GTRC, FIRST YEAR CONTRIBUTION TO PROGRESS IN COMBUSTION AND ENERGY SYSTEMS

Bowen, P.J., Syred, N, Roberts P.A., Marsh R., Griffiths A.J., O'Doherty T., Crayford A.P., Kay P.J., Morris S.M.

Cardiff School of Engineering,
Queens Buildings,
The Parade,
Cardiff CF24 3AA

***Roberts Group**
Nic. Beetslaan 17,
1985 HH Driehuis
The Netherlands

ABSTRACT

The relocation and commissioning of Cardiff University's new gas turbine research centre (GTRC), based on facilities donated by QinetiQ (formerly the UK Defence Evaluation Research Agency, (DERA), Pyestock, UK) was reported at the previous IFRF members conference. This paper reports the contribution of GTRC first year in operation to progress in combustion and energy systems.

The centre aims to generate original data to enable model validation or empirical model development, and the potential contribution of GTRC is distributed over eight identified technical themes. Progress in each area is discussed in turn. The Centre has interacted with a number of companies, and has delivered training to some 75 students and industrial employees.

Alternative fuels, emissions and environment, swirl and instabilities, risk and hazards and diagnostic technique development have been the main technical areas of focus. Already some 14 conference papers from the research have been presented at international meetings, and 6 journal papers are currently under review.

1. INTRODUCTION

The relocation and commissioning of Cardiff University's new gas turbine research centre (GTRC) based on facilities donated by QinetiQ (formerly the UK Defence Evaluation Research Agency, (DERA), Pyestock, UK) was reported at the previous IFRF members conference [1]. Here the contribution made to progress in combustion and energy systems through various joint industry and EU programmes subsequent to the GTRC launch in 2007 during the first full year of operation (Oct. 2007/8) is summarised.

The mission of the centre is to provide original, high-quality validation data to enable the development of models of gas turbine combustion and sustainable energy-related processes [2]. The centre has delivered research progress consistent with this aspiration, for a broad range of applications. Several of the published papers were funded through a large 23-partner EU framework programme which investigated 'Alternative Fuels for gas Turbines' (AFTUR), where the GTRC contribution was delivered as a subcontractor to QinetiQ, with close association with Siemens Industrial Turbomachinery Ltd.

(a)

(b)

Figure 1: Cardiff Gas Turbine Research Centre (GTRC)
(a) Externally (b) Internally (HPCR)

The current areas of research, innovation and engagement offered by GTRC http://www.cu-gtrc.co.uk through its facilities and expertise of its academic directorate comprise (i) combustion and fuels, (ii) emissions and environment, (iii) swirl, instabilities and combustor dynamics, (iv) risk and hazard quantification, (v) atomisation, sprays and fuel mixing, (vi) novel diagnostic techniques, (vii) heat and mass transfer, (viii) novel propulsion systems, and (ix) professional training. Most of these areas have been addressed during the first year of operation.

In keeping with the GTRC's research and innovation status, it is reassuring to note that whilst some of the work has been undertaken under contractual client confidentiality, still the majority of the research undertaken has been allowed to be published in the open literature, hence proving to be of mutual benefit to, and an excellent example of industry/academic interaction. Furthermore, the diversity of contracts attained enabled a broad range of GTRC's suite of rigs and diagnostic capability to be commissioned and utilised. Whilst this proved demanding for the GTRC research and technical personnel, it ensured that the Centre was fully utilised during its first year, and allowed the facility capabilities to be fully commissioned. Contributions to each of the theme areas stated above over the first year of operation are summarised in the following sections.

2. COMBUSTION AND FUELS

The drive towards sustainability means that future gas turbine designs are going to have to be able to accommodate a range of non-traditional fuels including hydrogen-rich and CO_2 rich gases. However, information of the basic combustion properties associated with fuel blends and mixtures is scarce even at atmospheric pressure let alone those conditions pertaining at the elevated gas turbine pressure and temperatures. This has lead to substantial work programmes in this area.

2.1 Turbulent Burning Rate of Alternative Fuels for Gas Turbines Using Stationary Flame Burner at GTRC – High Pressure Combustion Rig (HPCR)

The main focus in this research area was funded by the EU FP 'AFTUR' programme to investigate the turbulent burning rate characteristics of a range of 'alternative fuel' mixtures – such as hydrogen/methane and methane/CO2 - under conditions of elevated temperature and pressure of relevance to gas turbines [3]. This research programme was undertaken on the HPCR (high-pressure) arm of the GTRC facility (Figure 1b). A new optical rig (HPOC) has been designed and commissioned to operate on the HPCR arm. Equivalence ratios studied ranged from 0.65-1.45; pressure and temperature conditions considered are summarised in Table 1.

Gas mixture	Methane %	Carbon dioxide %	Hydrogen %	Pressure, bara	Temperature, K
$100\%CH_4$	100	0	0	3, 7	473, 673
$85\%CH_4$-$15\%CO_2$	85	15	0	3, 7	473, 673
$70\%CH_4$-$30\%CO_2$	70	30	0	3, 7	473, 673
$85\%CH_4$-$15\%H_2$	85	0	15	3, 7	473, 673
$70\%CH_4$-$30\%H_2$	70	0	30	3, 7	473, 673

Table 1. Mixtures Specified in the AFTUR Turbulent Burning Rate Programme

Turbulent conditions were characterised using a DANTEC laser Doppler anemometry (LDA) system. The flame boundary was identified using seed combined with a PHOTRON high-speed camera with laser sheet to highlight the reactant zone and to attain enough images for statistical analysis (Figure 2). The combustion conditions prevailing were determined to reside within the 'corrugated flamelet' region of the traditional Borghi diagram through evaluation of the turbulent intensity and integral turbulent length scale.

