simple fuels.
- 1.2) Examine the role of minor species addition to the mixtures from Task 1.1.
- 1.3) Assess and contrast the reaction zone structure of premixed and non-premixed flames from Tasks 1.1 & 1.2.
- 1.4) Extend simulations beyond 1 atm and simple fuels.

**Task 2:** *Verification of jet flame models.*

Previous detailed experimental measurements are available for a range of existing atmospheric pressure open flames under MILD combustion conditions. Computational modelling of these flames, both laminar and turbulent, will provide a test-case for future modelling efforts. The particular focus of these verification models will be the turbulence-chemistry interactions, which are critical under the low Damköhler number conditions associated with MILD combustion. The following sub-tasks are proposed:

- 2.1) Comparison of laminar flames against previous simulations/experiments.
- 2.2) Validation of turbulent flames against existing experimental data.
- 2.3) Examine the role of minor species addition to the oxidant stream.
- 2.4) Conduct a parametric study covering a wider range of operating conditions available from the previous experiments.

**Task 3:** *Develop confined and pressurised jet flame burner.*

Streaming jet flames in a vitiated coflow environment are ideally suited for the study of the fundamental aspects governing ITB burner conditions. The vitiated coflow burner design shares the same operating principle as the ITB, and each parameter may be varied independently for systematic studies, and has well-controlled boundary conditions which are required for accurate modelling. The fundamental insight that has been gained from open-flame vitiated coflow burners (such as the jet-in-hot-coflow burner) operating under MILD conditions is limited, and existing burners lack the capacity to investigate liquid fuels at elevated pressure. To address this need, a new design for a confined and pressurised experimental burner is proposed.

Commissioning of the burner will take place in the following stages, with the results from each stage adding to the parameter-space of the combustion regime diagram.

- 3.1) Design and build a new open-flame vitiated coflow burner to expand and contrast existing regime diagrams using a single platform. The burner will operate on both gaseous and liquid fuels, and suitable for both laminar and turbulent flows.
- 3.2) Confine the new burner to assess and understand the effects of limited volume, residence time and the effects of the walls. Artificially-induced turbulence will also be introduced.
- 3.3) Pressurise the new burner to expand the regime diagram to cover conditions previously unexplored operating conditions.

**Task 4:** *Develop understanding of turbulent flame stabilisation mechanisms.*

Development of a comprehensive regime diagram for turbulent flames spanning a wide range of operating conditions. Key parameters of interest include:

- 4.1) Coflow temperature.
- 4.2) Coflow O<sub>2</sub> concentration.
- 4.3) Coflow major and minor species concentration.
- 4.4) Jet velocity, Reynolds number and turbulence intensity.
- 4.5) Jet fuel type (phase and composition).

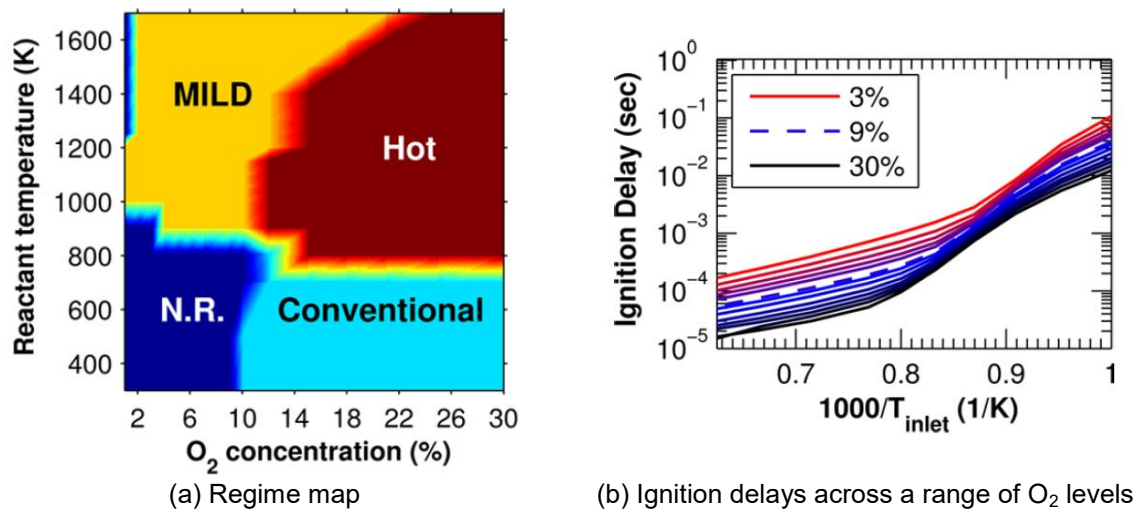
### 3. SUMMARY OF ACHIEVEMENTS

References to papers arising from this work are summarised in Section 3.5, and prefixed with the letter 'P'.

#### 3.1 Develop chemistry-dominated regime diagrams [Task 1]

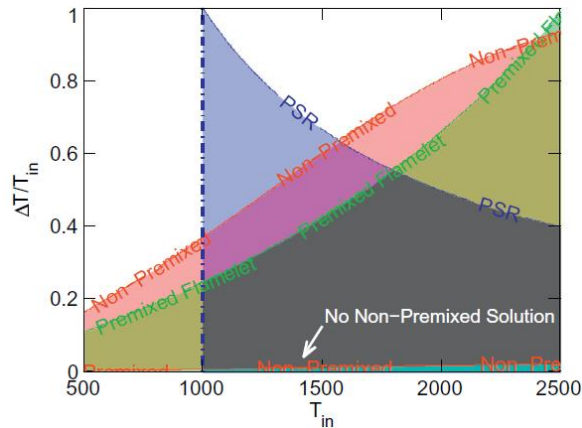
##### 3.1.1 Compare ignition delay for flames at 1 atm with simple fuels [Task 1.1]

From this work, a methodology has been developed to demarcate the flames in different combustion regimes. Based on well-stirred reactor models, the temperature increase and the autoignition temperature are used to classify flames as either 'conventional', 'hot' or 'MILD'. The autoignition temperature is determined from the ignition delay calculations, which also shed light on differences in flame behaviour under different operating conditions. Examples of the regime maps and ignition delay calculations results are presented in Figure 4.

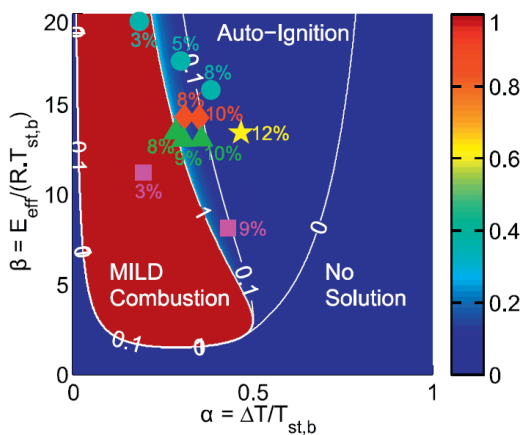


**Figure 4:** Calculation results across a range of O<sub>2</sub> levels: C<sub>2</sub>H<sub>4</sub>/N<sub>2</sub>/O<sub>2</sub> mixture ( $\Phi=1$ ). From P10.

