

University of Southern Queensland
Faculty of Engineering and Surveying

Effects of On-board HHO and Water Injection in a Diesel Generator

A dissertation submitted by

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In fulfilment of the requirements of

Courses ENG4111 and ENG4112 Research project

Toward the degree of

Bachelor of Engineering (Power)

Submitted: October 2012

Abstract

HHO otherwise known as hydroxy or Browns Gas is the gas produced from splitting water into hydrogen and oxygen from electrolysis and allowing the gas to stay in a premixed state for use on-demand without the need for storage. In 1918 Charles Frazer, a North American inventor, patented the first water electrolysis machine act as a hydrogen booster for internal combustion engines. Yull Brown, a Bulgarian born Australian inventor patented and attempted to popularize Browns Gas as a cutting gas and fuel additive during the 1970's and 80's. During the 2000's there was a huge influx in Browns Gas devices coming to the mark, with many sensational claims of bringing dramatic reductions in fuel consumption and exhaust emissions in internal combustion engines.

This research project involved experimentally validating the effects of on-board HHO addition on fuel economy and emissions in a 28kW diesel generator. The diesel generator was run at 30% and 55% of the engines rated power output with three rates of HHO injection, with and without water injection.

Results include accurate measurement and analysis of diesel consumption and exhaust emissions of the diesel generator under 16 combinations of generator loading, HHO injection and water injection. The HHO and water are injected into the air intake manifold of the engine. Error margins and calibrations are detailed, and environmental conditions accounted for in the findings.

HHO was shown to increase diesel consumption under all conditions tested, proportional to the rate of injection – up to a 5.2% increase at 55% load with 6L/min of HHO addition. Oxides of nitrogen (NO_x) emissions were reduced up to 11.8% with the addition of water and HHO from an externally powered electrolyser. Even if the efficiency of the HHO system could be raised to 100%, the thermal losses in the engine stage would still outweigh the economy gains from on-board HHO addition.

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ENG4111 Research Project Part 1

ENG4112 Research Project Part 2

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Certification

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I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Acknowledgment

Dr Les Bowtell, for his support and interest in the topic and his advice during difficult periods

Dr Paul Baker, for his insight into environmental corrections for engine testing and access to the engine lab

Brett Richards, for all his supervision and availability in the testing phase

Dr Ron Sharma, for allowing me to use the diesel generator set as a contingency

Bill McHugh, for providing a good example of a dissertation

Racheal Cameron, for her support

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Nomenclature and Acronyms

AC	Alternating Current
ADC	Analog to Digital Converter
BG	Browns Gas
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTDC	Before Top Dead Centre
DAC	Digital to analog converter
DC	Direct Current
EGR	Exhaust Gas Recirculation
HCCI	Homogeneous Charge Compression Ignition
HHO	Gas mixture made of 1/3 oxygen and 2/3 hydrogen by volume
HMI	Human-machine interface
HOD	HHO on demand
H ₂ -O ₂	HHO
NO _x	Nitrate of oxides
PLC	Programmable Logic Controller
STP	Standard temperature and pressure: 298.15 K, 101.325 kPa

Chapter 1 Introduction

1.1 Outline of the Study

The outline of this study is to research the effects of HHO produced on-demand combined water injection as an additive for combustion in a diesel generator. The effects of current known phenomena of HHO and water on diesel engine exhaust emissions and fuel consumption will be discussed. This study will describe the design of the experiment – stating the controls and variables. Chapter 5, *Experimental System*, will include analysis of the water injection system, the on-board water electrolyser system, the industrial control system, the diesel supply system and the data logging system used in the experiment. The results of this test will be focussed at proving the quality and magnitude fuel consumption and exhaust emissions of HHO on-demand systems similar to what is currently available on the market.

1.2 Introduction

There has been much conjuncture in the public domain as to the effects on fuel economy of hydrogen on-demand systems made for internal combustion engines, as is evident with a simple search on the internet. There is little solid experimental evidence from controlled repeatable tests quantitatively proving the economy enhancing effects of on-board HHO for naturally aspirated or turbo diesel engines. Two independent sets of researchers have shown experimentally that HHO on-board can reduce diesel consumption [1, 2], while another team found a reduction in engine efficiency [3]. To the authors knowledge no on-board testing has been performed under a controlled environment where the systems variables and environmental conditions are accurately controlled and corrected for. On-board HHO addition means HHO produced by taking a portion of the engines power to crack water into a small volume of HHO to be fed back into the air intake as a fuel saving additive. This study will experimentally verify the economy and emissions effects of adding small rates of HHO produced on-demand by a diesel generators own power combined with 0% water injection and 10% water injection.

1.3 Research Objectives

The rationale behind the research objectives are derived from the research gap in testing hydrogen on demand by other researchers, as well as the need to experimentally prove or disprove the validity of the claims of hydrogen on demand vendors.

The experimental research objectives of this research include;

- Experimentally test the effect on fuel consumption and exhaust emissions of adding 0L/min to 6L/min of HHO to a constant speed 28kW diesel generator under two loading conditions - 30% and 55% of the engines rated load.
- Accurately automate and data-log the experiment with an industrial control system, where water injection rate, HHO production and generator load are the independent variables.
- Optimize HHO and water injection ratios to yield lowest brake specific fuel consumption, if HHO is shown to have a positive effect on fuel economy.
- Record and discuss the effects of HHO on oxides of nitrogen (NO_x) emissions.
- Discuss the financial feasibility of on-board HHO, if HHO proves to reduce diesel consumption.

Chapter 2 Literature Review

2.1 Literature Review: Properties of Brown's Gas

BROWN'S GAS is created via the process of water electrolysis where the hydrogen and oxygen are allowed to stay mixed. Water contains a ratio of 2 parts hydrogen to one part oxygen bonded in a tetrahedral molecular arrangement with two lone pairs of electrons and two bonding pairs of electrons connecting the hydrogen atoms to the central oxygen atom. Eckman [4] proposed that when water is electrolysed and the gas products are not separated by a semi-permeable membrane, Rydberg clusters may be formed. These clusters are of a mixture of hydrogen and oxygen species including linear water molecules in the highly energized trigonal-bipyramidal geometry, monatomic and diatomic hydrogen, free electrons and oxygen.