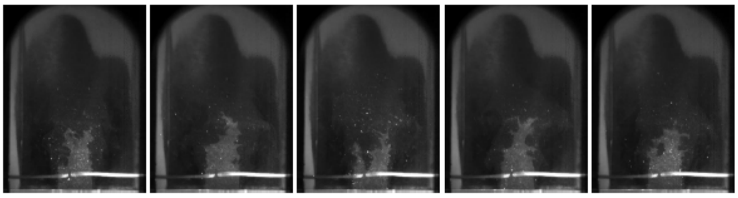


Figure 2. Example of High-Speed Turbulent Flame Images Using Seed-Density Approach

Various methods for analysing the turbulent flame images were appraised and optimised. The processed data showed that the methane-hydrogen mixture results correlated reasonably well with some, though not all, of the limited data available for comparison. The effect of reducing burning rate by CO2 addition to methane was quantified for the mixtures specified in Table 1, and it was shown that an increase in initial ambient gas temperature significantly increased turbulent burning rate of the mixtures (Figure 3ii), whilst increased pressure induced a reduction. Methane and methane/CO2 mixtures demonstrated similar trends with respect to the influence of ambient conditions. In the case of lean hydrogen/methane mixtures, an increase in temperature (Figure 3i) or pressure augmented turbulent burning rate, whereas the influence of ambient pressure was minimal for rich mixtures. The results are analysed further in the full reference.

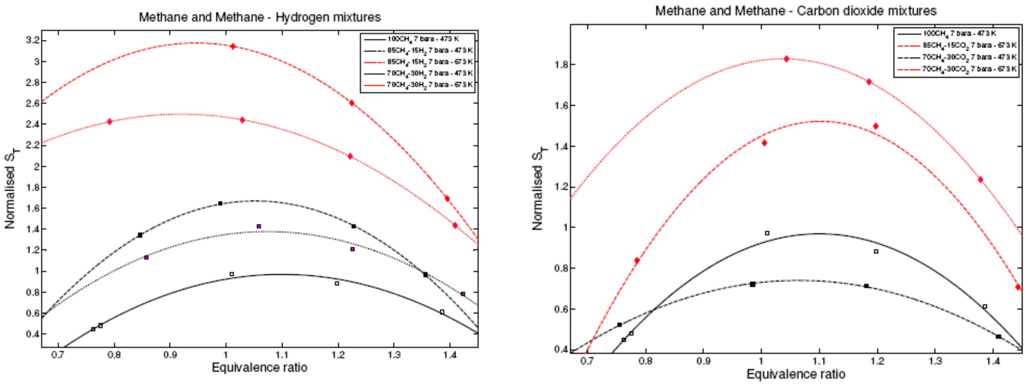


Figure 3. Effect of Ambient Temperature at Elevated Pressure on Turbulent Burning Rate : (i) CH4 and CH4/H2 (ii) CH4 and CH4/CO2

2.2 Laminar Burning of Alternative Fuels Using Propagating Flame Methodology

Other burning rate data was generated through industrial contracts at GTRC throughout the year utilising the propagating flame methodology within the GTRC optical cloud combustor described in [1]. These programmes considered other multi-component and 'alternative' fuels on behalf of QinetiQ and BP, but the data are currently subject to client confidentiality constraints.

3. EMISSIONS AND ENVIRONMENT

There is a continuing pressure on gas turbine manufacturers to produce machines with increasingly benign impact on the environment. This has historically meant stringent regulations on the production of NOx emissions, but as we increase our understanding of and ability to measure other pollutants, future legislation is likely to become more focussed on other airborne pollutants also, such as fine particulate matter.

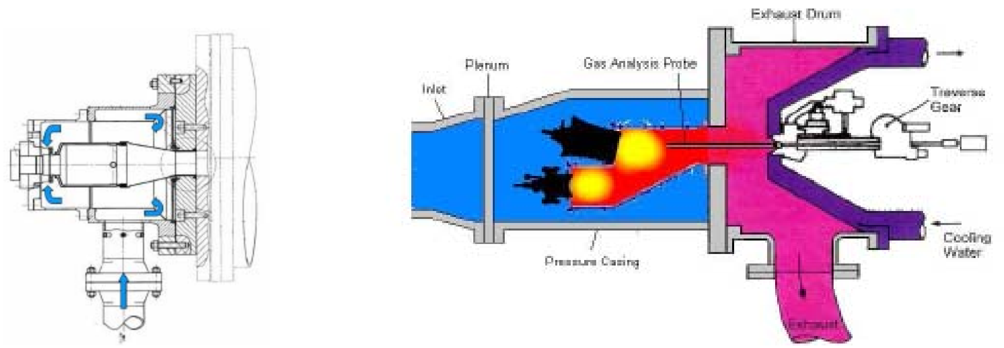
3.1 Detailed Internal Species Measurements of a Siemens Combustor at Gas Turbine Relevant Conditions

The aim of this QinetiQ-sponsored research contract undertaken at GTRC was to assist Siemens in their development programme for their family of liquid-fuelled DLE combustors, and more specifically to provide unique spatially-resolved combustion species measurements within one of their combustors [4] to appraise 2-phase Computational Fluid Dynamic (CFD) predictions.

Siemens Industrial Turbomachinery Ltd. has addressed the environmental demands for low NOx emissions by the development of a world-leading dual-fuel DLE combustor. For the size of engine considered in this programme (5-13MW), it is important to many Siemens customers to have a dual fuel capability in order to provide backup power in case of the non-availability of the primary fuel. One of the great advantages of the Siemens design is that it can provide a DLE liquid capability with minimal modification to the burner concept. However, diesel operation is more problematic than with gaseous fuelled operation, with greater attention required during the fuel delivery process, which can result in higher than expected emissions and/or induce combustor dynamics.

The Siemens burner (Figure 4i) is designed to operate on either natural gas or diesel, and in this programme, the burner was operated under lean conditions with two different fuels simultaneously for the first time, with a symmetrically-injected methane pilot and a grade 2 diesel main flame.