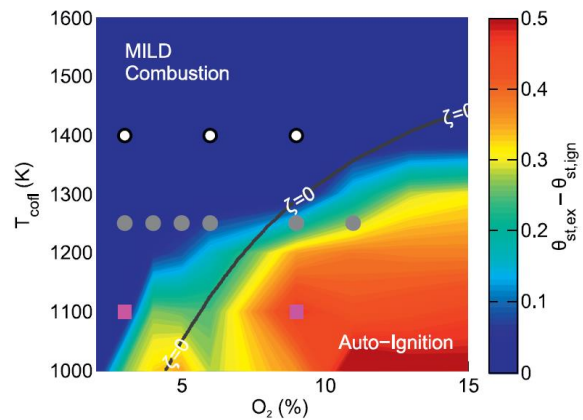
The regime maps have also been generalised and may be determined for arbitrary fuel/oxidiser mixtures. Figure 5(a) shows existing definitions based on different metrics for perfectly-stirred reactors, premixed flames, and non-premixed flames. These metrics have been consolidated based on non-dimensionalised parameters and independent on the system configuration: examples of such maps are presented in Figure 5 (b) and (c).



(a) Combined regime map for MILD combustion according to three definitions: PSR (blue), premixed flamelet (green) and non-premixed (red).



(b) Normalised autoignition temperature



(c) Contours of normalised excess temperature

**Figure 5:** Normalised regime maps from numerical analyses. From P14.

Using these approaches, regime maps can be developed for any fuel/oxidiser mixture and operating condition. However, it was also determined that differences in flame behaviour are not directly linked to global predictions from well-stirred reactors or autoignition delay time calculations. For example, the non-monotonic lift-off behaviour that has been observed in other previous experiments is not captured in these calculations. Therefore, characterisation of flames in the jet in hot co-/cross-flow (JHC) configuration requires more detailed analysis, incorporating additional details of the flow-field, to reproduce trends observed experimentally.

Further details of the results related to Task 1.1 have been presented in the following papers: P4, P10, P14.

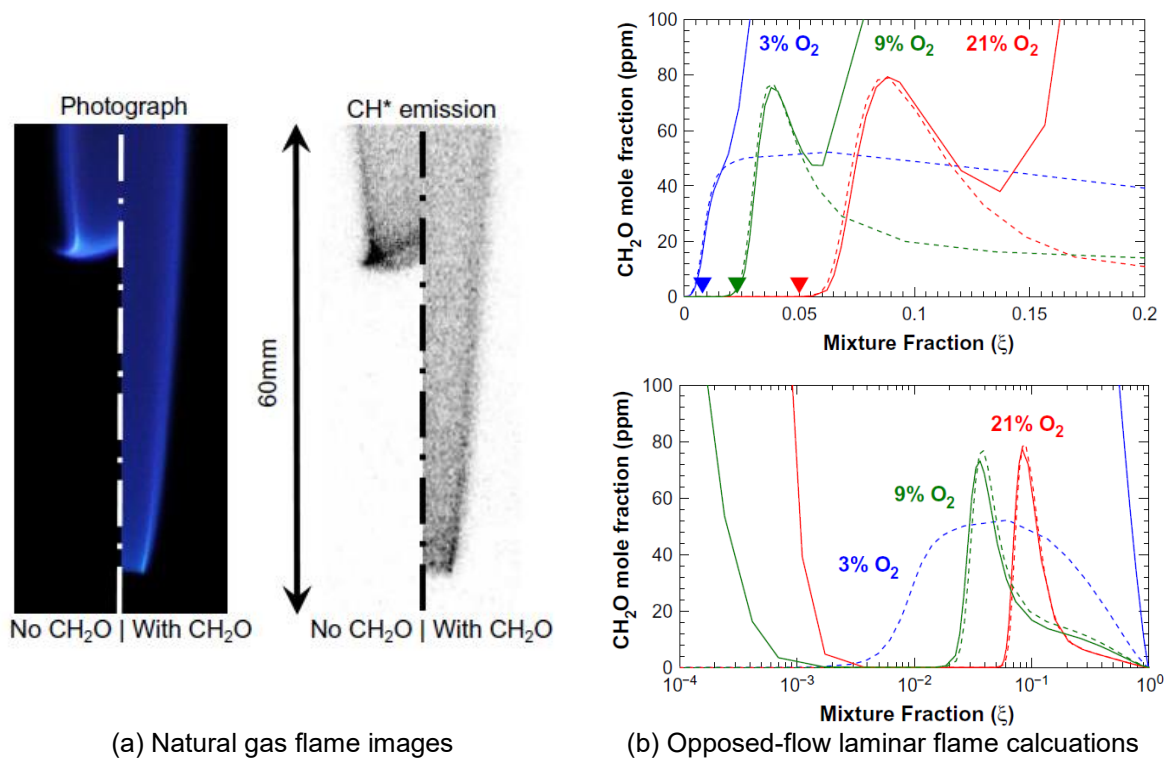
### 3.1.2 Examine the role of minor species addition to mixtures [Task 1.2]

In Task 1.1 (Section 3.1.1) it was identified that regime diagrams from well-stirred reactor calculations using simplified metrics are not well suited to predict the visual appearance of flames in the JHC configuration. Such diagrams tend to classify flames as MILD combustion even if their appearance and behaviour is not consistent with the expectations of MILD combustion. Therefore, prediction of flame behaviour

in these types of flames requires a more thorough analysis. In particular, it is essential to take into consideration the presence of minor species that occur in the oxidiser streams of these types of flames.

With the inclusion of minor species into a well-stirred reactor mixture, it is possible to replicate the temporal trends in ignition that are observed to occur in experimental flames. Although incorporating minor species indicates that it is possible to obtain useful information from well-stirred reactor models, determining the local composition may be challenging in practical flames and therefore negates the advantages of simplified maps. Similarly, interpretation of the time-dependent solutions requires additional analysis beyond simple definitions based on temperature of the system.

Notwithstanding the limitations of regime maps, it was shown that formaldehyde ( $\text{CH}_2\text{O}$ ) is a key species in the reconciling the differences in stabilisation mechanism under MILD combustion conditions. Experimental measurements revealed the influential role of  $\text{CH}_2\text{O}$ , and calculations compared how  $\text{CH}_2\text{O}$  is transported into the reaction zone at various  $\text{O}_2$  levels. The impact of  $\text{CH}_2\text{O}$  is presented in Figure 6.



