Safe Operation of Combined Cycle Gas Turbine and Gas Engine Systems using Hydrogen Rich Fuels

S J Hawksworth[1], K Moodie[1], J Gummer[1], B Ewan[2],

H Michels[3], P Linstedt[3], P Winstanley[4], A Pekalski[5]

1. Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire, UK
2. HSL Associate
3. Imperial College, Exhibition Road, London, UK
4. Energy Technologies Institute, Loughborough, UK
5. Shell Global Solutions, UK.

This paper describes work performed by a consortium led by the UK Health and Safety Laboratory (HSL) to identify the safe operating conditions for combined cycle power generating systems running on high hydrogen fuels. The work focuses on hydrogen and high hydrogen syngas and biogas waste-stream fuel mixtures, which may prove hazardous in the event of a turbine, or engine flame out, resulting in a flammable fuel mixture entering the hot exhaust system and igniting.

The paper describes the project, presenting some initial results from this work, including the development of large scale experimental facilities on the 550 acre HSL site near Buxton, Derbyshire, UK. It describes the large scale experimental facility which utilises the exhaust gas from a Rolls-Royce Viper jet-engine (converted to run on butane) feeding into a 12 m long, 0.60 m diameter instrumented tube at a pre-combustion velocity of 22 m/s. A variable geometry simulated heat exchanger with a 40 % blockage ratio is present in the tube. Flammable mixtures injected into the tube close to the Viper outlet, together with make-up oxygen, are then ignited. Extensive optical, ionisation, temperature and pressure sensors are employed along the length of the tube to measure the pressures and flame speeds resulting from the combustion event. Some preliminary results from the test programme are discussed including deflagration to detonation transitions at high equivalence ratios.

1.0 INTRODUCTION

Global energy demand is expected to increase by 35% before 2030 as a result of rapid economic growth in developing countries such as China. Clear indicators of this are recent figures that show China committed almost 50% of an estimated US$850bn of external investment (for the period 2005-14) in the Energy Sector(1). At the same time as this growth, we need to reduce global warming, prolong the availability of conventional oil and gas and use the remaining sources of fossil fuels more efficiently. A key part of the future energy landscape has to be the adaptation and improvement of current power generation technologies (such as gas turbine (GT) and gas engines (GE) systems) to continue to provide a significant portion of global energy demand at relatively low cost and high efficiency, but relying on cleaner gas (such as synthesis gas) and alternative fuels.

In the developing hydrogen economy, the headlines obviously focus on fuel cell technologies for a range of applications, including small scale stationary feeding localised grids, businesses and households (2), fuel cell vehicles which are now, in 2015, available in the market place from several manufacturers (3). Centralised large scale power generation using hydrogen fuel cells also exists in a number of countries (4) and clearly represent a growing trend for the future.

Table 1: Representative fuel gas sources incorporating hydrogen.

Fuel stream	Fuel composition (mol%)							CV (MJ/kg)	Avg Mol Wt	Fuel kg/s/MW
	H_2	CO	CH_4	H/C	N_2	CO_2	H_2O			
Hydrogen	100							120.00	2.00	0.0083
Syngas 1	14.5	23.6	1.6		49	5.6	5.7	9.47	24.40	0.106
Syngas 2	34.4	35.1	0.3	0	0	30.2		8.21	23.85	0.122
Syngas 3	61.9	26.2	6.9	0	2.2	2.8		25.65	11.53	0.039
Syngas +CCS	47	1	1		41		10	8.85	14.66	0.113
COG	61.6	6	23	2.2	5.4	1.2		42.42	9.60	0.024
Refinery Gas	28		28	34	3.5	6.5		41.00	23.8	0.024
Bio Syngas	18	20	7	2	30	23		6.50	26.5	0.154

NB: Syngases 1 - 3 and Syngas + CCS are taken from Todd, D. M., Battista, R. A., 2000(5), COG is taken from reference J. Wolf, & M. Perkovec., 1992 (13). Refinery Gas is taken from (R. Dragomir et Al, 2010 (6). Bio-Syngas is taken from (A. Demirbas, 2008(7).