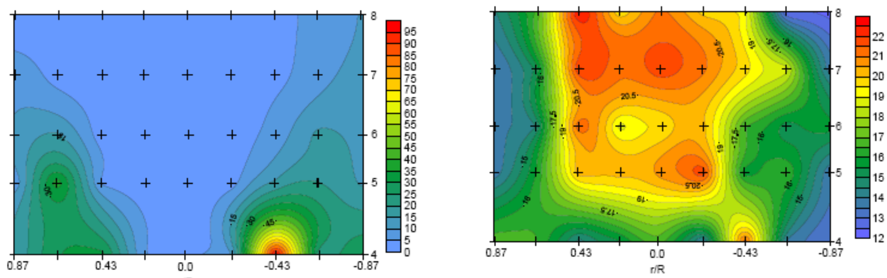
GTRC offers a unique combustion test capability where the Sector Combustion Rig (SCR) allows a gas sampling probe to the inserted into an active gas turbine combustor at realistic operation conditions (Figure 4ii). Inlet conditions in terms of temperature (up to 900K, non-vitiated), mass flow (up to 5kg/s) and pressure (up to 10barA) can be individually controlled to provide a range of operating conditions. The design of the water-cooled probe (originally designed and manufactured by QinetiQ) allows four degrees of freedom (pitch, yaw, axial and rotational translation) of probe movement.



(i) (ii)

Figure 4. Siemens Burner (i) and Unique Internal Traversing System

Measurements were taken at eight discrete planes along the length of the combustor, from the entry of the pre-chamber to a significant distance into the combustor. Two axial traverses were made along the combustor centreline, one with gas pilot and the other without. At each plane, measurements with a resolution of 9mm were made along a horizontal diameter. A further line of data was taken 10mm below the central axis with a resolution of 18mm in order to demonstrate off diameter behaviour of the burner. Data was also taken to assess combustor asymmetry.
The probe is connected to a heated stainless steel sample line which is maintained at a temperature of 463K +/- 10K, which is used to convey the gas sample to a suite of Signal gas analysers. The suite includes analysers for CO, CO2, NO, NO2, UHC and O2. More detail of the gas sampling/analysis procedure and operation is referenced within the paper [4], and the raw data is processed to ARP 1533.
Results were presented in the form of either line plots or surface contours - with examples given in Figure 5 – to enable direct comparison with CFD output. It is shown that the pilot flame had minimal influence on the results, and detailed analysis and discussion of the spatial variation of species, AFR and combustion efficiency presented.



(i) (ii)

Figure 5. Examples of plots of (i) Normalised AFR and (ii) Dry NOx (ppmvd 15% O2) in the Siemens combustor 10mm below the burner Centreline for CFD Validation Studies

The programme is noteworthy and influential in that it provides the first internal traverse of a diesel-fuelled gas turbine burner at gas turbine relevant conditions. Whilst CFD validation of a traditional liquid fuel such as diesel is important in the development of new diesel burner designs, it is with alternative liquid fuels in mind that the study was initiated – post CFD validation, models may be applied with greater confidence to alternative fuels, ultimately allowing the use of more environmentally friendly liquid fuels in gas turbines. It is also important to the development of GTRC that the SCR with internal traversing is now available for liquid fuel studies, as well as simultaneous dual-fuel (gas-liquid) operation, which enable more studies of gas turbine performance during fuel changeover.

3.2 Spatially-Resolved Particulate Emission Measurement from Gas Turbines

A programme of work has been undertaken with GTRC in collaboration with an established OEM to enhance understanding of fine particulate matter (PM) formation from gas turbine engines. Fast-response PM measurements were taken by GTRC researchers during this collaborative programme. The results from this research programme are currently subject to confidentiality, although it is anticipated they will be published in the near future.

4. SWIRL, INSTABILITIES AND COMBUSTOR DYNAMICS

Lean premixed combustion using swirl flame stabilisation is widespread amongst gas turbine manufacturers. The use of swirl mixing and flame stabilisation is also prevalent in many other non-premixed systems. Problems that emerge include those due to flame stabilization as a mechanism dependent upon fuel type, combustor geometry and thermo-acoustic instabilities.

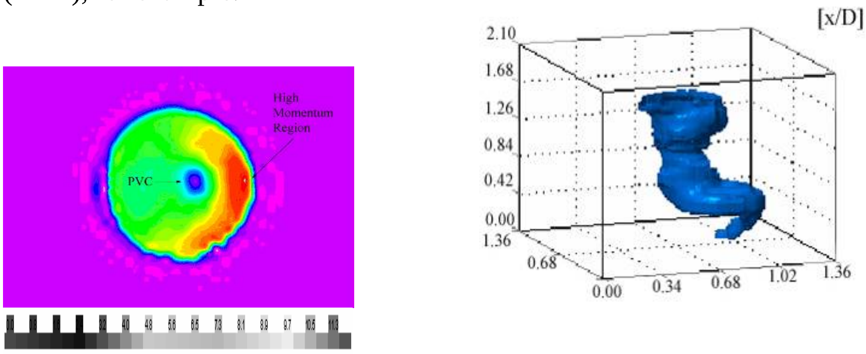
Low NO_x and syngas burners are technologies that are used to considerably reduce emissions and to accommodate new fuels, and are used extensively in the gas turbine industry. Swirling flows and often lean premixing of fuel and air are at the core of these processes. The effectiveness of these emissions reduction techniques are due to the more uniform temperature profiles generated by the very stable and lean combustion processes produced by swirling flows. However, localized in homogeneities in air-fuel ratio are known to stimulate instabilities in the burning region via unbalanced combustion regimes, often coupled with system or combustor acoustic modes, fluid dynamic instability and stimulated by the Rayleigh criterion. The effectiveness of any premixing system is also clearly influential here.

Swirling flows have been studied extensively for numerous combustor/burner applications with special emphasis on their three dimensional characteristics and methodology for flame holding. These flows are designed to create coherent recirculation zones capable of recycling hot chemically active reactants to enable excellent flame stability to be achieved. It has been found that the levels of swirl used in some combustors, coupled with the mode of fuel injection can induce the appearance of unwanted and undesirable regular fluid dynamic instabilities. These can couple with natural resonances, exciting large amplitude oscillations which can damage equipment, provoking partial or complete failure of the system. Combustion may also occur in and around these structures causing fundamental changes of flame stabilization mechanisms owing to changes in length scales, turbulent flame speed, flame stretch and other related parameters. Simultaneously combustion may occur in flame fronts which engulf these coherent structures again giving rise to different flame stabilization mechanisms. Combustion may also suppress some time-dependent coherent structures, although evidence is that acoustic coupling may well re-introduce them.