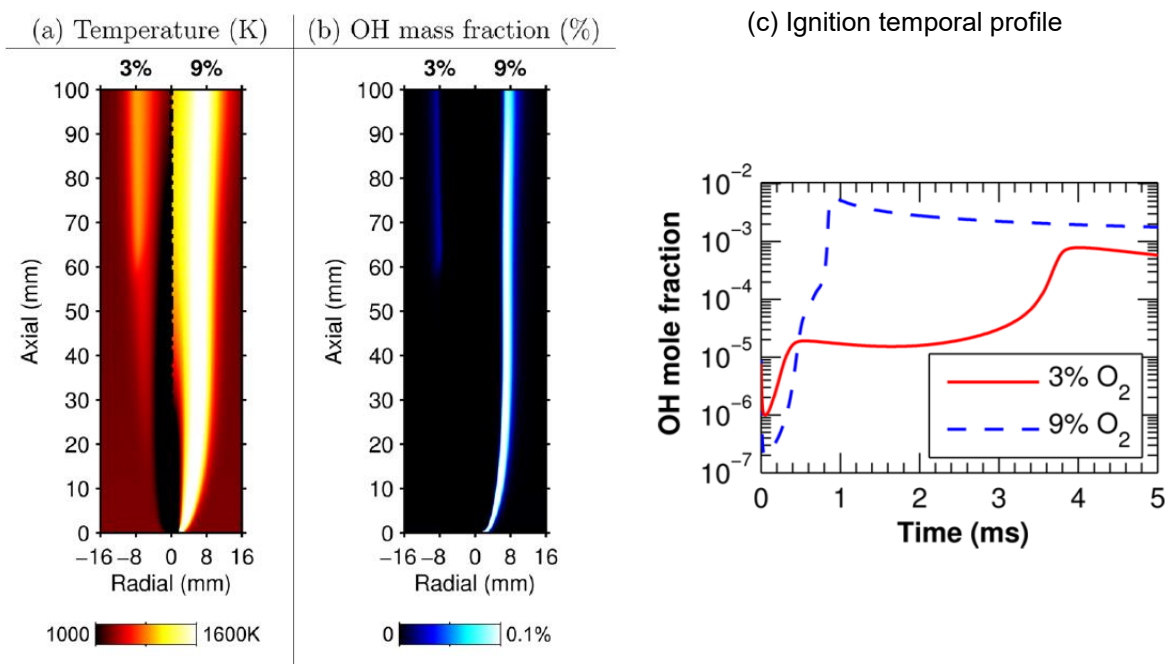
**Figure 6:** The impact of  $\text{CH}_2\text{O}$  on a laminar flame: (a) Experimental measurements. (b) Calculations with  $\text{CH}_2\text{O}$  (solid lines) and without  $\text{CH}_2\text{O}$  addition (dashed lines). From P7.

Further details of the results related to Task 1.2 have been presented in the following papers: P7, P9, P15, P18.



### 3.1.3 Compare the structure of premixed/nonpremixed flames [Task 1.3]

Laminar axisymmetric models of the flames show similar trends to the temporal ignition of the well-stirred reactors and agree with the behaviour observed experimentally. Analysis of ignition profile calculations has shown that it is possible to compare the ignition processes in premixed and nonpremixed flames; however, care in the interpretation of the data is needed. For example, Figure 8 presents two-dimensional DNS results of a laminar axisymmetric nonpremixed flame and results from a temporally-evolving well-stirred reactor. Whilst not all features are captured, the general trends between the 3% and 9% O<sub>2</sub> cases can be identified from both types of calculations.



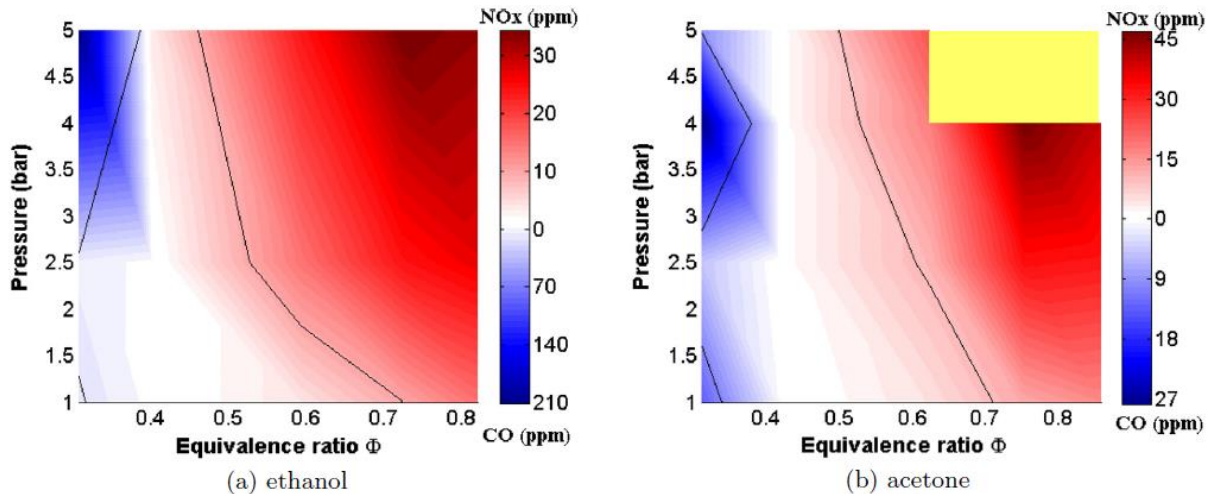
**Figure 8:** (a) Temperature, (b) OH mass fraction and (c) ignition temporal profile of C<sub>2</sub>H<sub>4</sub> flames with 3% and 9% O<sub>2</sub>. From P10.

To generalise these findings, a new nonpremixed flame definition for MILD combustion, based on an equivalent activation energy rather than prior assessment of a reference temperature, was derived and shown to be consistent with previous experimental observations of gradual ignition [P14]. This definition incorporates, and consolidates, previous definitions of the MILD combustion conditions and the suggested combustion regimes which exhibit similar ignition behaviours. The new definition has shown good agreement with steady-state flamelet simulations, demonstrating better agreement than previous classifications between the simulated and predicted boundaries between the non-premixed MILD and autoignitive regimes. These boundaries show that non-premixed MILD combustion is achievable by minimising the overall temperature increase, or increasing initial temperatures and may be achieved following forced ignition. The results of this work are presented in Figure 5.

Further details of the results related to Task 1.3 have been presented in the following papers: P1, P2, P4, P10, P11, P14, P15.

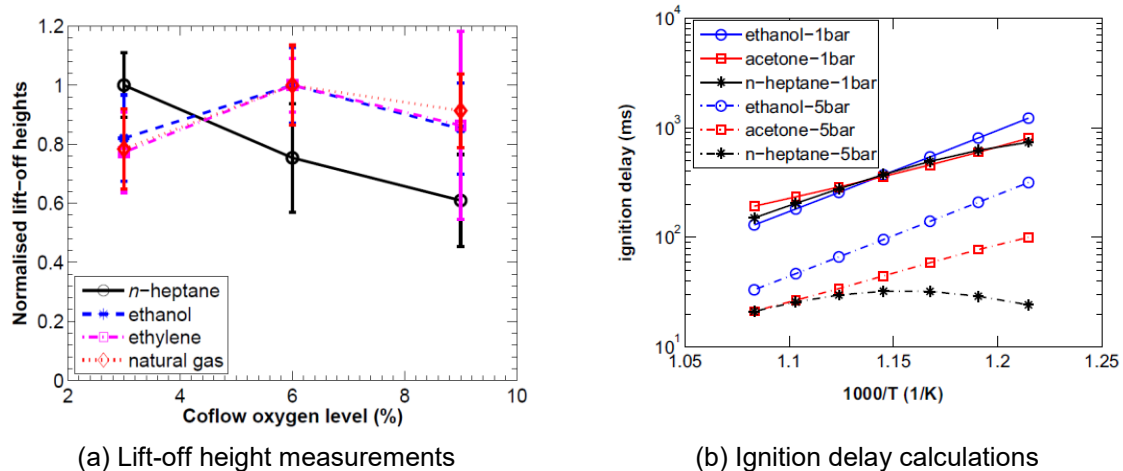
### 3.1.4 Extend investigations beyond 1 atm and simple fuels [Task 1.4]

MILD combustion of prevaporised ethanol, acetone and n-heptane was successfully established in a MILD combustor over a broad range of equivalence ratios with the chamber pressure ranging from 1–5 bar. The combustion stability is affected by fuel type, even though similar levels of emissions were measured from different fuels. It was found that ethanol burns well under the test conditions while acetone and n-heptane became unstable at higher equivalence ratios and higher pressures: under pressurised conditions the MILD operating domain becomes smaller (Figure 9)..