Combined Cycle Gas Turbine (CCGT) and Combined Cycle Gas Engine (CCGE) power generation systems are also widely identified in the future energy landscape, including Japan's Strategic Road Map and the IEA HIA (8 & 9), and figure prominently in forward looking energy models such as the UK Energy Technologies Institute's Energy System Modelling Environment (10). Operation on a range of potential fuels/ waste streams (see Table 1 which presents examples of potential alternative fuels) utilising high hydrogen sources such as clean coal technologies, gas waste streams, pre-combustion CCS.. In the short term such options provide significant benefit in terms of better use of resources, and in addition provide a basis for the development of hydrogen based technologies.

Recognising the importance of CCGT and CCGE technologies, the ETI initiated High Hydrogen project, addresses some of the key safety issues relating the use of hydrogen, and hydrogen rich fuels for both technologies. The team delivering this project led by the UK's Health and Safety Laboratory, includes Imperial College London, and Scitek Ltd based in Derby in the UK. The early stages of the project gathered and assessed available information relating to the operation of CCGT and CCGE systems, including a detailed survey of critical properties and operational parameters relating to the use of gaseous fuel mixtures. These fuel mixtures were of high hydrogen content within the systems of interest, particularly those with the potential to generate high overpressures under fault conditions in the GT and GE exhausts and in the heat recovery steam generation units (HRSGs).

2.0 BACKGROUND TO CCGT AND CCGE SYSTEMS

2.1 Combined Cycle Gas Turbines (CCGT)

The operation of Combined Cycle Gas Turbines (CCGT) is currently (using natural gas) one of the most efficient methods (Starr, 2010(11)), for converting the energy in gaseous fuels, into electrical energy, achieving efficiencies over 60%. In such systems the CCGT consists of a gas turbine which produces about two thirds of the power. The waste heat in the exhaust system from the gas turbine is then used to raise steam, which powers a steam turbine producing the remaining third of the power. The steam is raised via a heat recovery steam generator (HRSG), which is situated in the exhaust stream of the primary turbine, and is connected to it by ducting that also serves to expand the flow in order to obtain appropriate velocities for optimum heat transfer. The exhaust gas temperatures are for various thermodynamic reasons relatively low, in the region of 300-600^{o}C. This has resulted in large HRSGs often with two or more evaporators operating at different pressures, typically 60-90 bar and 5-10 bar. The larger plants may include up to twelve stages.

The exhaust gas temperature limitations are well recognised. To compensate for this, many industrial scale CCGTs utilise a supplementary duct burner, situated in the gas turbine exhaust. This utilises the residual oxygen in the gas turbine exhaust to raise extra process steam. A fan may be used to supply additional air, which may also enable the burner to be used in the auxiliary mode, whereby it can operate independently to provide heat when the gas turbine is not operating.

Gas turbines intended for CCGT plant, usually run at significantly lower pressure ratios than those used in the aerospace sector, (Starr, 2003(12)). This has several advantages, which more than compensate for the lower efficiency that results. A lower pressure ratio simplifies the design of the compressor, which is particularly critical since an industrial machine needs to rotate at constant rpm, no matter what the power output.

The successful operation of gas turbines using syngas (including hydrogen fuel concentrations >90%) has been demonstrated at numerous facilities over the past few years, although there have been difficulties (13). The syngas mixtures can vary widely in the relative hydrogen and carbon monoxide concentrations, complicating turbine operation and design. The high-temperatures associated with the hydrogen combustion can lead to high nitrogen oxide emissions, and existing dry low-NOx gas-turbine technologies are not amenable to the high mass flow rates and fuel concentrations (from 15% to 40%) required for syngas mixtures. As a result, the current approach is to fire syngas with high levels of dilution (typically using nitrogen or steam).

Todd and Battista (14) state that significant progress has been made in the development of market applications for hydrogen fuel use in gas turbines. These applications include integrated gasification combined cycle (IGCC) and other types of process/power plants. Development of a new application using gas turbines for significant reduction of power plant CO2 emissions has initiated extensive efforts to expand the range of hydrogen combustion capabilities. Testing program results also show the feasibility of hydrogen use for 20-90% CO_2 emission reduction with control of NO_X emissions to below 10 ppm at 15% oxygen.

Wolf et al (15) discuss the safety aspects and environmental considerations of operating a 10 MW cogeneration gas turbine burning coke oven gas with 60% hydrogen content. The power plant was a duel fuel arrangement using light distillate oil as the secondary fuel. An inert nitrogen buffer was considered necessary for safety reasons when switching between fuels, in order to prevent oxy-hydrogen formation at the transition point. Sophisticated control and regulation systems, details of which are not given in the paper, were developed and because of the increased hazards, explosion proofing was also provided. Controlling the NOX emissions was a major problem.