Numerical simulation has also been used in an attempt to explain the complex interactions between large swirling flow coherent structures and combustion. Despite some successes, the results obtained for more intricate cases with high flow rates, high swirl involving combustion, leave much to be desired. Therefore, systems that use high swirl numbers require extensive and expensive experimentation for optimization.

GTRC academic staff has a wealth of experience in characterising and analysing the 3-dimensional coherent structures associated with high swirl number flows through a research team which has developed over 30 years [5], [6]. To advance these studies, a relatively simple 100kW swirl burner design has been utilised throughout 2007/8 to characterise a whole family of coherent structures which arise from complex combusting flows of direct relevance to gas turbine burners.

Significant progress has been made in 2007/8 in this area through doctoral research sponsored by the Mexican government (CONACYT) which is reported in a series of papers by Valera-Medina et al. ([7],[8],[9],[10]). Of particular note is the development of a new integrated diagnostic technique which enables the 3-dimensional characteristics of structures associated with vortex breakdown, such as precessing vortex cores and reverse flow zones, to be identified and their characteristics in terms of geometrical shape and kinematics to be quantified. Phase-resolved particle-imaging velocimetry (PIV) – integrated with a suitable triggering device such as a hot-wire - enables efficient generation of temporally-resolved planar flow fields as exemplified in Figure 6i. There is considerable time benefit in using a planar characterisation technique such as PIV in this instance, as it now becomes possible to build fully 3-dimensional plots of these complex structures (Figure 6ii) by systematically traversing downstream, which would have been impractical using the previously utilised systems with phase-resolved laser Doppler anemometry (LDA), for example.



(i) **(ii)**

Figure 6. (i) 2D P1V Image at the Nozzle Outlet, 150 frames/section, z = 0.00 D. Color scale from 0.00 to 12.00 m/s, increment 0.8 m/s.(ii) Identification of the 3D Precessing Vortex Core Structure

This hybrid diagnostic technique has allowed the identification of hitherto unreported dual-vortex systems (Figure 7) which is consistent with previous dual-vortex predictions through an inviscid analysis of the problem using variational methods ([6]). The co-existence and interdependence of the PVC and CFZ is also established.

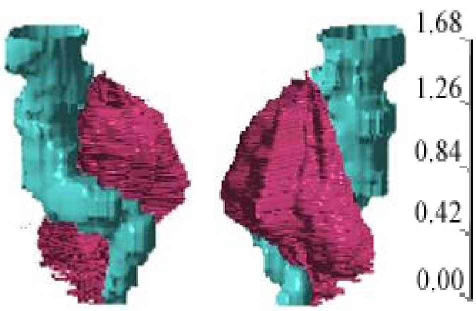


Figure 7. Two-vortex Structure, with PVC and CRZ[x/D].

More detailed analysis of the strong influence of relevant dimensionless groups such as swirl number, Reynolds number, equivalence ratio and geometrical variations are generated and discussed within the papers. Intermittent coherent structures are also noted, as well as the practical notification that very small quantities of diffusive fuel injection has a disproportionately strong influence on flame stabilisation for lean premixed swirling flames. Future work will develop this research programme into conditions of relevance to gas turbine operating conditions, through utilisation of GTRC high-pressure facilities.

5. RISK AND HAZARD QUANTIFICATION

The transition to utilisation of alternative fuels and alternative combustion strategies such as lean, premixed systems for gas turbines introduces the potential for new risks and hazards which need careful study to enable risk minimisation at the design stage as well as good risk management during operations. Two joint-industry projects delivered in 2007/8 fall into this category of research.

5.1 Auto-ignition Characteristics of Traditional and Bio- Fuels with Application to Gas Turbines

As discussed in section 3, compliance with increasingly tough emissions legislation is critical to the business of gas turbine manufacturers and operators alike. Emission reduction has been technically difficult to achieve, especially those for ultra low NOx in land based gas turbine engines. However, in most current applications, reduced emissions are being achieved with the use of lean burn, premixed combustion processes which produce less thermal NOx as a result of having relatively low flame temperatures. Unfortunately, one of the inherent disadvantages of premixing fuel and air prior to combustion is exposure to auto-ignition. The onset of auto-ignition can present a major threat to the integrity of the combustion system. Provided that the auto-ignition temperature of the fuel is reached, spontaneous auto-ignition will occur after a characteristic auto-ignition delay time (ADT). If premix ducts can be designed to achieve adequate mixing in timescales shorter than the characteristic ADT, auto-ignition will be avoided. Thus, the design of a premix duct is heavily reliant upon knowledge of the auto-ignition delay time for a given fuel-air mixture and operating range.

Furthermore, there is current pressure on industrial gas turbine manufacturers to extend the operation of their machines to a range of renewable fuels in order to both protect the environment and to provide enhanced energy security. Extending the capability of Dry Low Emission (DLE) gas turbine technologies based on lean premixed combustion to a wider range of fuels, including those of lower calorific value produced by gasification of biomass and hydrogen-enriched fuels would require relevant auto-ignition knowledge. However, no ADT data is available for the types of fuels being proposed. Furthermore, there is wide variety of measurements of ADT in the literature, and not a great deal in the region of interest to gas turbine combustor inlet conditions. This is due to a range of different experimental methodologies being employed to measure ADT, as well as the focus traditionally being on other areas of application e.g. automotive compression-ignition engines.

ADT is usually expressed as a function of equivalence ratio, ambient temperature and pressure using the global reaction correlation:

$$\tau = A \times \phi^{m} \times p^{n} \times e^{E/RT} \qquad (1)$$

The aim of the 2007/8 GTRC research programme was to develop such correlations for alternative fuels [11]. Table 2 shows the gaseous fuel mixtures considered in this programme.