**Figure 9:** Operating regime (region between black lines) showing a narrowing operating range of MILD combustion under elevated pressure conditions. From P8.

Calculations reveal that the ignition delay is greatly shortened when the pressure increases from 1 to 5 bar. This indicates that early ignition is likely to occur before effective mixing, especially for n-heptane. In addition to increasing the chemical timescale to improve combustion stability, the flow timescale needs to be decreased to guarantee fast mixing, especially in a high-pressure MILD combustion device. The behaviour of the different fuels considered is presented in Figure 10.



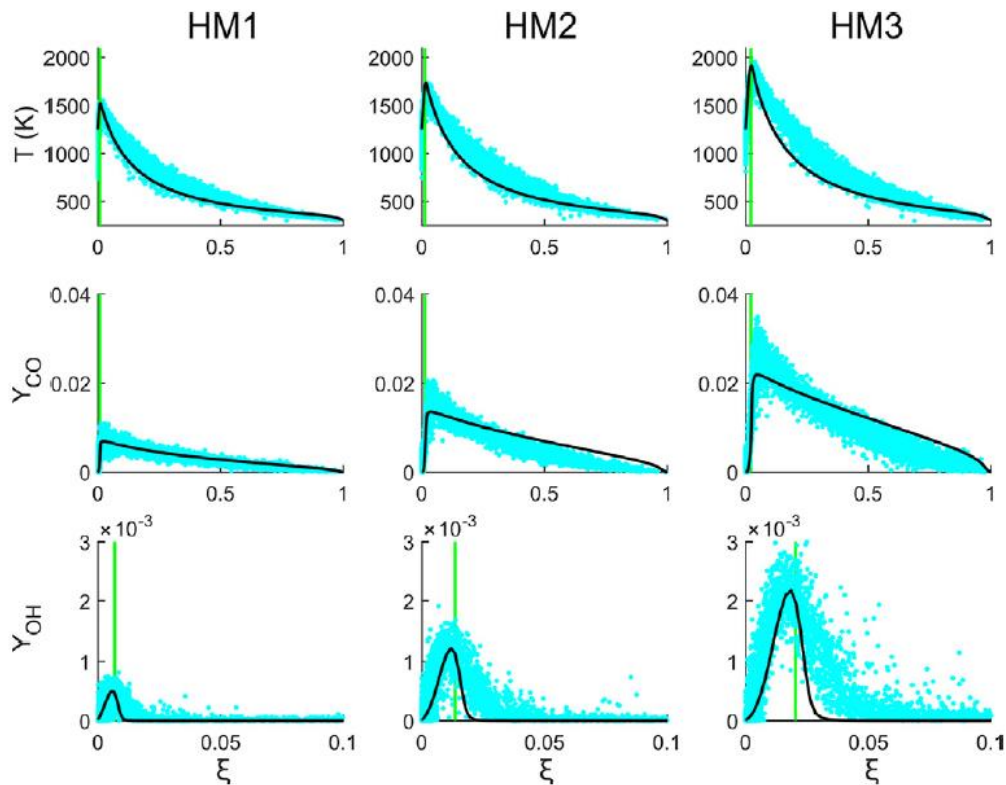
**Figure 10:** (a) Lift-off height and (b) ignition delay calculations for a range of different fuels. From P17.

Further details of the results related to Task 1.4 have been presented in the following papers: P3, P8, P16, P17, P19.

## 3.2 Verification of jet flame models [Task 2]

### 3.2.1 Compare laminar flames against previous results [Task 2.1]

The validity of laminar flame models in predicting experimental trends in MILD combustion flames has been shown. This was an implicitly a part of Task 1, but is also explicitly demonstrated in Figure 11 by comparing laminar flame calculations with single-point detailed data in a series of well-characterised turbulent jet flames.



**Figure 11:** Comparison of laminar flame calculations with experimental measurements of jet flames in various  $O_2$  levels. From P15.

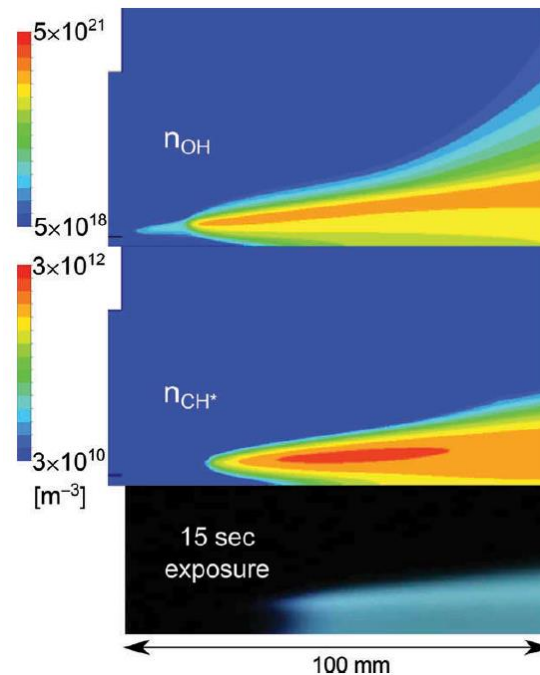
Laminar flame calculations were also shown to predict flame appearance, especially transitional flame behaviour, through examining the negative heat release region on the fuel-rich side of the reaction zone. The suppression of pyrolytic reactions is a feature of MILD combustion, and its identification in laminar flame calculations was found a more reliable metric to classify flames, than others based on temperature and/or ignition delay. The negative heat release profile was also shown to be a reliable predictor for a range of different fuels (for example, P17).

Further details of the results related to Task 2.1 have been presented in the following papers: P1, P4, P10, P11, P15, P16, P17.

### 3.2.2 Validation of turbulent flames against existing data [Task 2.2]

Lifted jet flames in a heated and depleted oxygen coflow stream in the transition to MILD combustion present an interesting test case for models. The use of RANS-based EDC models is particularly attractive due to the low computation cost yet retaining the capacity to model finite-rate chemical kinetics. However, previous

RANS-EDC modelling efforts of the JHC burner have failed to accurately predict the experimental observations of transitional flames. These flames are characterized by measurements of combustion reactions in a region that visually appears lifted. Through a parametric investigation, it has been demonstrated that by manipulating the EDC constants to take into account the different physical process under the hot and vitiated conditions, it is possible to obtain good CFD results of turbulent flames under MILD conditions even with relatively computationally-cheap EDC models (Figure 12). Importantly, the optimised EDC model also shows less sensitivity to boundary conditions, such as jet inlet turbulence intensity and jet temperature and robustness to the chemical composition of boundary conditions.



**Figure 12:** Comparison of OH and CH\* from EDC CFD model with an experimental photograph for a turbulent C<sub>2</sub>H<sub>4</sub>/N<sub>2</sub> jet in a 9% O<sub>2</sub> coflow. From P9.