Schneider (16) describes the successful operation of gas engines running on various hydrogen containing fuels including coke gas (55 to 70 % H_2), pyrolysis gas from domestic waste gasification (35% H_2) and wood gas (15-40% H_2).

2.2 Combined Cycle Gas Engines (CCGE)

Typical of the gas engines used for Combined Cycle Gas Engine (CCGE) type systems are those of GE Jenbacher, GE Waukesha, Caterpillar, Rolls-Royce and others. These types of engines are designed from the outset to run on gas (not diesel engine conversions), natural gas, biogas or special gases, and are around 0.25-10MW in output when used as stationary continuous operation units. Gas engines of this type can be up to 44% efficient, with very low exhaust emissions. They are very durable and highly reliable in all types of applications, particularly when used for Combined Heat and Power (CHP) applications. They are able to constantly generate the rated output even with variable gas conditions.

Gas engines can usually operate on gases with extremely low calorific value, low methane number and hence a low degree of knock, but also gases with a very high calorific value. Typical gas sources vary from low calorific gas produced in chemical industries, wood gas, pyrolysis gas produced from decomposition of substances by heat (gasification), landfill gas, sewage gas, natural gas, propane and butane which have a very high calorific value. Coke gas is also used as a fuel for gas engines; it is a by-product of coke production from hard coal. Coke gas consists mainly of hydrogen (50 to 60%), methane (15 to 30%) and carbon monoxide, but due to the extremely high hydrogen content of coke gas, specially modified engines are used to generate power from this fuel source. Gas engines are often down rated to utilise higher hydrogen content fuels because of knocking (detonation) in cylinders. The limits on fuel composition are based on auto ignition since ignition must occur when sparked and not prior to it. The flame speed is also of importance since if it is too high ignition timing is compromised.

2.3 Other Important HRSG Features

In common with gas turbine plant, although less common, a supplementary duct burner, situated in the gas engine exhaust, may be used to raise extra process steam, utilising the residual oxygen in the engine exhaust as its source of oxygen. A fan may be used to supply additional air, which may enable the burner to be used in the auxiliary mode, whereby it can operate independently to provide heat when the gas engine is not operating.

Another important issue arising from running CCGT/CCGE systems on high hydrogen fuels is the production of high NOx emissions. The primary post-combustion NOx control method is selective catalytic reduction (SCR). Ammonia is injected into the flue gas and reacts with NOx in the presence of a catalyst to produce N_2 and H_20. The SCR system is located in the exhaust path, typically within the HRSG where the temperature of the exhaust gas matches the operating temperature of the catalyst. The operating temperature of conventional SCR systems ranges from 250 to 450^0C.

The primary reactions occurring in SCR require oxygen, so that catalyst performance is best at oxygen levels above 2-3%. Several different catalysts are available for use at different exhaust gas temperatures. In use the longest and most common are base metal catalysts, which typically contain titanium and vanadium oxides, and which also may contain molybdenum, tungsten, and other elements.

Low temperature SCRs have been developed as they are ideal for retrofit applications where they can be located downstream of the HRSG, thus avoiding the potentially expensive retrofit of the HRSG to locate the catalyst within a hotter zone of the HRSG.

High temperature SCR installations, operating at up to 650^oC, have also been developed. The high operating temperature permits the placement of the catalyst directly downstream of the turbine exhaust flange. High temperature SCR’s are also used on peaking capacity and base-loaded simple-cycle gas turbines where there is no HRSG.

Other potential developments in this area include CCGT systems operating on pure hydrogen and oxygen combustion. See Siemens for more information(17).

3.0 PROJECT SCOPE AND PROGRAMME OF WORK

A key issue for the safe operation of CCGT and CCGE systems is the potential for a flame out to occur in the GT or GE power unit, leading to flooding of the system downstream of the fuel injection point (exhaust and HRSG) with a flammable gas mix, which could then be ignited.

The risks associated with such an occurrence are not insignificant because of:

- The potential variability of the fuel composition of what are in effect high hydrogen waste streams.
- The high fuel flow rates required to power multi mega-watt output systems
- The large volume of the HRSG systems, and
- The high levels of congestion and potential ignition sources within the HRSG.