	COMPONENT						
ALTERNATIVE FUEL	H_2	CO	CH_4	C_2H_4	C_3H_8	CO_2	N_2
Bio/Methanication	-	-	64.8%	-	-	35.2%	-
Pyrolysis gas	20.9%	44.5%	16.1%	-	5.8%	12.2%	0.6%
Air-blown gasification	11.4%	16.8%	5.0%	1.1%	-	15.4%	50.3%
H_2-enriched gas	42.4%	31.5%	11.6%	-	4.0%	8.7%	1.8%
DATUM FUEL	CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO_2	N_2	
Natural gas	85.5%	3.1%	0.6%	0.1%	1.5%	9.2%	
Methane	100%	-	-	-	-	-	

Table 2. Gaseous Fuel Mixtures Studied within Programme

The ADT of different gaseous and liquid fuels were measured at GT-relevant conditions using a flow rig previously designed by QinetiQ, but re-commissioned in 2007 and now owned by GTRC. The programme of work was undertaken in collaboration with and subcontracted to QinetiQ, as part of the AFTUR EU programme. Detailed description of the experimental methodology for gaseous fuel testing is reported in the full paper [11]. The cross-sectional design is presented in Figure 8. Air is fed into the working section through a venturi flow meter at up to 16 bar and 880K. The remainder of the airflow is allowed to bypass the working section in order to insulate the test duct. Downstream of the venturi flowmeter, the working section comprises a fuel injection housing and the instrumented test duct.

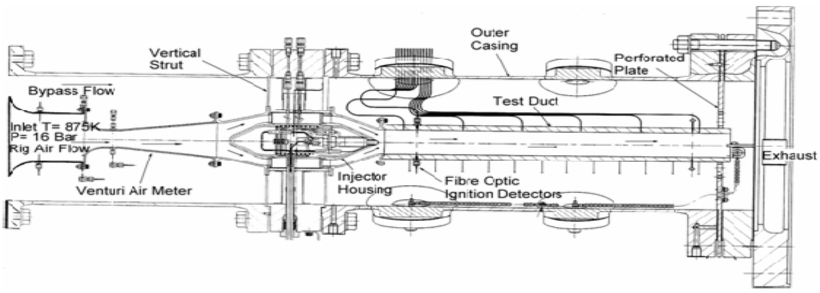
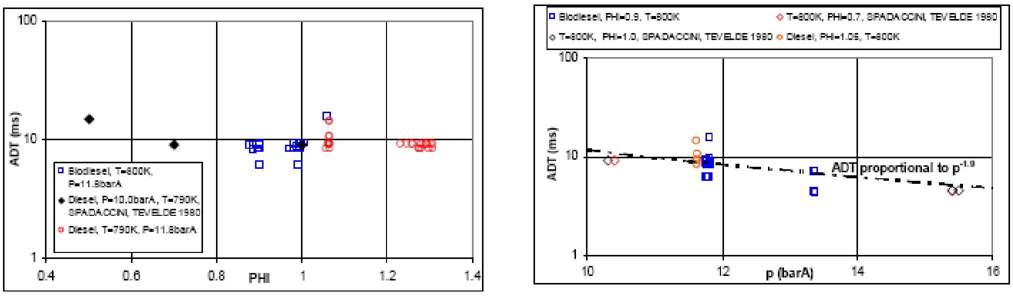


Figure 8. Cross-section of the GTRC Auto-Ignition Flow Rig

For both gaseous and liquid fuel, the fuel was preheated and injected via a pulsed injection system into the leading edge of the test section. Considerable laboratory characterisation studies of the fuel injection process using CFD and optical diagnostic techniques were undertaken to optimise and quantify fuel delivery.

No measurable auto-ignition could be achieved at any condition for any of the gaseous fuels tested across a broad range of equivalence ratios. The auto-ignition delay times of all the gaseous fuels tested was thus demonstrated to be greater than the measured test duct residence time at the cited conditions for this particular experimental configuration. Hence, ADT for these gaseous fuels and conditions were predicted using a previously-developed chemical kinetic scheme; details of these results are presented in the full paper [11].



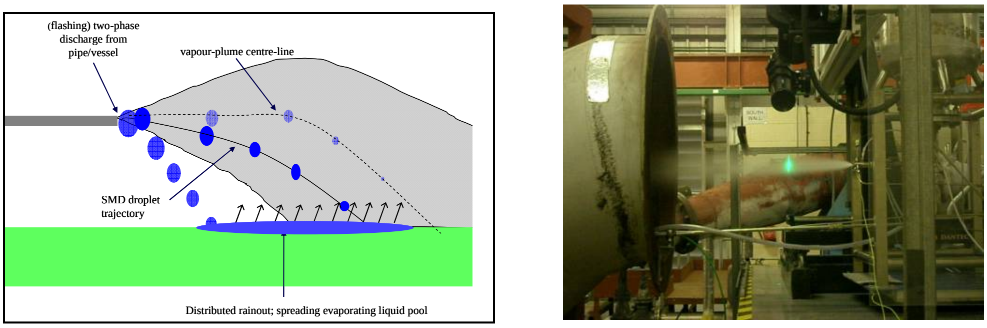
(i) (ii)

Figure 9. (i) Relative Independence of Equivalence Ratio on ADT for Diesel and Biodiesel at P ~ 11bar, T ~ 800K (ii) Influence of Elevated Pressure on ADT for Diesel and Biodiesel.

Figure 9 presents representative graphs of data for (i) diesel and (ii) bio-diesel showing the influence of equivalence ratio and pressure respectively for particular operating conditions. From such data, appropriate exponents for use in Equation 1 were derived, and compared with the limited previous data available in the literature.

5.2 Accidental Two-Phase Flashing Releases of Liquified Fuels

Many chemicals such as alternative fuels (e.g. LNG) and toxic materials may be stored or transported under liquefied conditions. This raises the possibility of a two-phase 'flashing' release should accidental loss of containment occur. Indeed, many accidents have involved the two-phase release of hazardous chemicals into the atmosphere. The potential for subsequent rainout results (Figure 10) in reduced concentrations in the remaining cloud, but can also lead to extended cloud duration because of re-evaporation of the rained-out liquid.



(i) (ii)

Figure 10. (i) DNV- PHAST Philosophy for 2-phase Liquified Fuel Releases (ii) Flashing-Jet Phase Doppler Anemometry (PDA) Measurements being undertaken at GTRC

For accurate hazard assessment one must accurately predict both the amount of rainout and re-evaporation of the pool. Det Norke Veritas (Norway) Ltd. is an international leader in the development of commercial hazard consequence and risk assessment software through development of their commercial models such as 'PHAST' (Figure 10i). The aim of this research programme is to improve the 2-phase flow rate and the atmospheric dispersion capability (via UDM - Unified Dispersion Model) of the DNV 'PHAST' software suite. The work undertaken in 2007/8 ([12]-[14]) represents 'Phase III' of an ongoing 8-year industry-funded programme between DNV and Cardiff School of Engineering, and was funded by DNV software, Gaz de France, RIVM (Dutch Government), TOTAL, Norske Hydro and Statoil (merged into StatoilHydro during the period of the programme).