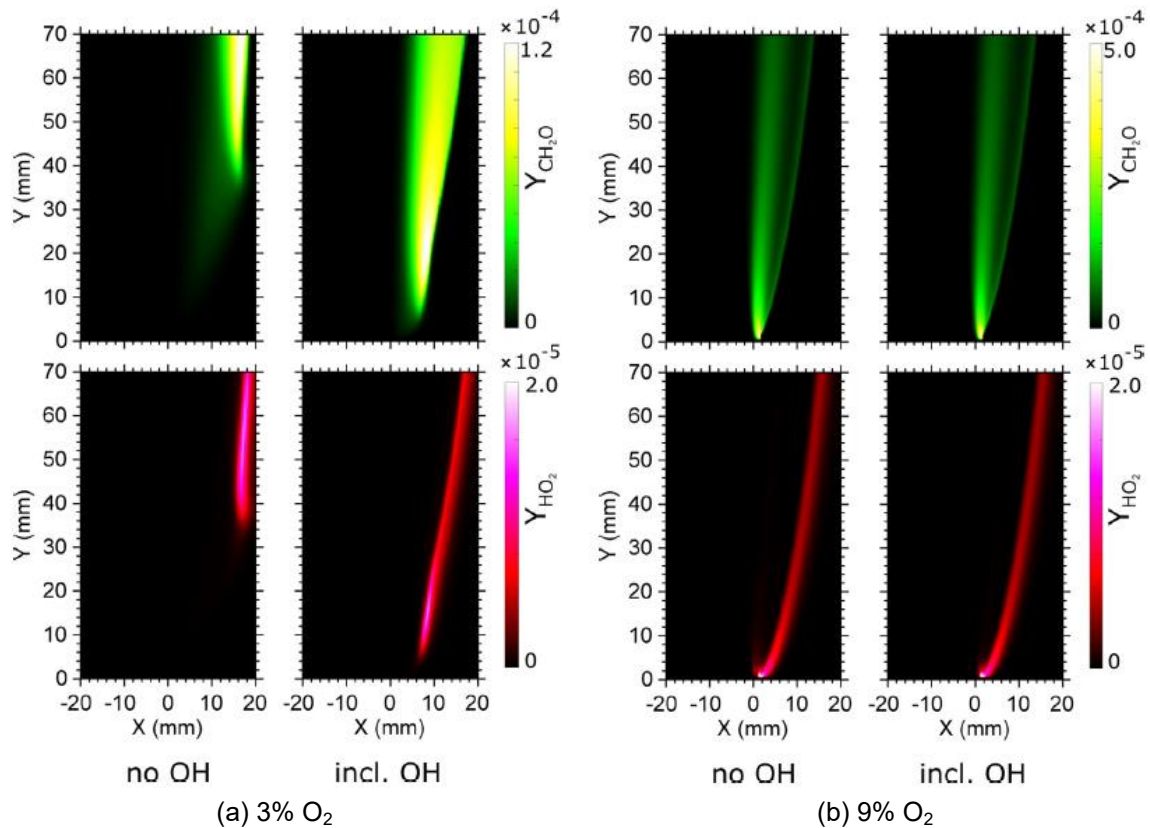
In addition to validation, two-dimensional RANS modelling supports the hypothesis that flames stabilise in regions of low strain rate, on the lean side of the jet shear layer. Distributions of HRR from two-dimensional RANS modelling can qualitatively replicate the gradual ignition processes and non-monotonic trends in visual lift-off seen experimentally in the transition to the MILD combustion regime.

Further details of the results related to Task 2.2 have been presented in the following papers: P9, P14.

### 3.2.3 Role of minor species addition to the oxidant stream [Task 2.3]

In addition to identifying the role dominant role of CH<sub>2</sub>O in the reaction zone (Section 3.1.2), the impact of minor species in the coflow stream have also been investigated. It has been shown that minor species in the coflow can drastically affect the flame behaviour under MILD combustion conditions, and needs to be properly

captured in models. In particular, it was found that calculations need to take into account the equilibrium levels of OH that exist in the coflow of these types of flames: examples of which are presented in Figure 13.



**Figure 13:** The impact of OH in the oxidiser stream of natural gas flames at (a) 3% O<sub>2</sub> and (b) 9% O<sub>2</sub>. From P15.

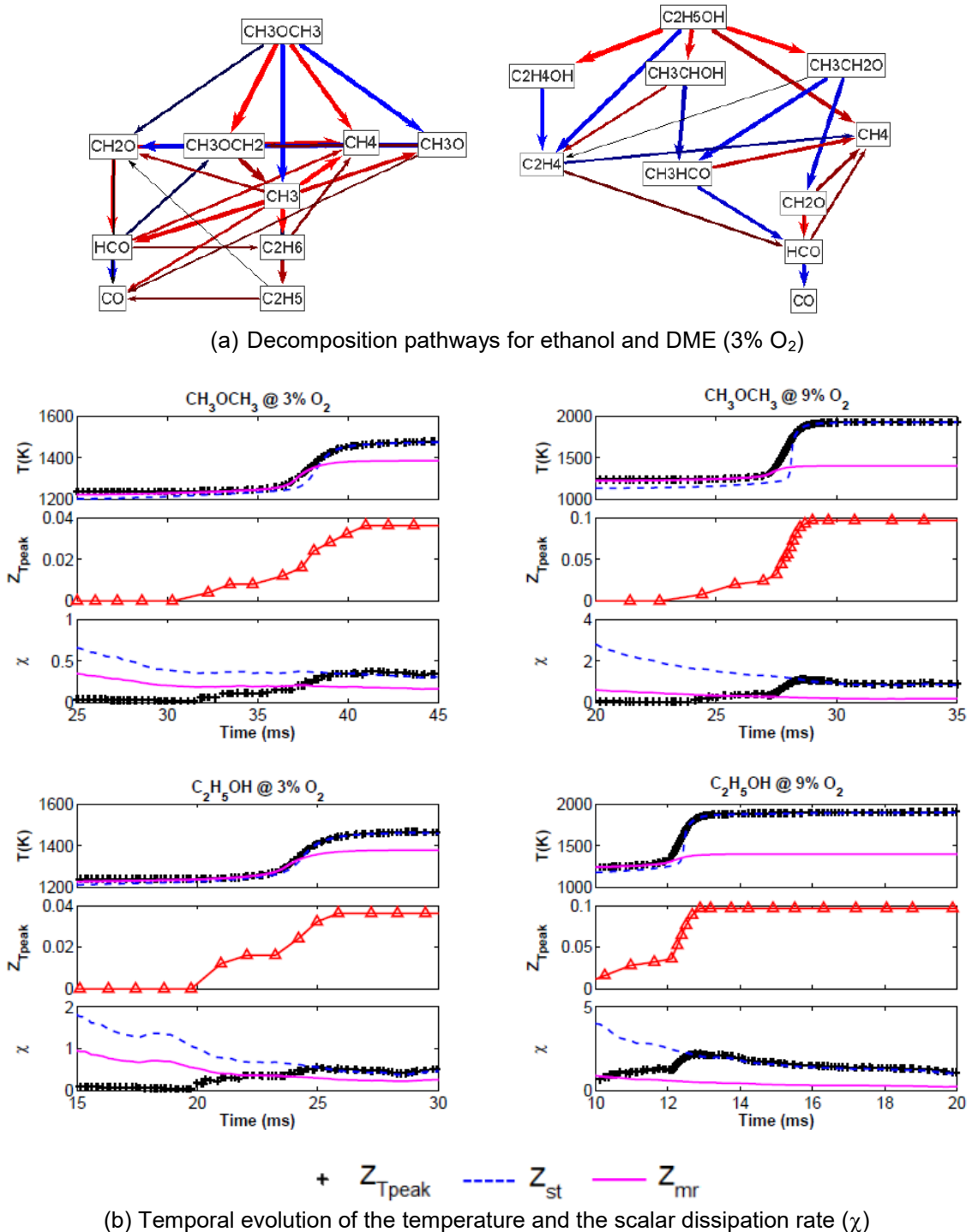
Further details of the results related to Task 2.3 have been presented in the following papers: P7, P9, P15.