To understand these hazards careful thought has been given to unusual conditions of flow, temperature and scale found in the facilities of interest. Based on these factors and the typical properties of the mixtures identified in Table 1, a staged program of work was developed focusing on fuel mixtures of H_2, CO and CH_4. The programme objective is to understand their behaviour under the extreme conditions of flow and temperature found in the exhaust's and HRSG's of these systems, and in particular the detonation limits under these conditions. The stages of the experimental program are outlined below:

3.1 Laboratory Based Experiments

Laboratory studies were performed at Imperial College where they investigated the impact of fuel reactivity changes on a number of key parameters. To achieve this, experimental configurations were chosen to investigate the relative influence of chemistry and flow. Ignition delay times were measured using a shock tube configuration in order to provide a purely chemical kinetic related measure of reactivity. Auto-ignition in a turbulent shear layer formed between a fuel jet and a stream of hot combustion products was investigated in order to explore the influence of turbulence under conditions that can be correlated with the ignition delay time results, using a configuration related directly to the practical case where reactants are ejected into hot combustion products. Turbulent burning velocities were determined using fractal grid generated turbulence in an opposed jet configuration in order to determine the strength of turbulent deflagrations as a function of fuel composition. The Deflagration to Detonation (DDT) potential in a turbulent flow was assessed using an obstructed shock tube configuration with explosion over-pressures determined and related to the fuel reactivity and the strength of the turbulent deflagration phase.

The study accordingly provides a comprehensive assessment of fuel reactivity in systems related to the use of hydrogen rich mixtures under CCGT and CCGE relevant conditions and showed the impact of CH_4 and CO on the reactivity of the mixtures. The experimental results from these studies are very extensive and are expected to be published at a later date.

3.2 Cylindrical Duct Experiments

Using the findings from the analysis of CCGT and CCGE systems combined with the findings from the laboratory experimental work, an experimental facility has been developed to investigate the flame out of CCGT/CCGE systems and the consequences of unburnt fuel passing through the turbine (in the CCGT case) and into the exhaust system. It has been designed to allow for the circumstances where a hydrogen concentration in the downstream mixture will be in the flammable, potentially detonable region (when fuelled with pure hydrogen), and be at temperatures of the order of 400–600^{0}C. Re-ignition in the exhaust system is then assumed to occur and the potential consequences assessed, particularly with reference to the flame acceleration and the detonation propensity of the air/fuel mixtures. This facility provides a reduced scale model of an actual turbine exhaust system, comprising a jet engine, to provide a hot vitiated air flow, and a nominal 600 mm diameter duct, some 12 metres long. More details of this facility are provided in Section 4 below.

The rationale for using this size of rig is based on the consistent experimental and theoretical evidence for hydrogen mixture compositions with marginal detonation behaviour, for which the detonation cell size is characteristically several times that of a stoichiometric fuel mixture and rises asymptotically towards the detonation limit within a few percent for further mixture dilution. With an established detonation cell width for stoichiometric hydrogen-air of approximately 10 mm at near ambient conditions and a critical channel width for detonation propagation of no more than this, it will be feasible to accommodate, close to the detonation composition limits, a potential hydrogen detonation with multiple cells across the width of the 600 mm duct.

3.3 Simulated HRSG experiments

This third stage is the further development of the cylindrical duct facility by the addition of a "scaled" HRSG, complete with features such a tube bundle giving 40% congestion etc. This is currently under development and further details will be available at a later date.

4.0 DESCRIPTION OF FACILITY

The test facility comprises a Rolls-Royce (R-R) Viper gas turbine, Type 301, whose exhaust feeds into the 0.6 m diameter circular duct, which is 12 metres in overall length. The duct comprises four by 3 m long insulated sections, flanged and bolted together and designed to withstand a maximum operational pressure of 22 barg with a maximum average wall temperature of 400°C. An interface section is incorporated between the engine's turbine and the start of the 0.6 m diameter duct. This provides a pathway from the engine turbine into the duct such that the turbulence levels in the flow are minimised. It also provides a means of controlling the amount of exhaust flow that enters the test duct such that a range of velocities, typical of those found in full size CCGT/CCGE systems, can be replicated. A series of nozzles are integrated into this section to provide a means of injecting and mixing the test gas mixtures radially into the main hot gas exhaust flow from the engine. These gases are injected at about ambient temperature, thus minimising the risk of ignition at this point.

Figure 1. Rolls-Royce Viper in position.