Initially, the lack of an appropriate atomisation model for large-scale 'flashing' releases had been highlighted as a significant limitation in determining downstream dispersion characteristics (UDM). Subsequently, a semi-empirical modelling approach was proposed for an improved 'flashing' atomisation model, based on a combination of albeit limited observations of rainout and atomisation fundamentals. The proposed model was based on a tri-functional model which depends upon the release thermodynamic and aperture characteristics. However, there was limited data upon which to validate this proposed methodology.

Hence, the research programme presented in Table 3 was agreed to enable variation of model input variables (via the appropriate dimensionless groups – Weber, Reynolds, Jakob, etc..) to justify the modelling approach across a broader range of conditions, as well as highlight areas of quantitative deficiency for future development. The experimental programme was undertaken at GTRC, where facilities were upgraded to enable spray characterisation of alternative fuels under a broad range of release conditions.

Fluid	Release condition	Stagnation temperature (°C)	Nozzle diameter (mm)	L/d_o (-)	Pressure (barg)
Water	Sub-cooled	Atmospheric	1, 2	1.01, 0.505	6, 10, 14
Cyclohexane	Sub-cooled	Atmospheric	0.75, 1, 2	1.4, 1.01, 0.505	6, 8, 10, 12, 14
Gasoline	Sub-cooled	Atmospheric	0.75, 1	4.53, 3.4	6, 8, 10, 12, 14
Water	Superheated	185	0.75, 1	3.54, 4.5	10
Cyclohexane	Superheated	180	1, 2	1.01, 0.505	7.5, 10
Butane	Superheated	Atmospheric	0.75,1,2	1.4,1.01,0.5	9.5,8,7.5
Propane	Superheated	Atmospheric	1,2	1.01,0.5	6.5,7.5
Gasoline	Superheated	180	1	1.01	10

Table 3. Agreed Experimental Programme for Flashing Jet Releases

Figure 11 shows for the first time the direct justification for a tri-linear approach to the flashing-jet atomisation model.

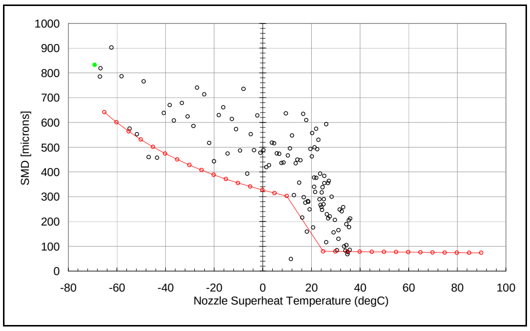


Figure 11. Comparison of Proposed Flashing-Jet Atomisation Model (Red Line) Against Experimental Data

These types of trends were observed for all the experimental conditions considered. Whilst the trends observed are extremely encouraging, it is noted that quantitative improvements are required, particularly under release conditions of low-superheat.

6. ATOMISATION, SPRAYS AND FUEL MIXING

The main development in 2007/8 in this area was the commissioning of a new high-flowrate spray characterisation cell for traditional and alternative fuels, with the availability for pre-heat or superheat, and with capability for secondary atomisation gas (e.g. for air-assist, effervescent, etc..). The flashing jet joint industry programme discussed in the previous section utilised these new facilities, and several research programmes are funded for the 2008/9 GTRC research programme.

7. NOVEL LASER DIAGNOSTIC SYSTEMS FOR COMBUSTION SYSTEMS

The development of new diagnostic techniques is required for a vibrant research and innovation culture at GTRC and to enable it to pursue its mission statement. It has already been noted in previous sections that in 2007/8 laser diagnostic systems were applied to new rigs for the first time, and that hybrid diagnostic systems have been developed to elucidate new thermo-fluid structures of relevance to gas turbine development. In this section, enabled through a UK government strategic research equipment grant (SRIF), two new planar fluorescent imaging techniques have been proposed and developed. This work has been sponsored by Ricardo Consulting Engineers primarily in the context of providing CFD validation data for direct-injection automotive engines (G-DI). However, the processes under consideration, namely fuel film quantification after spray impingement, and relative liquid/vapour air-fuel ratios are very relevant to the gas turbine community also, and GTRC has already been in discussion with a Gas Turbine OEM concerning their adaptation to similar 2-phase gas turbine fuel problems.

7.1 Quantifying Transient Liquid Fuel Films During Spray Impingement (TIR-LIF)

The interaction between sprays and solid surfaces is a phenomenon encountered in a wide variety of industrial applications such as direct injection engines, gas turbines, spray coating, spray cooling, and spray painting among others. In order to quantify this process accurately it is crucial to determine correctly two interacting characteristics: the generation of secondary droplets and the accumulation of a liquid fuel film on the wall. The relative interaction of these characteristics is influenced greatly by pre-impact conditions, such as: pre-impinging spray characteristics, ambient conditions, and impact angle, and also surface characteristics such as geometry, temperature and roughness.