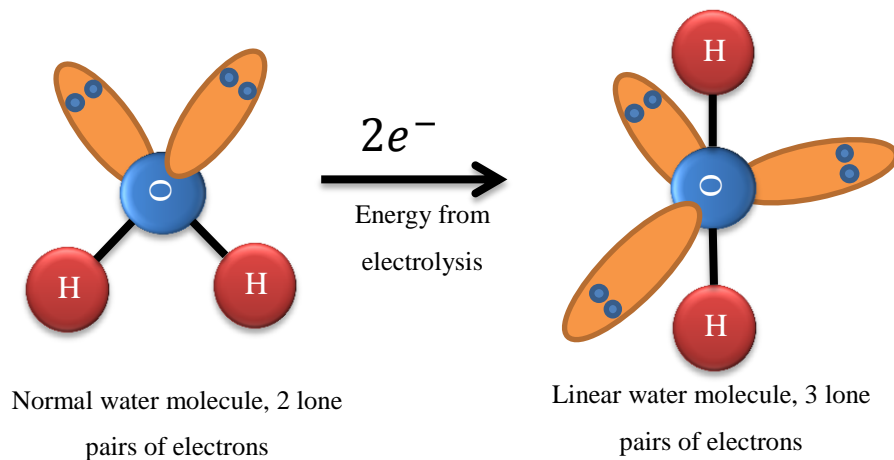


Figure 1: Rydberg clusters containing water molecules with highly energized electrons, but unenergized nuclei[4].

The extra energy stored in one litre of HHO due to Rydberg clusters is theorized to be $600 \pm 34 \text{ J}$. Rydberg clusters are most common in solids and liquids and are typically stable from nanoseconds to hours. In the case of HHO or Brown's Gas these clusters have shown a life span of 11 minutes [4]. Due to these highly energized clusters HHO contains much more energy than equivalent stoichiometric

ratio of hydrogen and oxygen in the form of extra electrons, this state has been explained as cold plasma. Cold plasma is a state of matter where the atom nuclei are relatively unenergetic or slowly moving, but the electrons are in highly energized states at higher atomic orbitals. If this is true HHO releases additional electrons during combustion that are stored in the gas resulting in higher electrical and thermal energy transfer compared to the equivalent mixture of hydrogen oxygen and water. Normally the presence of water in a burning fuel gas greatly reduces the heat energy due to the high specific heat capacity of water (4.18J/g-K), however the linear water content of HHO has greatly reduced hydrogen bonds and electrically transfers its electrons under combustion at the surface of the contacting material. The flame temperature generated by HHO can range from 150°C to over 9000°C [5] based on the contact materials' electrical conductivity, thermal conductivity, density and vapour point. The HHO generated for addition into the diesel engine in this research project will not have a water vapour removal (desiccant) stage at the output, so as to test the effects of the claimed additional energy release during combustion.

2.2 Literature Review: Hydrogen Assisted Combustion

This review covers tank hydrogen-diesel experiments that have several similarities to the experimental setup in this research project. Conditions for commonality include naturally aspirated diesel engine, constant engine speeds at or near 1500r/min replicating a generator, small rates of either hydrogen or HHO injection into the air intake, with fuel consumption and NO_x emissions analysis. Throughout this paper, all gas mass flow rates are converted to volumetric flow rate at standard temperature and pressure – 298.15K and 101.325kPa. HHO injection is most commonly cited in terms of volumetric flow rates, so all references to hydrogen or HHO injection will be on a litre per minute injection base unit. Chapter 6 will discuss the energy required to crack water into hydrogen. Three values will be taken from chapter 6 to tie the reviewed literature into this research project. Firstly it takes 7.79kJ to produce 1L of HHO, and secondly the net efficiency of converting the equivalent diesel energy to HHO energy was between 11.4% and 16%. Thirdly 4.4Wh of electrical energy was required make 1L of HHO with the experimental setup; this includes losses from the switch mode power supply. Taking an arbitrary net HHO

conversion efficiency of 15%, it would require 51.9kJ or 14.426W·h of diesel energy to produce 1L of HHO.

Adnan et al. [6] found gaseous hydrogen injection rate of 20L/min at standard temperature and pressure (STP) doubled oxides of nitrogen (NO_x) emission at 1500r/min in a 7.4kW 406cm³ naturally aspirated Yanmar diesel engine, with a compression ratio of 19.3:1. The engine load or power output was not stated. The cylinder peak pressure increased 11% and delayed the peak pressure event 10° in the combustion stroke, indicated power increased 33% at 1500r/min. The power gain would correspond to a reduction of fuel consumption all things being equal. If the hydrogen was produced on-demand at 4.4Wh/L then the added load would be 5.3kW, leaving around 29% of the engines power for useful work, and most likely dramatically increasing diesel consumption.

Bose and Maji [7] injected 27.8L/min of hydrogen and EGR gas into a 5.2kW, 17.5:1 compression diesel engine running at 1500r/min under various loads. Brake Specific Energy Consumption (BSEC) was reduced 64% and 36%, NO_x emissions increased 70% and 90% at 20% and 40% load respectively due to hydrogen injection. The efficiency of the diesel engine increased due to the increased lean limit and flame speed due to the properties of hydrogen combustion. 27.8L/min of hydrogen is a high injection rate for a small engine if the hydrogen had to be split from water by the engines own power. If this hydrogen were to be produced on demand at 4.4Wh/L, the added load due to electrolysis would be 7.34kW – 41% greater than the engines rated power.

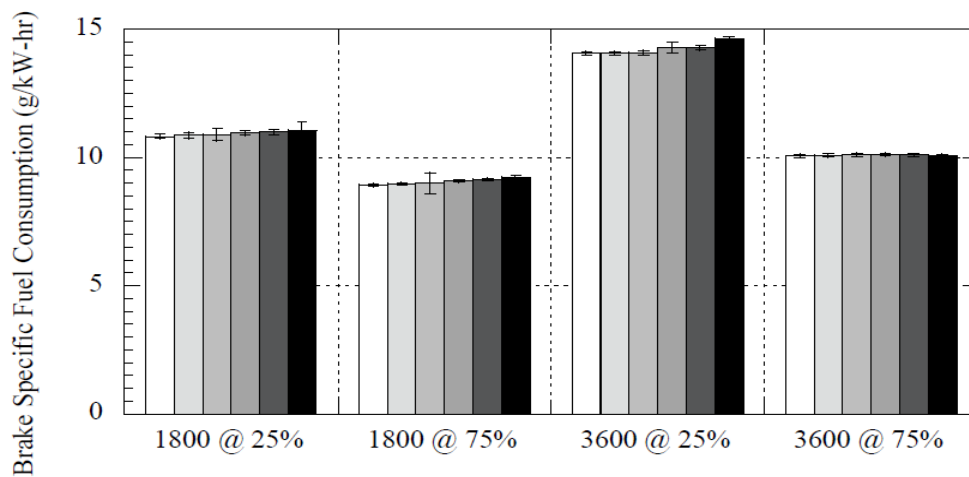
Miyamoto et al. [8] injected tank hydrogen at varying rates into a 551cm³ single cylinder diesel engine with a 16.7:1 compression ratio operating at a constant 1500r/min. The engine had varying diesel injection timing, and the coolant and air temperature were maintained at a constant level. Diesel injection timing was from 12° to 0° BTDC, NO_x emissions due to 6.0% vol. H₂ injection caused NO_x to drop 24% at 12° BTDC injection timing, to equal the NO_x emissions with no hydrogen injection.