### 3.2.4 Parametric study covering wider range of operating conditions [Task 2.4]

This task could continue almost *ad infinitum* to include a wide range of operating conditions. One example of a parametric study that has already been performed is the comparison of the isomers ethanol and di-methyl-ether (DME). A transitional flame structure revealed by OH-LIF was observed in the ethanol and the DME flames issuing into a 9% O<sub>2</sub> coflow but not in a 3% O<sub>2</sub> coflow. The occurrence of this transitional flame structure suggests that the ethanol and the DME flames deviated away from the MILD combustion regime as the coflow oxygen level increased from 3% to 9%. The initiation of the ignition of both fuels is characterised by a moderate temperature increase and a steady build-up of radicals. In comparison with DME, the onset of ignition of ethanol occurs much earlier and with a more rapid build-up of radicals. It also occurs under relatively richer conditions with a higher scalar dissipation rate than DME. This indicates that ethanol is more reactive than DME at the conditions investigated here, which could explain why DME flames always appeared more lifted than ethanol flames in experiments. Ethanol and DME are

destroyed via different pathways (Figure 14(a)), leading to differences in the intermediate species pool. However, temperature sensitivity analysis indicates that the differences in the fuel decomposition pathways play a minor role in the overall oxidation processes in the 3% O<sub>2</sub> cases. Under these conditions, the H<sub>2</sub>/O<sub>2</sub> pathways are very important for both fuels, contributing to the similarities between them.

Further details of the results related to Task 2.4 have been presented in the following papers: P2, P11, P14, P15, P18, P19.



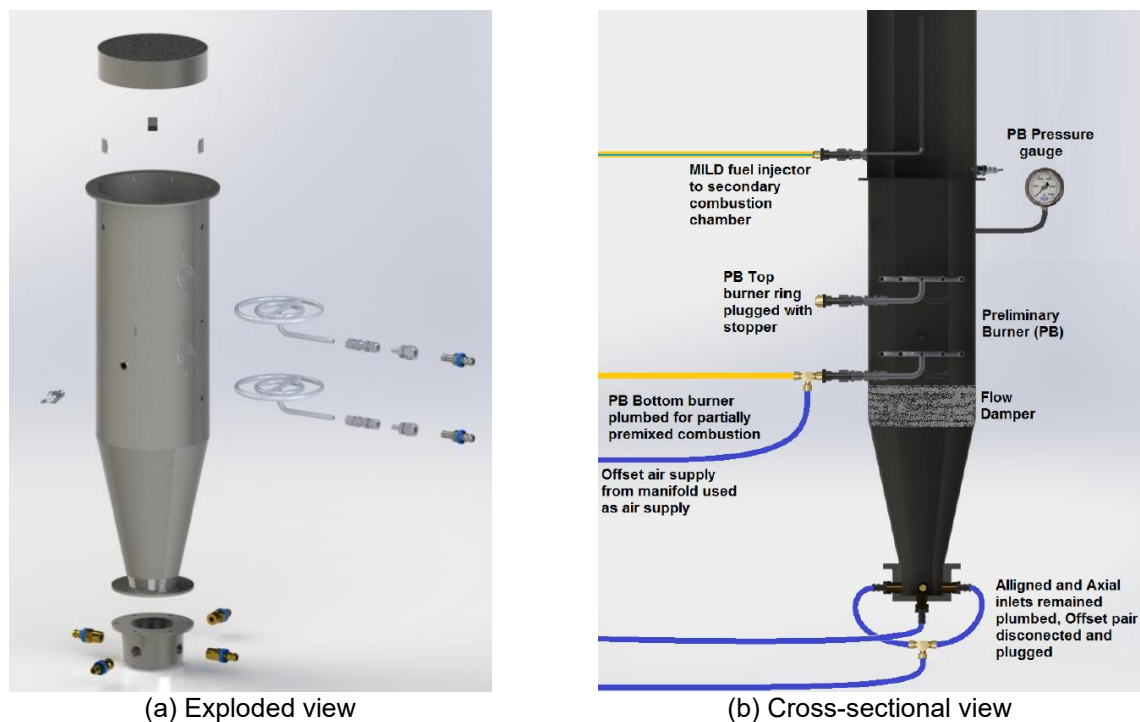
**Figure 14:** Comparison of ethanol (C<sub>2</sub>H<sub>5</sub>OH) and DME (CH<sub>3</sub>OCH<sub>3</sub>) at 3% and 9% O<sub>2</sub>. From P19.

### 3.3 Develop confined and pressurised jet flame burner [Task 3]

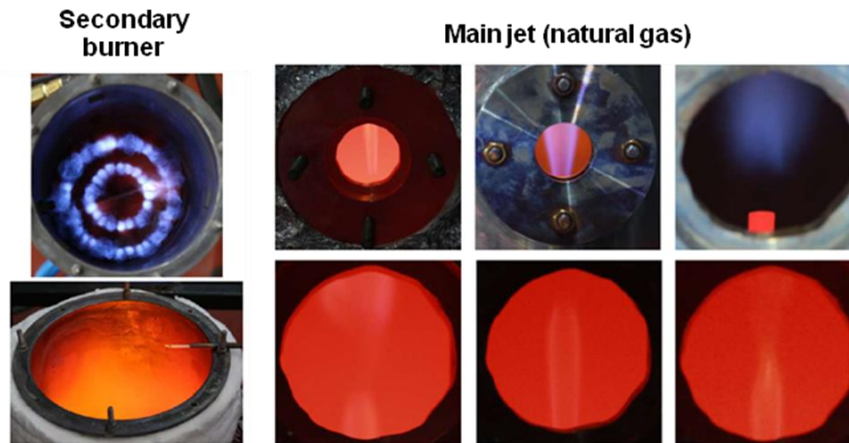
#### 3.3.1 Design and build a new open-flame vitiated coflow burner [Task 3.1]

A prototype burner has been designed and built. The operating principle remains consistent with previous jet in hot coflow burners, which have proven to be suitable for the intended fundamental-level experiments. To save costs whilst testing the burner only a prototype has been constructed. In its own right this is a useful piece of apparatus, that addresses Tasks 3.1 and 3.2; however, the choice of materials will not allow completion of Task 3.3. Nonetheless, the preliminary results show the validity of the design. Importantly, some design improvements have been identified. These were easier to address in the prototype burner, with refinements implemented in the final system (Task 3.3).

Figure 15 shows an exploded view of the preliminary burner (that can be used as a vitiated coflow burner, or have an extension tube to become a confined burner: refer to Task 3.2). Figure 16 shows photographs of the burner during operation. These are only preliminary testing results, and are not any pre-defined specific operating conditions. The purpose of these experiments was to confirm basic functionality of the burner.