This research programme proposes and develops a new temporally-resolved laser induced fluorescence (LIF) technique to analyse and quantify the fuel film formed due to impingement of a pressure swirl G-DI spray on a flat quartz surface. The technique complements time resolved post-impingement spray characterisation developed by GTRC staff, where post-impact secondary droplets are measured using Phase Doppler Anemometry (PDA). It also follows GTRC work through which a LIF technique was proposed to quantify the fuel film thickness formed as a result of impingement of a pressure swirl injector on a flat surface. The technique relies on the principle that upon excitation by laser radiation, the intensity of the fluorescent signal from a carefully-selected dopant such as 3-pentanone is proportional to the film thickness. Initial results at atmospheric conditions showed that airborne droplets affected the fluorescent signal from the fuel film. This is due to the fact that the laser continues its path upwards and the light thereby excites the airborne liquid fuel above the piston surface, increasing the fluorescence signal detected by the camera. Hence, a new methodology was proposed, based on the principle of total internal reflection of the incident laser radiation, and subsequent laser induced fluorescence (hence TIR-LIF – see Figure 12)

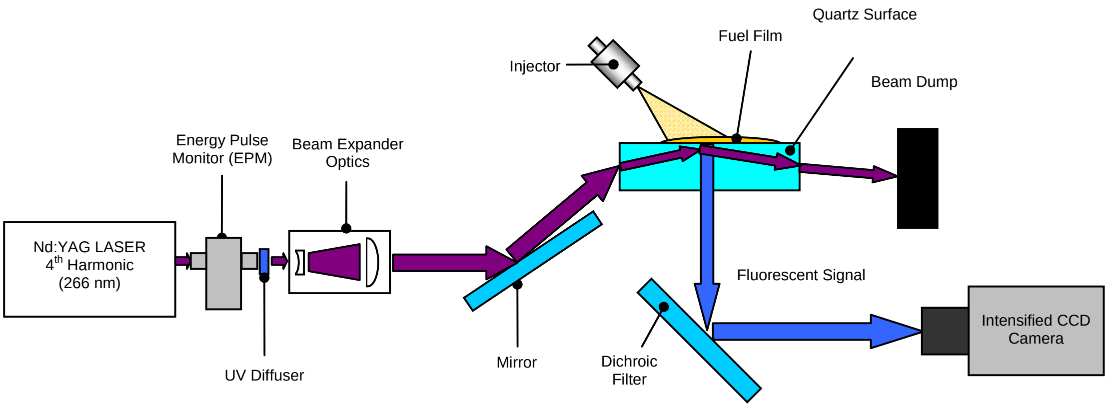


Figure 12. New TIR-LIF Optical Set-up

A binary solution of 10 % by-vol of 3-pentanone in iso-octane was used as a test fuel with a Nd:YAG laser utilising the fourth harmonic at wavelength 266 nm as the excitation light source and an intensified CCD camera used to record the results as fluorescent images. The propagation of the excitation laser beam through the optical piston is carefully controlled by total internal reflection (TIR-LIF). Other known sources of error, such as shot-to-shot variation in laser-pulse energy, are also carefully minimised.

Calibrated temporally-resolved benchmark results of a transient spray from a gasoline direct injector impinging on a flat quartz crown under atmospheric conditions are presented (e.g. Figure 13), facilitating observations and discussion of the transient development of the fuel film [15].

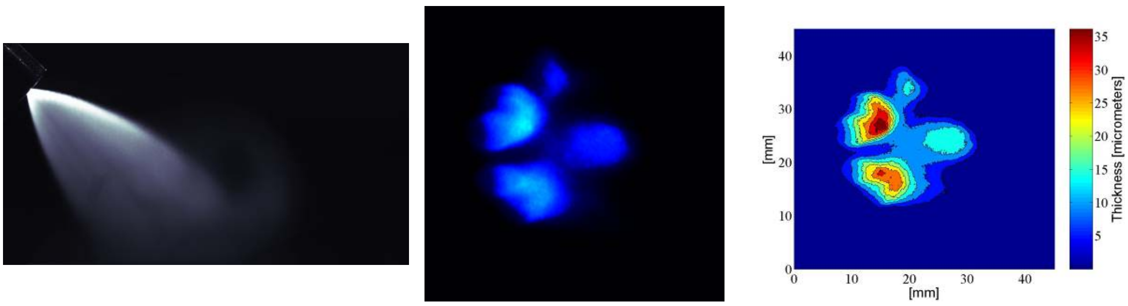


Figure 13. Fuel Injection 1.75 ms after Start of Injection (i.e. towards end of injection) (i) high-speed image (side view), (ii) corresponding uncalibrated TIR-LIF fuel-film footprint (as viewed from underneath optical piston, spray moving left-to-right) (iii) TIR-LIF image post-calibration

These spatially, temporally resolved data-sets are ideally suited to validation of 2-phase CFD models such as Ricardo’s commercial code VECTIS. Spatially-averaged fuel-film accumulation measurements are consistent with previous less detailed studies of this event, showing approximately 80% of the injected fuel remaining on the fuel piston post-impingement under these ambient conditions. This provides confidence in the overall performance of the technique. The potential utilisation of the TIR-LIF under conditions of elevated pressure has also been demonstrated [16], whilst elevated temperature and pressure studies are planned.

7.2 Development of Exciplex LIF (LIEF) for Airborne Relative Fuel-Air Ratios

The purpose of this research programme [17] is to quantify the vapour fractions in an evaporating spray using Laser Induced Exciplex Fluorescence (LIEF), a problem of interest to gas turbine applications (e.g. LPP combustion systems). LIEF is an optical diagnostic technique that generates spectrally separated fluorescence signals from liquid and vapour phases of a spray, providing temporal and spatial resolution of both species simultaneously. A mixture of triethylamine (TEA) and benzene in isooctane was used as the test fuel for the purpose this gasoline engine application, as they have very similar properties to the mid-boiling point of gasoline. This mixture forms an exciplex complex upon excitation of a Nd:YAG utilising the fourth harmonic at wavelength 266nm. Two intensified CCD cameras were used to record the results as fluorescent images (Figure 14).