Lilik [9] Tested the effects of small ratios of hydrogen injection on a 2.5L turbo diesel engine operating at 1800r/min, 25% and 75% rated engine load. Some of the key results are shown in Table 1. Overall NO_x emissions and brake specific fuel

consumption increased with tank hydrogen injection – H₂ has a negative impact on BSFC. The hydrogen injection in the turbo diesel engine had the opposite effect on diesel consumption.

Table 1: Change in NO_x emissions and BSFC on a 2.5L turbo diesel at 1800r/min

Parameter	2.5% FE H ₂	2.5% FE H ₂	5% FE H ₂	5% FE H ₂
	25% Load	75% Load	25% Load	75% Load
NO	-16.9%	-3.4%	-24.2%	-5.4%
NO ₂	+53.3%	+72.1%	+68%	+87.1%
BSFC	+0.3%	+0.4%	+0.6%	+0.6%



Brake specific fuel consumption of the four modes tested, with □ 0%, ■ 2.5%, ■ 5%, ■ 7.5%, ■ 10% and ■ 15% hydrogen substitution on an energy basis.

Figure 2: Brake specific fuel consumption for a 2.5L turbo diesel engine, courtesy Lilik [9].

With all the literature reviewed so far, NO_x increases with load and hydrogen injection rate. The increase in fuel economy due to hydrogen injection is not sufficient to offset the energy required to make the equivalent volume of hydrogen by electrolysis of water using the engines power. A small rate of water injection could be a means to offset in-cylinder temperature rises created from hydrogen and therefore reduce NO_x emissions, without significantly reducing the reduction of fuel energy made available from electrolysis. Based on hydrogen experimental research, on-board HHO would appear to increase diesel consumption, and proportionally decrease the available usable engine power.

2.3 Literature Review: HHO as an additive in diesel engines

Bari and Esmail [2] operated a 4L direct injection (DI) diesel engine in simulated generator mode at three loads at constant speed, supplying 0-32L/min of HHO supplied by an externally supplied high power water electrolyser. Yilmaz et al. [1] injected small rates of HHO into a diesel engine and performed tests with engine load, speed and two stage unspecified HHO delivery rates as the system input variables. Experiments performed by both teams of researchers showed positive results in improving the fuel efficiency of the engines, but the quality of the data and equipment varied significantly.

Bari and Esmail [2] operated a 4L DI diesel engine generator at three loads at 1500r/min, supplying up to 32L/min of HHO supplied by an externally powered electrolyser. They sought to verify whether an on-board electrolyser can reduce fuel consumption in a diesel engine. They reported around 14-15% reduction in fuel energy consumption (diesel and hydrogen energy both included) across all loading conditions and HHO injection rates. They found HHO is best used in small ratios, up to 4% because up to this injection rate HHO acted as an additive rather than a 1:1 diesel replacement fuel. NO_x emissions increased up to 27% with an increasing rate of HHO injection, the same as for tank hydrogen injection.

There were a couple of problems with the experimental setup, the first was in the use of a Dwyer air flow meter, and the second was in the assumption of unattainably high oxy-hydrogen efficiency. The author attempted to use the same brand of flow meter to measure HHO production, but found the Dwyer flow meter indicated 4.5L/min of gas when in fact 6L/min was measured using an upside down bucket test due to the lighter density of hydrogen in the HHO mixture. If there is this much constant measurement error, then the HHO gas rates would be 33% higher than stated in the paper, significantly over optimizing the BSFC results. The water electrolyser used in the experiment was an Epoch model EP-500 water electrolyser, rated for an input power of 11.5kW, consuming 1.4L/h of water – the equivalent of 47.53L/min of HHO at 4Wh/L (using the $pV=nRT$ gas volume formula), this would confirm the 33% underestimate of HHO addition.

Table 2 below takes Bari and Esmaeil’s HHO volume and energy claims and modifies them to reflect the previously stated assumptions for the power requirements of a realistic water electrolysis system (4Wh/L) and the volumetric flow rate discrepancy due to using an air flow meter. Running such a high rate of HHO would reduce the available power to supply useful electrical loads – and potentially reduce fuel economy if the HHO gas did not have a strong additive effect.

Table 2: Added electrical load due to on-board water electrolysis.

Dynamometer load	HHO (claimed)	HHO (adjusted)	Electrolyser power	% Electrolyser load/Dyno load
19kW	31.7 L/min	42.3L/min	10.14kW	53.37%
22kW	29.8 L/min	39.7L/min	9.54kW	43.3%
28kW	30.6 L/min	40.8L/min	9.79kW	35.0%

Yilmaz et al. [1] reduced diesel consumption an average of 14% across the range of speeds tested, with the highest gains in economy at the higher engine speeds. This could be due the HHO mixture speeding the combustion, leading to a more efficient pressure profile. There are several omissions and major concerns with the Yilmaz et al research paper. Firstly the volume of HHO injected and the efficiency of the HHO system was not mentioned, only the power used to run the electrolyser. The HHO was not injected at a constant ratio to diesel, unlike the Bari and Esmaeil experiment, rather in two rate profiles – 43W of HHO below 1750r/min and 120W above 1750r/min. The data plotted as one series as can be seen below in Figure 3.