The operating procedure chosen requires the engine to be run for a period in order to heat the test duct to the desired operating temperature such that the desired gas temperature in the range of 400 - 600°C along the duct is achieved. The engine is then kept running and a high-hydrogen fuel sample together with oxygen, sufficient to restore the level in the exhaust stream to 21%, are injected at approximately the same time into the engine exhaust immediately downstream of the engine turbine. This procedure reduces slightly the exhaust stream temperature assuming that the gases are injected at ambient temperature. The flammable gas/oxygen mixture injection process lasts 2-4 seconds, during which time ignition of the mixture is obtained using an electrical spark.

4.1 Rolls-Royce Viper

The Viper jet engine provides a mass flow rate of around 11-15 kg/s, with a turndown ratio of 4:1. The engine has a power output of 3.0-3.5 MW, and jet velocities in the 600 mm diameter duct are between 20 - 90 m/s. A dedicated mass flow meter type intake ensures that the airflow is smooth and that the mass flow rate can be measured from the pressure drop at the throat of the intake.

The engine output is variable from idle conditions, when the mass flow rate is 3 kg/s, up to maximum power when it is 15 kg/s. Once at or above idle the exhaust temperatures remain at approximately 560°C until almost the full power output is reached. It is not intended to operate the engine at a mass flow rate of more than 15 kg/s.

The complete test facility comprising the jet engine and the duct, with its associated components housed in an approximately 20 metre long by 3.0 x 3.5 metre cross section ventilated building. The test rig itself is attached directly to a substantial concrete pad, which is capable of withstanding the dynamic reaction loads resulting should a stoichiometric hydrogen detonation occur within it. The test duct is fixed at one point only, through an anchor plate attached at the beginning of the test duct proper. The rest of the duct is simply supported in order to allow for thermal expansion. The R-R viper engine is mounted independently with a flexible connection between the exit from the turbine and the entrance to the test duct to minimise exhaust spillage and allow for thermal expansion.

The jet engine has been converted to run on butane in order to minimise the possibility of soot particles affecting the DDT behaviour of the gasses being tested. Consequently the design of the gas turbine rig required modification of the engine prior to commencing the test programme and obtaining a 9000 litre liquid butane storage tanks for the duration of the test programme. Modifications to the engine to run on butane involved the removal of its existing fuel pump and fitting an external variable speed positive displacement pump to meter the fuel flow into the engine and therefore control its speed. To this end expertise from Reaction Engines, who have specialised knowledge of running a Viper engine on butane, was obtained so that the risks of any unforeseen technical difficulties arising from the conversion of the engine were minimised.