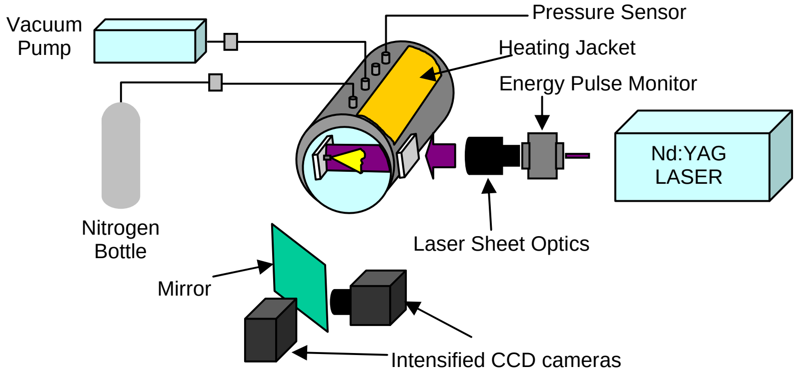
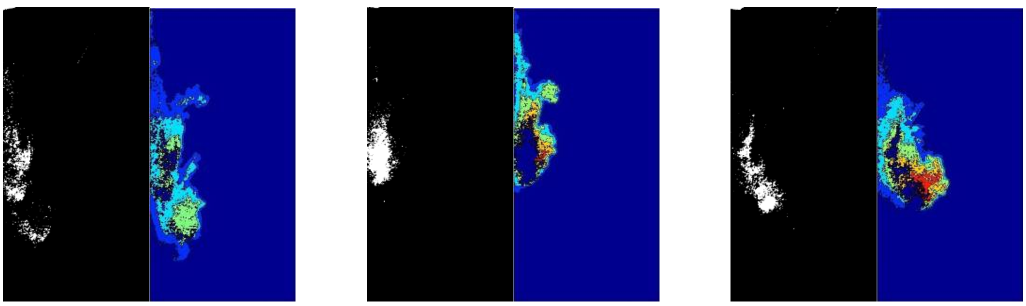


Figure 14. Optical Set-Up for LIEF

The experiments were performed in a nitrogen atmosphere, at three sets of ambient conditions to investigate the characteristics of vapour fraction at elevated ambient temperatures and pressures (Figure 14). Characterisation of the transient spray from a pressure swirl injector is presented, with observations of the spatial distribution of vapour and liquid fractions. Calibration of the vapour fractions was possible using a two-phase characterisation methodology (Figure 15), which again provide data compatible with the requirements of CFD validation. Quantitative analysis of vapour concentrations is discussed along with potential limitations for quantitative results for dense sprays [17].



T_a = 423 K; P_a = 0.14 MPa T_a = 423 K; P_a = 0.58 MPa T_a = 373 K; P_a = 0.10 MPa.

Figure 15. Exciplex-LIF vapour concentration measurements for different ambient conditions at 2.5ms after start of injection (left: binary liquid image, right: calibrated vapour concentration measurements)

8. HEAT/MASS TRANSFER AND NOVEL PROPULSION SYSTEMS

Whilst no work was undertaken directly at GTRC in these areas, ongoing collaborative programmes are being developed which will be reported in subsequent years. The heat/mass transfer activity is being developed through the partnership with Ukrainian Academy of Science, through our honorary Professor and head of thermofluids in Kiev, Professor Artem Khalatov, who has been developing alternative gas turbine blade cooling technologies, such as use of dimples for example.

Concerning novel propulsion, an ongoing PhD programme is developing understanding of Pulse Detonation Engines (PDE) using liquid fuels, and will be undertaking a practical programme of work at GTRC in 2008/9. This programme did develop a new atmospheric rig facility at Cardiff School of Engineering for detailed visualisation secondary droplet breakup for validation of free-boundary droplet deformation and breakup numerical models.

9. PROFESSIONAL TRAINING AND ENGAGEMENT

A 'sister' research centre was established in 2007/8 which co-locates with GTRC. This is the 'Corus Centre of Excellence in Energy and Waste Research' directed by co-author Professor A.J. Griffiths. Clearly there are strong synergies between the Corus Centre and GTRC, with a core of the same academic staff involvement, but with separate research and technical staff. One example of the complementary nature of the two Centres is the development and delivery of professional training 'short courses' to graduate and technical staff in the areas of 'Combustion Fundamentals' and 'Explosion Hazards'. In 2007/8, 50 Corus technical and graduate employees completed the short courses - .with very positive feedback - and which are continuing into GTRC financial year 2008/9.

GTRC also supports the EU Marie-Curie training programme through the INECSE consortium, led by ENEL, with the theme of Sustainable Energy and Environment. Two Marie-Curie fellows have studied at GTRC during 2007/8, one studying burning rates of alternative fuels under gas turbine conditions [3], and another who undertook a CFD modelling study investigated large-Eddy simulation of the GTRC HPOC burner on a 3-month secondment from his host institution, ENEL. Several other PhD students utilised the GTRC facilities to generate data contributing to their doctoral research programmes.

Finally, Masters Degree case studies are now annually hosted at GTRC as part of students' assessed work towards the Cardiff University MSc in 'Sustainable Energy and Environment'. Seventeen post-graduates undertook the GTRC 'Gas Turbine' case study in 2007/8.

Hence, a total of 75 students received training at GTRC in 2007/8, 50 on post-graduate degrees and short-courses, with the remainder technical and process engineering staff.

10. CONCLUSIONS

The first year of operation for GTRC since its launch in October 2007 has seen the Centre fully utilised and successfully pursing its mission: As proposed, all the programmes undertaken in 2007/8 were utilised to validate existing (e.g. CFD) or develop new semi-empirical models of combustion or energy systems. Research has already been undertaken and published in five of the eight stated GTRC theme areas during the first year.

Innovation has further been demonstrated through the proposition of new optical diagnostic techniques and methodologies, identifying new phenomena and providing invaluable new validation data. These 2007/8 research and innovation programmes have collectively resulted in 14 publications in conference proceedings, with a further 6 journal papers currently under review.

Six international companies in the sector directly sponsored work at GTRC during the year, with another 30 companies and universities indirectly engaged through joint industry sponsored or EU collaborative research programmes. About half of the annual utilisation time was invested in re-commissioning the broad range of bespoke rigs and facilities originally donated by QinetiQ; about half of which have now been fully commissioned and utilised. Hence, 2008/9 is likely to

show a similar utilisation pattern, with a significant proportion devoted to re-commissioning rigs and facilities prior to research utilisation.
In terms of training and engagement, the Centre was very successful during its first year, with some 75 post-graduate and technical engineering staff benefiting from degree or short CPD (continual professional development) training programmes. GTRC now co-locates with another industrial centre of excellence in ‘Energy and Waste’ research - the ‘Corus Centre of Excellence’ - hence building critical mass at the ECM2 site on the theme of ‘Combustion and Energy Systems’.
Finally, during 2007/8 GTRC has made firm steps towards providing an exemplary model of how universities and industry can interface to effectively provide high-impact research and engagement with tangible economic benefits.

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