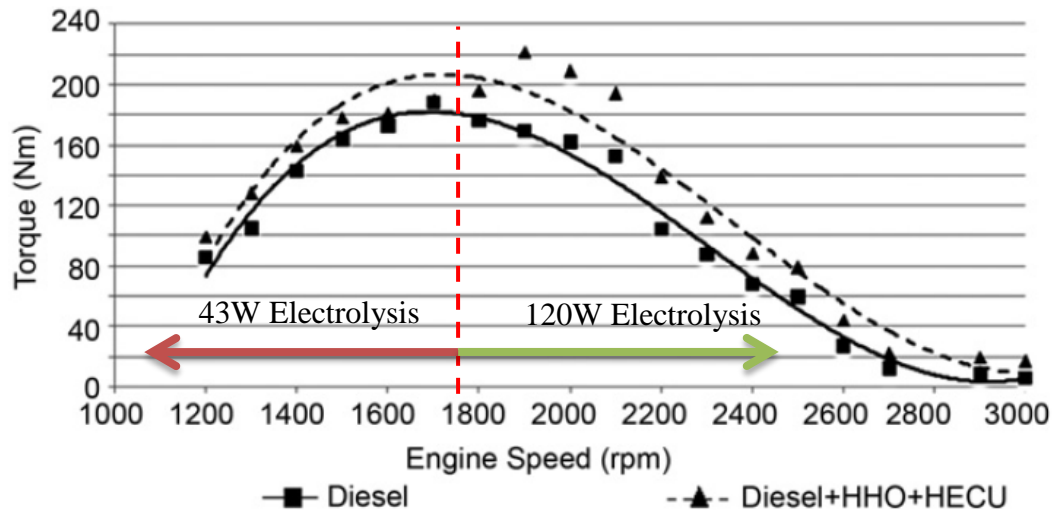


Figure 3: Variation of engine torque with speed, and two rates of HHO from Yilmaz et al. experiment [1].

Another concern was with the BSFC of the test engine. Under both stock conditions and HHO test conditions, specific fuel consumption was inordinately high; ~1100g/kWh at 1800r/min to ~1750g/kWh at 3000r/min – compared to a range of 232-262g/kWh for a similar sized engine operated by Bari and Esmail, leading to doubt in the integrity of their data measurement system.

2.4 Literature Review: Water injection in diesel engines

Tauzia et al. [10] Compared the effects of EGR and water injection on exhaust emissions on a 2.0L turbo diesel engine. Water injection was more effective for reducing NOx emissions. At 60% water injection to fuel usage, NOx was reduced by 50%, but only 30% of this reduction was due to the cooling effect of water. BSFC increased, due to lower peak temperatures, delayed ignition and increased heat losses at the cylinder wall. Either water injection alone or on-board HHO addition alone both appear to reduce fuel economy of the diesel engines.

2.5 Summary

There are no reliable indicators that on-board HHO has the potential to decrease diesel fuel consumption in a naturally aspirated generator based on the literature reviewed. There is no point testing the claims of externally powered HHO for

reducing fuel consumption, as the energy required to make it could be more effectively used directly, and HHO needs to be produced on-board and on-demand to reflect the current application of this technology. This necessitates an experiment using a real water electrolyser with real losses, and seeing if the additive effect can outweigh the considerable inefficiencies of on-board hydrogen production. NO_x emissions were increased in all the papers review, but the factors that may lead to a reduction in this experiment are the water content in the HHO and the added water injection.

Chapter 3 Safety

3.1 Construction

This research project had a large experimental portion requiring fabrication of a few different components. The components included manufacture of intake and exhaust manifolds for the engine, plumbing the diesel supply and metering system, rebuilding of electrolyser, and calibrating the electrolyser. The activities requiring risk assessment included cutting, drilling, grinding, welding and removal of old sodium hydroxide electrolyte (drain cleaner). A risk assessment was performed on each task so as to reduce the risks to as low as reasonable practicable. In each case two layers of controls were used to reduce risk and consequence of harm - personal protective equipment (PPE) and competence. PPE was used as the means to reduce risk of injury to acceptable levels. PPE for this task included wearing leather gloves, long sleeve shirt, welding mask for welding, room ventilation, face shield for cutting, grinding and drilling.

An example risk assessment for grinding and cutting with an angle grinder is shown in Table 3. The controls included face shield with earmuffs, well ventilated room, and leather gloves.

Table 3: Risk assessment for grinding and cutting steel with an angle grinder

Damage	Safe guards	Consequence	Probability	Risk rating
Sparks in eyes	Face shield	Requires 1 st aid	Rare	Low risk
Burns on skin	Long sleeve shirt Gloves Grinding guard	Requires 1 st aid	Rare	Low risk
Hearing damage	Ear muffs <2hr exposure	No injuries	Rare	Low risk

Table 4: Probability versus consequence table

Probability	Consequence				
	Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
A (Almost certain)	M	H	E	E	E
B (Likely)	M	H	H	E	E
C (Possible)	L	M	H	H	H
D (Unlikely)	L	L	M	M	M
E (Rare)	L	L	L	L	L

Working with the water electrolyzers involved potential for exposure to sodium hydroxide salt and solution, a base with a pH of 14. PPE including gloves and clear safety glasses were the primary safety measures used to reduce risk to a reasonable level. The tasks that required risk management included rebuilding the dry cell electrolyser with extra plates for higher voltage electrolysis, and filling the electrolyzers with fresh electrolyte solution – 10% w/w aqueous solution of NaOH.

Building the metered diesel supply system for the 28kW diesel generator set involved disassembly of the original supply system for inclusion of solenoid control valves for automated fuel flow rate measurements. The fuel lines contained diesel and posed a risk of diesel flicking into eyes. Safety glasses were worn to reduce this risk to acceptable levels.

3.2 Oxyhydrogen as an additive

Hydrogen is highly explosive at standard temperatures and pressures when mixed with air. There are eight layers of safety redundancy in the hydrogen system making it almost impossible even to cause any injuries.

- 1. Small volume of HHO storage.** The hydrogen and oxygen are produced on demand, so the only storage is in the supply lines and the gas void in the electrolyte tank and molecular sieve. The maximum storage/worst case scenario is around 1L stored in the bubbler flash back arrestor. The energy in 1L of HHO could be calculated as the HHV of the stored volume of hydrogen.

Mass of hydrogen in 1L at STP;

$$\begin{aligned} m_{H_2} &= \frac{p \cdot V \cdot MW}{R \cdot T} & (3.1) \\ &= \frac{101325 \times 667 \times 10^{-6} \times 2.016}{8.3145 \times 298.15} = 55.0 \text{ mg} \end{aligned}$$

Where m_{H_2} is the mass of hydrogen

p is the pressure of air [Pa]

V is volume of gas [m^3]

MW is the molecular weight of hydrogen [$g \text{ mol}^{-1}$]

R is the ideal gas constant [$J \text{ K}^{-1} \text{ mol}^{-1}$]

T is the temperature [K]

Energy in 1 litre of HHO in terms of the product of the higher heating value of hydrogen (HHV_{H_2}) and equation (3.1);

$$\begin{aligned} E_{H_2} &= m_{H_2} \cdot HHV_{H_2} & (3.2) \\ &= 55.0 \times 10^{-6} \times 141.86 \times 10^3 = 7.8 \text{ kJ} \end{aligned}$$

Where HHV_{H_2} is the higher heating value of hydrogen [J/g]

This is the equivalent to the energy contained in 0.17g of diesel [11].