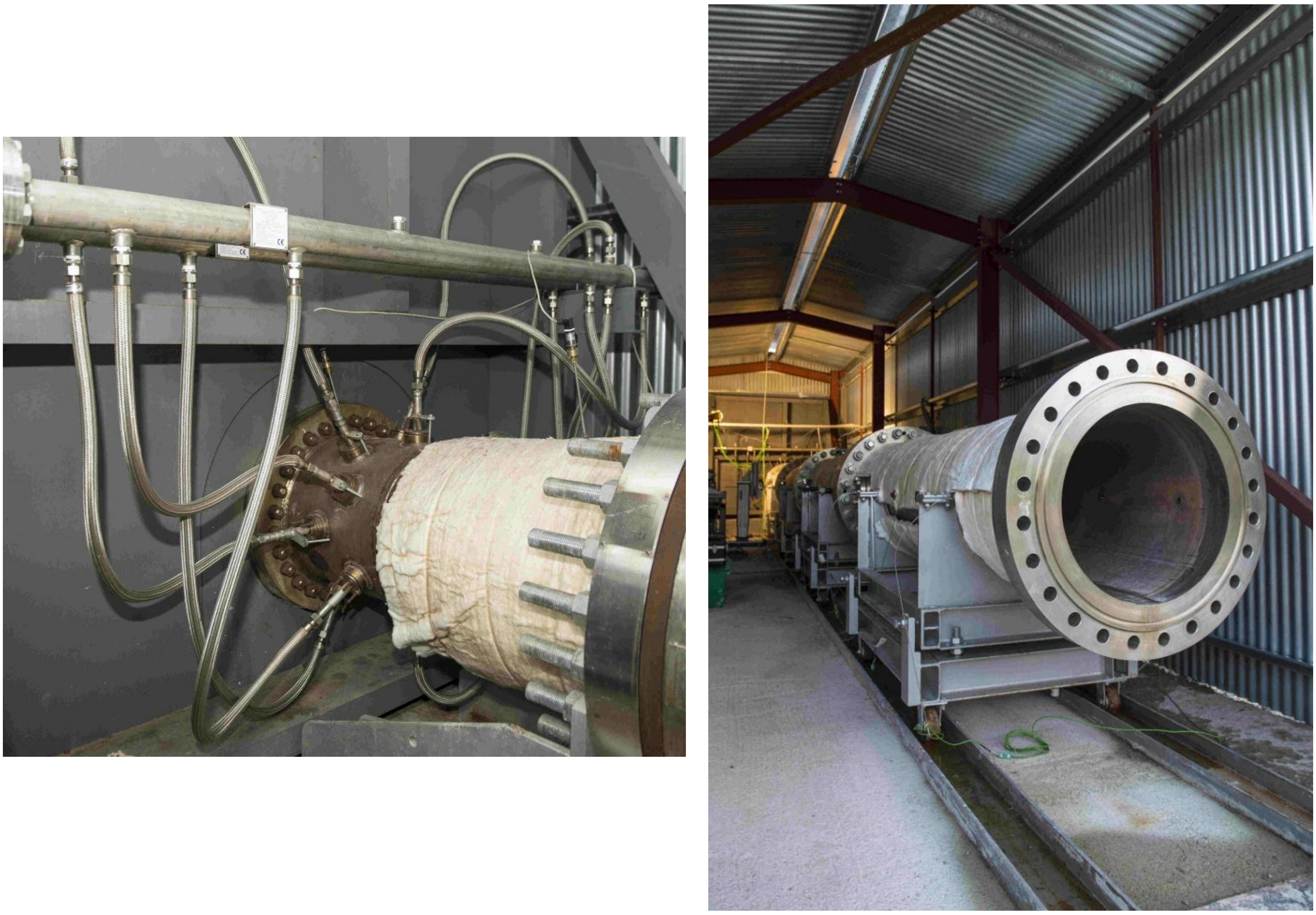

Figure 2a & b. Gas Injection system (left) and experimental duct (right)

4.1.1 Engine Control System

The control system for the engine is an adaptation of the established control system used when running the Viper engine in its normal mode on kerosene. A dedicated PLC system programmed to control the engine and ensure the prescribed safe operation of the engine, rig and facility. The specialised experience of Reaction Engines was used again in the development of the control system, incorporating extra safety features relating to the use of butane fuel. The engine is started using an electrical starter to spin it to about 800 rpm; it then uses pilot fuel injectors to spool it to idle (4000 rpm) before switching over to the main fuel injectors.

The control system reads and records a number of engine and rig parameters such as RPM, oil pressure, compressor pressure, exhaust temperature and pressure, intake mass flow rate etc. Software was written to communicate with the PLC system and display these parameters on computer screens as well as storing them on a hard drive. The clock of the control system is synchronised with that of the data acquisition system so that data from other instruments can be correlated to engine parameters. The PLC is located in close proximity to the engine, feeding and storing the engine parameters to the control room which for safety reasons is situated some 90 metres from the engine. Engine start, speed settings and shutdowns are carried out from the control room. Failsafe hardware is installed, which in the event of a power failure, gas leakage, and engine over speed or over temperature, automatically shuts down the engine.

4.2 Explosion Duct and Gas Mixing

Instrumentation ports are provided along the length of the tube at 500mm intervals, drilled and tapped to take a range of fast response sensors for measuring pressures and ‘K’ type thermocouples to measure pre combustion temperatures along the tube, as well as optical and ionisation probes to detect flame. The latter are the principle means of flame detection, ionisation probes detecting flame at the wall and the optical probes across the whole of the cross-section. In addition 80mm diameter viewing ports are provided in each tube section at a distance of 500mm from the beginning of each 3 m length of tube. An optical quartz window is provided which allows LDA measurements to be made of the flow velocities and turbulence intensities across the tube at up to four different downstream positions.

A multi-channel data logging and processing system is used for data collection and processing. This has a sampling rate of at least 120 kHz per channel, and 32-bit resolution for rapid data collection. The fast response pressure sensors measure pressures across the wave fronts in the duct. The thermocouples measure the gas temperature outside the boundary layer, whilst other thermocouples l monitor the duct wall temperature, fully developed turbulent flow being assumed. Optical and ionisation probes detect the passage of flame. All of the probes can be used to monitor flame propagation parameters i.e. distance/ time/ velocity. Several additional pressure transducers are available for measuring operational pressures in the duct and around the engine exhaust as necessary.