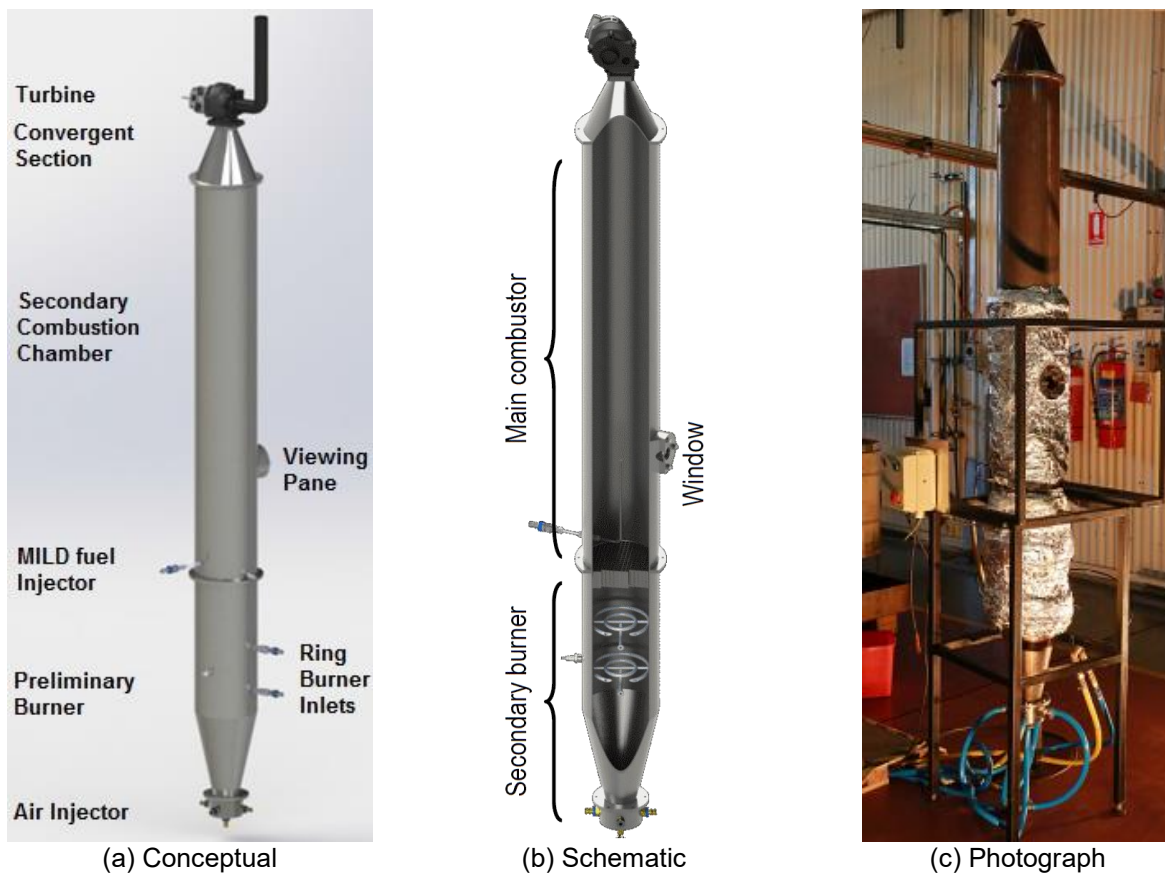
**Figure 15:** Prototype vitiated coflow burner (confined jet in hot coflow burner, CJHC)



**Figure 16:** Photographs of prototype confined jet in hot coflow (CJHC) burner. Photographs of the secondary burner were taken with the main combustor removed.

### 3.3.2 Confined new burner [Task 3.2]

Using the prototype burner (outlined in Task 3.1) a confinement section has been added. Testing showed that confinement using the proposed approach is viable and indicates that this arrangement will also be possible in a pressurised configuration. The basic configuration is shown in Figure 17.



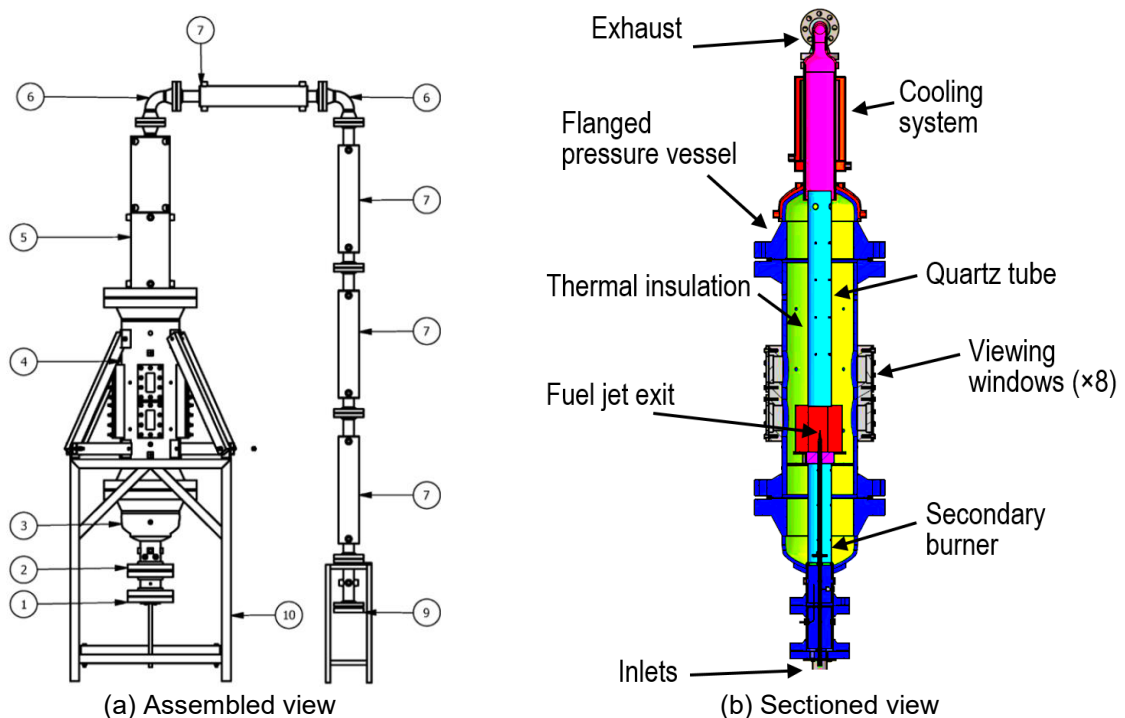
**Figure 17:** Prototype confined jet in hot coflow burner (CJHC) with main section installed.



### 3.3.3 Pressurised new burner [Task 3.3]

Based on the experience learned from the prototype burner, a pressurised confined jet-in-hot-coflow burner has been designed, built and manufactured. As required by Australian regulations for pressure vessels, the design has been verified and registered with the Government for operation to 10 bar.

The basic configuration follows the prototype described in Tasks 3.1 and 3.2. The design incorporates new insight learned from the prototype burner. It consists of a central quartz tube encased in thermal insulation and housed in an outer stainless steel pressure vessel. Figure 18 shows some of the design drawings. The central jet diameter is 4.6 mm, which issues into a hot coflow of 100 mm diameter. Including the cooling system, the overall height is 3.5 m.



**Figure 18:** Detailed design of pressurised confined jet-in-hot-coflow burner

The burner has been assembled and tested to 5 bar, so far. Two photographs of it in operation are shown in Figure 19. A detailed commissioning process is continuing. Once fully operational, an extensive experimental campaign is planned, including both gaseous and liquid fuels over a range of operating conditions and pressures. This work will continue on a long-term on-going basis and the foundation for subsequent follow-on projects.