2. HHO injection below flammability limit. The maximum rate of HHO injection is 6L/min. The test engine is a 3.9L four stroke engine operating at 1500r/min. Volume of air drawn in by the engine V_e per minute is determined by the engine displacement V_d , and engine speed n assuming there are no pumping losses:

$$V_e = \frac{V_d \cdot n}{2} = \frac{3.9 \times 1500}{2} = 2925 \text{ L/ min of air} \quad (3.3)$$

Where V_e is the volume of gas pumped into the engine [L]

V_d is the displacement of the engine [L]

n is the engine speed [r/min]

So the highest air fuel ratio for hydrogen as a percentage considering HHO contains 66.7% hydrogen is:

$$\begin{aligned} \text{fuel air ratio (volume)} &= \frac{V_{HHO}}{V_e} \cdot \frac{2}{3} \cdot 100\% \quad (3.4) \\ &= \frac{6}{2925} \cdot \frac{2}{3} \cdot 100\% = 0.137\% \end{aligned}$$

Where V_{HHO} is the maximum rate of HHO addition [L/min]

This means the highest rate that hydrogen is injected at 29 times below the flammability limit, if the hydrogen is fully mixed with the incoming air.

3. No ignition source inside system. There are no spark energy sources inside the HHO system. The control of HHO production being open loop, so there are no sensors in the HHO supply or production zones.

- 4. High auto ignition temperature of 585°C [11].** The hottest part of the exhaust pipe was measured at 440°C under full load, so this is ~140°C below the flammability limit. There is no mechanism to allow HHO to be vented to the exhaust manifold in any case of failure.

- 5. Leak tested.** The system was tested for hydrogen flow at the electrolyte tank and then at the bubbler where the gas leaves the system. The seals in the flash back arrestor were leak proofed with Vaseline for easy of servicing.

- 6. Hydrogen is highly dissipative.** Hydrogen is 14 times lighter than air rising at 20m/s [11].

- 7. Room ventilation.** USQ's engine laboratory is fully ventilated, even if it was sealed the hydrogen would dissipate out of the room quicker than it could be produced.

- 8. Emergency stop isolation.** The emergency stop button (E-stop) breaks power to the diesel supply valve, and makes a separated isolated contact to the PLC control system. On activation the DC electrical supply to the water electrolyser is isolated, preventing any more production of HHO. The main supply relay is supplied from generators 24V DC PLC power supply, which is only active when the engine is running.

3.3 Operation

A hazard operability assessment was conducted before the experimental equipment was installed on the diesel generator set as per Appendix B: Experiment HAZOP. Two academic staff (one having RPEQ registration) and an electrical technician were present to review all plant and procedure to be used in the experiment that differed from standard procedure. All risks identified were reduced to acceptable levels primarily through procedural safeguards and having hearing and eye protection. Safe operation of the experiment mainly involved operators understanding the correct start, run, stop and emergency shutdown procedures for the equipment.

Chapter 4 Methodology

4.1 Question

Can on-board HHO addition and water injection in any ratio provide significant fuel savings and reduce exhaust emissions over baseline conditions for a natural aspirated diesel engine? The independent variables include on-board HHO addition at varying rates, and water injection at 0% and 10% of the baseline diesel consumption. The dependant variables include brake specific fuel consumption and NO_x emissions. The test bed is a naturally aspirated 39kW diesel engine mechanically coupled to a 28kW three phase 415V AC generator. This generator loads the engine to 30% and 55% of its rated capacity via a resistive load bank.

4.2 Hypothesis

According to the literature reviewed, HHO takes more energy to create through electrolysis then can be recovered from using HHO addition as a fuel additive. The combined losses of the diesel engine, generator, switch mode power supply and water electrolyzers are significant. The additive effect of HHO for improving combustion would have to be greater than the combination of these losses to increase fuel economy. However the benefits of combining water injection and on-board HHO addition may allow a reduction in NO_x emissions while still maintaining the fuel economy of the diesel generator.

4.3 Test

An experiment was performed to prove the effects of on-board HHO and water addition to a diesel generators performance. The test was automated with an industrial PLC system for the sake of repeatability of the test and experimental rigour in the results. The final test involved injecting 0-6L/min of HHO produced on-board, with and without 10% water substitution for diesel. The key results of the test included the trend in relationship between the on-board HHO addition, water injection and generator load with the diesel consumption and NO_x emissions.

Chapter 5 Experimental System

5.1 Experimental Design

The experiment is designed to automatically cycle four rates of HHO injection, two rates of water injection at two engine loads. Primary goals of the experimental design include;

- Repeatability of tests
- Accurate control over the input/system variables
- Adjustment for environmental conditions such as ambient air temperature and relative humidity
- Steady state engine operating conditions – constant 1500 r/min engine speed and stable exhaust gas temperatures.

The generator used in the tests was a Cummins 4B3.9 series naturally aspirated diesel generator set. The details of the engine and generator are listed in Table 5.

Table 5: Generator set specifications.

Make and Model	Cummins 4B3.9
Combustion System Type	Cast iron 4 stroke, 4 cylinder, inline, direct injection
Bore × Stroke	102 × 120 mm
Piston Displacement	3.9 litre
Compression Ratio	16.5:1
Rated Power	39 kW at 1500 r/min
Generator rated power	28 kW at 1500 r/min

5.1.1 Automated Tests

The test was controlled and automated with a Siemens S7-200 series PLC system. Industrial automation allowed good adaptability of the program structure, ease of

program design, real time monitoring of the engine states, and because of its 11 bit digital to analog converter (DAC) and analog to digital converter (ADC) resolution.

Initial Test Procedure

Initially the test cycle was designed to be fully automated, where the PLC stepped through the engine through three loads, having water injection rates incremented up to 25% of the diesel consumption, as well as stepping through sixty rates of HHO injection from 0-6L/min. This gave a total of 1500 system states. All sensors were programmed to be read every 100ms with the average value logged every 500ms. The data was processed immediately after each automated test into three dimensional surface plots of fuel consumption and exhaust gas temperature versus HHO injection and water injection. This method required heavy filtering of the data in the PLC with a digital filter and in the MATLAB script due to the noise in the fuel metering system. The noise was caused by the short time base magnifying the $\pm 1/7200$ ADC noise in the ultrasonic level sensor. The error in a single sequential pair of fuel consumption recordings was in the order of $\pm 33\%$ of the single load diesel consumption rate, for example $\pm 1200\text{g/h}$ for a 3600g/h diesel consumption rate. A digital filtering with a moving average of 12 samples reduced the error down to less than $\pm 36\text{g/h}$ over 3600g/h or 1% , but the time shift in the diesel consumption data and the low confidence level in the data resulted in a modified sampling algorithm over a much larger time base. Another issue was with the engine not being given enough time to reach its steady state operating temperature when the loads were increased automatically in the test cycle.