Figure 3. Congestion array.

The system of gas supply consists of two stainless steel pressure vessels with a maximum capacity of 225 litres and a MWP of 250 barg. One vessel contains oxygen the other the fuel mixture. The latter comprises mixtures of hydrogen/methane/carbon monoxide and nitrogen when required. Specific gas mixtures are prepared from individual gas cylinder packs using a booster pump, quantified using partial pressures.

The injecting the gas mixtures is a flow through system, injecting directly into the exhaust stream and relying on the injection process to ensure that the gases are fully mixed with the exhaust stream. This avoids waste and reduces the risk of a flash back. The mass flow rates of the injected gasses are measured using individual Coriolis mass flow meters and controlled using mass flow controllers. The supply line pressures are regulated using pressure regulators (40 barg maximum). This method of flow control and monitoring provides an accurate control system with better resolution and variability than can be obtained by direct injection through fixed diameter orifices. This provides precise control over the mixture concentrations injected, together with a wide range of mass flow rates to match the exhaust mass flow range. The same method of flow control is used with the addition of oxygen. The maximum mass flow rate from the fuel system is 2.74kg/s when operating with 100% CO.

The gas supply system is located in a well-ventilated area and is piped to the rig, with protective barriers between for safety reasons. The pipe work and its associated pressure regulators and flow controllers are designed and installed in accordance with the Pressure Systems Regulations, incorporating non-return valves as opposed to flame arrestors.

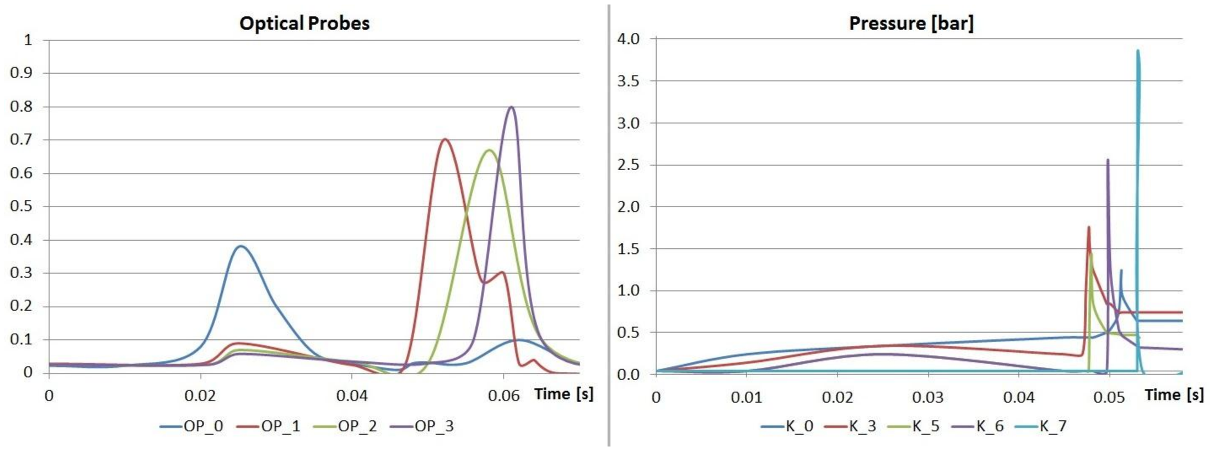

Figure 4. Preliminary data showing typical optical and pressure sensor records.

5.0 PRELIMINARY RESULTS & FUTURE WORK

The experimental programme to date has performed tests with a range of H_2/CH_4 mixtures and H_2/CO mixtures up to equivalence ratios of 0.8. These tests have been performed with a range of congestion levels and pre-combustion flows below 25m/s. Significant observations from these tests are the Deflagration to Detonation Transition (DDT) under certain conditions, with flame velocities of 2000m/s and overpressures in excess of 8bar.

Figure 4 below shows preliminary results from this first series of tests for a hydrogen-methane mixture. The left hand plot shows the raw data from optical flame detectors (optical signal vertical axis is arbitrary) at various positions along the tube. The right hand plot shows the data from the pressure transducers.

The experimental programme is ongoing, building on the data gathered to date, and investigating other key parameters.

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