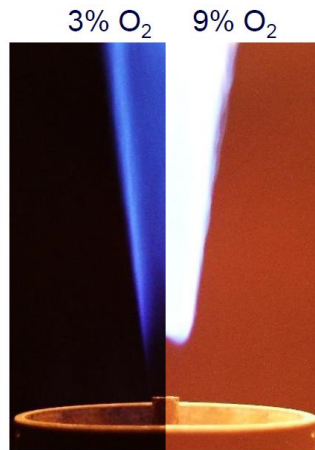


**Figure 19:** Pressurised burner commissioning.

### **3.4 Develop understanding of turbulent flame stabilisation [Task 4]**

A variety of activities directly contributing to the broad aims of this task looking at more complex fuels and operating conditions have been performed. The following papers have been published as steps towards Task 4, with further work expected to remain on-going well beyond the period of the project: P3, P5, P6, P8, P12, P13, P14, P15, P16, P18, P19.

To develop understanding of turbulent flame stabilisation, a range of experimental data from a large-scale experimental campaign has been collected. Measurements of temperature (via laser Rayleigh scattering) and OH & CH<sub>2</sub>O (via laser induced fluorescence) were coupled with OH\* and CH\* chemiluminescence imaging. Over 200 flame cases were considered, including three coflow temperatures, six coflow oxygen levels, five jet Reynolds numbers and six different fuel types (methane, ethylene, ethanol, acetone, n-heptane, dimethyl-ether). Due to the size of the experimental matrix, only some of the data has been processed, analysed and published. By way of an example, Figure 20 presents flame photographs of an ethylene/ethanol fuel jet issuing into a coflow of either 3% or 9% oxygen (camera settings constant between the photographs). It is apparent that despite the reduction in oxygen level the flame stabilisation point has not appreciably changed. This is consistent with previous measurements, but not consistent with conventional lift-off height and flame stabilisation theory. In contrast to previous experimental measurements, the wide range of conditions employed in this study will enable a more thorough validation of CFD models in addition to providing new understanding of flame stabilisation mechanisms. There are a large number of papers to be published from this work. A series of publication will continue to be released from this work over an extended period time, beyond the life of the project.



**Figure 20:** Sample split-photograph showing flame base. Ethylene/ethanol fuel mix in a coflow of either 3% or 9% O<sub>2</sub> level and temperature of 1400K (all camera settings constant between photographs).

From data already collected, the following journal papers are currently at various phases of preparation:

- Temperature and soot evolution of prevapourised liquid flames in hot and vitiated coflows (Medwell, Evans, Dally, Sun)
- Extension of the eddy-dissipation concept combustion model for low turbulence jet flames (Evans, Petre, Medwell, Parente)
- Parametric numerical and experimental study of ethylene flames in hot and diluted coflows (Evans, Medwell, Ye, Cuoci, Frassoldati, Parente)
- Experimental and numerical study of n-heptane flames in hot and diluted coflows (Li, Evans, Ye, Medwell, Parente, Dally)
- Diluted ethylene ignition processes with hot, vitiated oxidants (Evans, Chinnici, Ye, Ihme, Medwell)
- Effects of water dilution on ethylene jet flames in hot and vitiated coflows (Chinnici, Evans, Medwell, Dally)
- Stability and structure of dual fuel swirl flames with varying heat release and flammability limits (Evans, Sidey, Ye, Medwell, Dally, Mastorakos)
- Structure of dual fuel ethylene-ethanol flames in a hot and diluted coflow (Evans, Medwell, Ye)
- Turbulent toluene sooting flames (Ye, Kruse, Medwell, Sun, Dally, Pitsch)
- Investigation of turbulent jet flames of prevapourised gasoline surrogates (Ye, Kruse, Medwell, Pitsch)
- The significance of beam steering on laser-induced incandescence measurements in laminar counterflow flames (Medwell, Kruse, Pitsch)
- Characteristic time scale effects on the soot production of gasoline surrogate fuels in laminar counterflow burner (Kruse, Medwell, Pitsch)
- Behaviour and structure of gaseous jet flames in hot and diluted coflows (Medwell, Evans, Ye)

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- [P3] Ye, Medwell, Evans, Dally “The impact of carrier gas on ethanol flame behaviour in a Jet in Hot Coflow (JHC) burner”. *Australian Combustion Symposium* (2015), Melbourne, Paper 1B02.
- [P4] Medwell, Evans, Chan, Katta “The adequacy of laminar flame calculations for identifying MILD combustion”. *Australian Combustion Symposium* (2015), Melbourne, Paper 1B03.
- [P5] Evans, Medwell, Ye “Laser-induced fluorescence of hydroxyl in ethylene in jet flames in hot and diluted coflows”. *7th Australian Conference on Laser Diagnostics in Fluid Mechanics and Combustion* (2015), Melbourne, pg. 75.
- [P6] Ye, Medwell, Evans, Dally, “Quantitative Rayleigh temperature imaging in turbulent flames of prevaporised n-heptane”. *7th Australian Conference on Laser Diagnostics in Fluid Mechanics and Combustion* (2015), Melbourne, pg. 85.
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- [P8] Ye, Medwell, Varea, Kruse, Dally and Pitsch “An experimental study on MILD combustion of prevaporised liquid fuels”. *Applied Energy* (2015) **151**, pp. 93-101.
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- [P13] Ye, Kruse, Medwell, Sun, Dally, Pitsch “Effects of Di-n-butyl Ether Addition to Turbulent Toluene Sooting Flames”. *11<sup>th</sup> Asia-Pacific Conference on Combustion* (2017).
- [P14] Evans, Medwell, Wu, Stagni, Ihme “Classification and Lift-Off Height Prediction of Non-Premixed MILD and Autoignitive Flames”. *Proceedings of the Combustion Institute* (2017) **36** pp. 4297-4304.
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- [P16] Ye, Medwell, Dally, Evans “The transition of ethanol flames from conventional to MILD combustion”. *Combustion and Flame* (2017) **171**, pp. 173-184.

- [P17] Ye, Medwell, Evans, Dally "Characteristics of Turbulent n-Heptane Jet Flames in a Hot and Diluted Coflow". *Combustion and Flame* (2017) **183**, pp. 330-342.
- [P18] Evans, Chinnici, Medwell, Ye "Ignition Features of Methane and Ethylene Fuel-Blends in Hot and Diluted Coflows". *Fuel* (2017) **203**, pp. 279-289.
- [P19] Ye, Medwell, Kleinheinz, Evans, Dally, Pitsch "Structural Differences of Ethanol and DME Jet Flames in a Hot Diluted Coflow". *Combustion and Flame* (2018) **192**, pp. 473-494.

## 4. CONCLUSIONS

This project has made tangible progress towards understanding the behaviour of MILD combustion under conditions beyond simple fuels at atmospheric pressure. Amongst the various contributions, the following summary highlights some of the most pertinent findings:

- Robust methods for producing regime maps in the transition to MILD combustion have been developed. Whilst this approach is an improved method to classify flames, the applicability of generalised regime maps at predicting the appearance of turbulent flames is limited without *a-priori* knowledge of the flow-field.
- The importance of minor species has been identified. Formaldehyde ( $\text{CH}_2\text{O}$ ) plays a critical role in flame stabilisation under MILD combustion conditions. Equilibrium levels of OH in the oxidant stream needs to be considered in modelling of these flames.
- The results from calculations of simplified reactors can be applied to more complex and realistic flame conditions, providing the temporal and/or spatial effects are taken into consideration.
- Computational models of jet flames can reproduce experimental trends, including a-priori predictions.
- A new burner has been developed to facilitate future experimental campaigns of flames in a vitiated coflow—including MILD combustion—under elevated pressure conditions (up to 10 bar).