Final Test Procedure

The final test cycle involved running the engine with fixed input variables for the time the engine took to drain 100g of diesel – about 70 seconds at the 55% engine loading. This represents a 700x greater time base for acquiring diesel consumption data for a given combination of input variables compared to the previous test cycle used. The test procedure in this final experimental structure involved the operator setting the load and water injection rate then allowing the PLC to step through four discrete increases in HHO injection from 0L/min to 6L/min. There were a total of

four test cycles, running HHO injection with and without 10% water injection at 30% and 55% engine load. The PLC was programmed to only allow a new test cycle to commence after the exhaust gas temperature stabilized to a temperature rise of under 3°C/min. The exhaust temperature would rise in the order of 100°C over 10 minutes when the load on the generator was increased from 30% to 55% of the engine load.

The test cycle used to collect the data only had 16 system states but with much lower noise and error margin - under 1% for the diesel metering. When the initial automated test scheme was run, the engine was logged in 1080 states. It was apparent even at that stage that there were no significant reductions in fuel consumption could be obtained for any rate of HHO or water injection. There was no need to test a high number of system states, and there was no optimization required.

Optimized Testing

Optimized testing would have taken place if on-board HHO or HHO combined with water injection reduced diesel consumption. It was obvious after the full tests that there were no optimal rates or ratios of water injection. On board HHO injection led to no gains in fuel economy in any rates tested – with or without water injection. If a reduction in diesel consumption was discovered, the next step would have been to interpolate the optimal HHO to water injection ratio for a given engine load based on recorded data, and then confirm those rates with a final phase of testing.

5.2 System Design

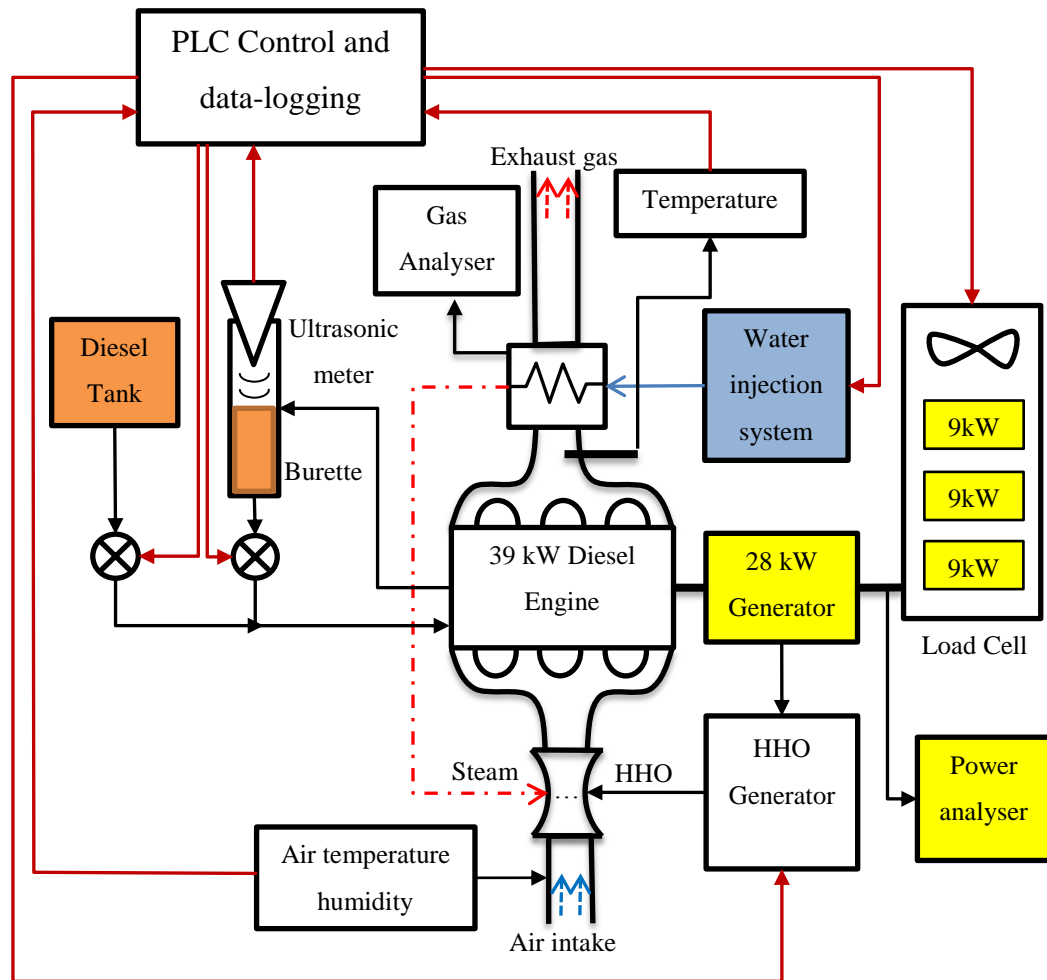


Figure 4: Test Bed Schematic

5.2.1 Introduction

The engine test included six main subsystems;

1. Water electrolyser subsystem
2. Water injection subsystem
3. Generator resistive load bank
4. NOx exhaust gas analysis subsystem
5. Diesel supply subsystem
6. Automated control and data logging subsystem

The selection process for each subsystem was based on balancing accuracy and reliability of control, availability of parts, simplicity of design, time constraints and replication of equivalent HHO products or concepts in the public domain.

5.2.2 HHO Subsystem

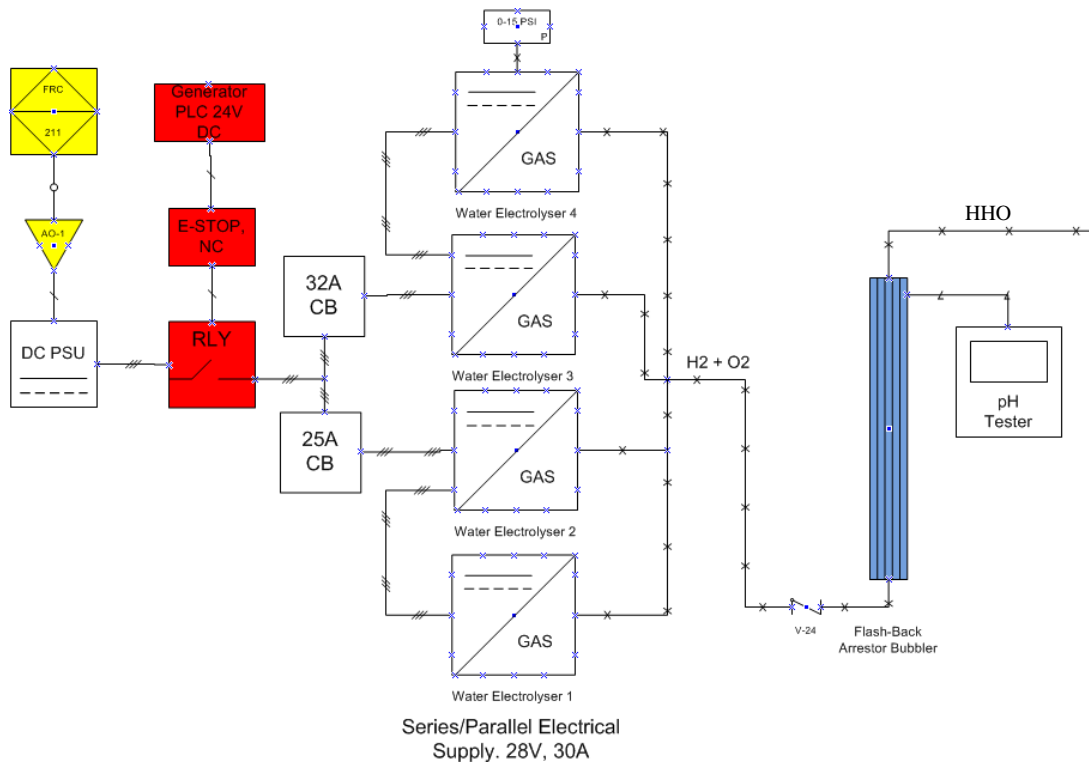


Figure 5: P&ID for the Water electrolyser

Principle of Operation

The HHO subsystem consists of an array of water electrolysers, programmable low voltage (up to 33V) DC power supply, a bubbler flash back arrestor and an electrical safety interlock. The plates in the electrolyser are set up the same as in a car battery. Electrically the electrolyser is the same as over charging a battery – hydrogen and oxygen are produced. There are effectively 13 stainless steel plates or tubes with 12 spaces containing electrolyte. The two end plates of the water electrolysers were supplied 12.5-14V DC, depending on the required current on HHO addition rate, resulting in a 2.08V to 2.33V drop across each successive plate in the electrolyser.

When the voltage is supplied current flows, work is done in the form of splitting water into hydrogen and oxygen and waste heat. HHO production is directly proportional to current flow, so the greater the current supplied to the electrolyzers, the greater the production of HHO in linear proportion. This process is explained in more detail in Chapter 6.

Electrolyser Control

The water electrolyser had its current supplied from a Sorenson XG 1700 series 33V, 50A DC programmable power supply. The power supply's current was controlled by a 0-10V DC signal from a PLC DAC output. Four 6-cell electrolyzers were used – two where rated at 18A and two where rated at 30A. To reduce the current at full HHO production, the cells were run in series/parallel. The 18A electrolyser were connected in series with each other and the 30A electrolyzers were connected in series with each other. These two sets of electrolyzers connected in parallel (Figure 5) so as two both have 25-28V. The cables and electrolyzers were protected by the DC power supply's current limiting function, and by two DC circuit breakers rated at 25A and 32A. The system could be isolated by manually activating the emergency stop button. This would break the current to the solenoid relay, and send a control signal to the PLC notifying the program that there was a fault.

Calibration

Calibration and measurement of HHO volumetric injection rate seems to be a missing factor in the HHO literature reviewed [1, 2]. Flow rate measured with a flow meter designed for air was found to show only 75% of the actual flow rate for HHO. This discrepancy was discovered by taking measurements with the HHO equipment flowing gas through a RMB series Dwyer flow meter in series with an inverted bucket in water. The time taken to displace 3.11L of water with HHO from an upside down container filled with water, was the procedure used to calibrate the PLC's open loop control of the HHO production. The measurement error margin was ± 0.5 seconds over a varying time base of 32-186s (Figure 6).

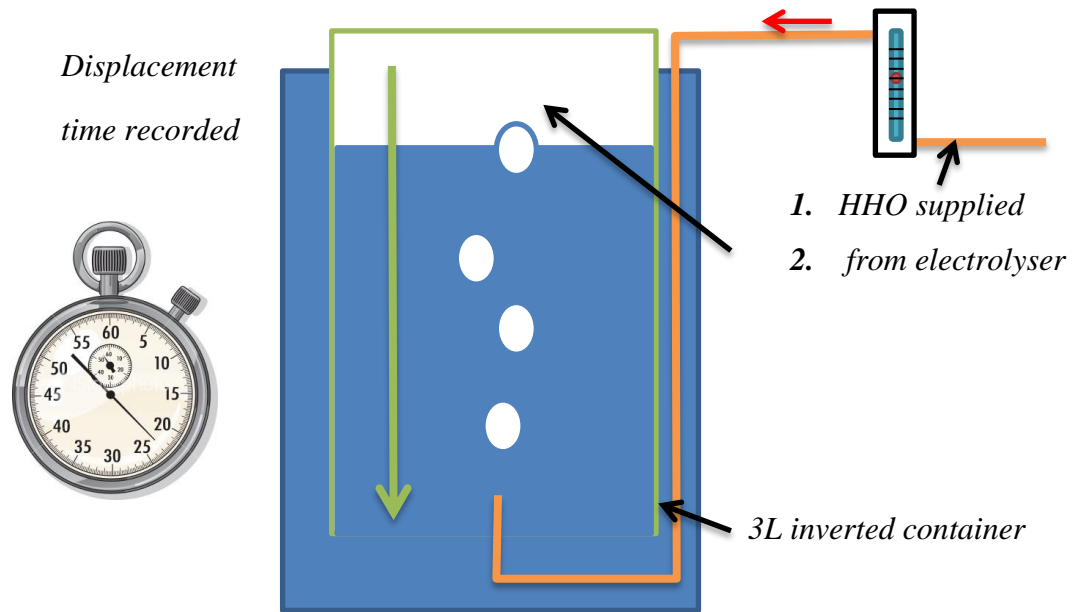


Figure 6: Representation of gas volume calibration setup.

The PLC span or scaling constant was determined calculating a span constant for the DAC – PLC – DC power supply interface, measuring actual gas production, and then adjusting the span constant. The initial HHO span constant for the PLC ladder logic was within 4% to 10% of the required span value, after correction the error was within -5% to +1% error. The measurement error would be due to user timing errors - $\pm 0.5s$ over the shortest time base of 29s (6 L/min), giving a $\pm 1.7\%$ time-volume error.

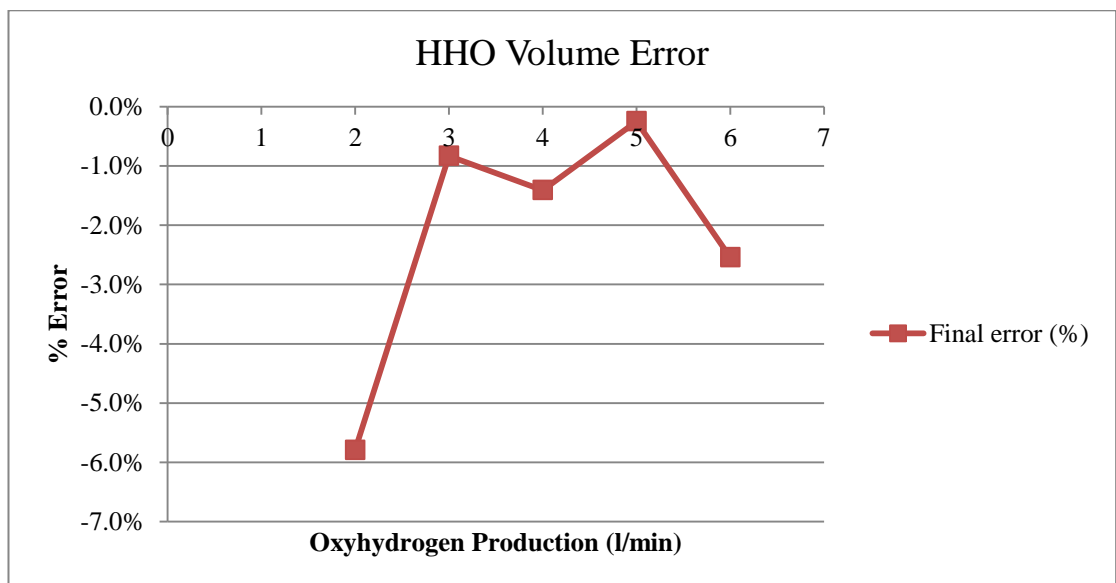


Figure 7: HHO volumetric flow rate error.

Electrolyser Performance

The water electrolyzers produced HHO at 3.1Wh/L at the DC output of the power supply, and an average of 4.06Wh/L at the 240V AC supply. The input power for the three production rates was higher due to the losses in the switching power supply in converting the higher voltage AC power to the lower voltage DC power. 100% efficient electrolysis in terms of power will be taken as 2.16Wh/L (Chapter 6).

Table 6: Energy requirements for on-board electrolysis

H₂-O₂ (l/min)	RMS Voltage	RMS Current	Electrical Power	Energy of production	Thermal efficiency
2	242.0V	2.1A	513W	4.27Wh/L	50.5%
4	239.9V	3.9A	943W	3.93Wh/L	55.0%
6	237.7V	6.0A	1426W	3.96Wh/L	54.5%

Table 7: HHO subsystem advantages and disadvantages

HHO Subsystem Appraisal	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Water electrolyser – 4Wh/L HHO input energy • Accurate control over HHO volumetric flow rate - > ±6% error • Unfiltered HHO injection – replicates system available on the market, and does not disturb potential Rydberg clusters 	<ul style="list-style-type: none"> • No desiccant used in final stage, leading to additional unknown water injection rates • Only DC current supplied, effects and claims of pulsed electrolysis untested • Unknown ratio of para-hydrogen and ortho-hydrogen in injection

5.2.3 Water Mist Injection Subsystem

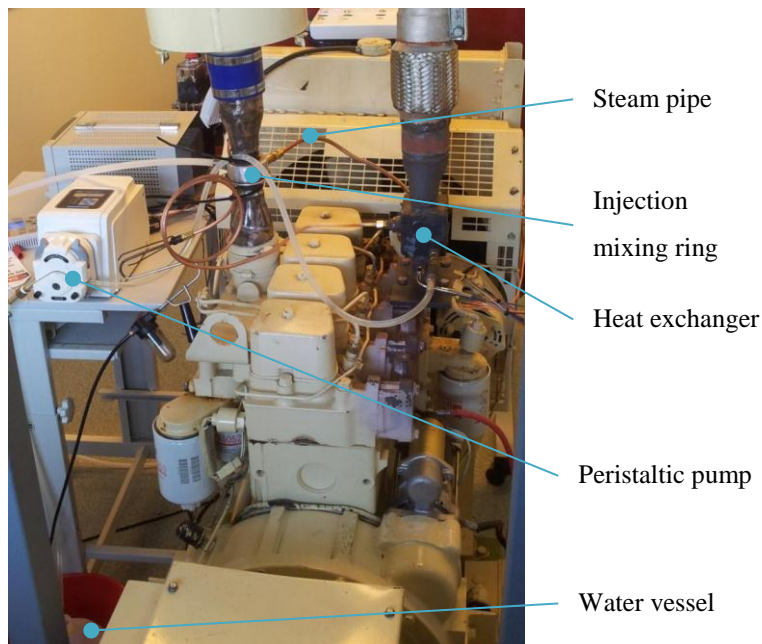


Figure 8: Water injection system layout

Water injection has benefits of reducing exhaust gas temperatures, converting heat energy into work by expanding the water into steam [12] and reducing NO_x emissions because of the lower combustion temperatures [10]. Water injection may provide a means for steam cracking the diesel into lighter hydrocarbons with lower lean flammability limits – this would aid in leaner combustion. For this experiment water was injected at 0% and 10% w/w water/base line diesel consumption, at the 4 HHO injection rates. The water was injected at the gas carburettor. The system included a small water tank, a voltage controlled peristaltic pump, a water to steam heat exchanger built into the exhaust manifold and the gas mixing ring mounted over the air intake. The water was pumped in at 10% of the diesel consumption, converted to steam and then injected into the air intake. A steam injection system was used because it allow atomization of the water – when the small volume of steam is injected into the intake air stream, it condenses into tiny droplets. This system also allowed some of the exhaust heat energy to be recaptured.



Figure 9: Exhaust water-to-steam heat exchanger on the left, and internal 6mm copper pipe coil inside the unit on the right.

The peristaltic pump used in the experiment to deliver the water was a Langer Instruments model BT100-2J pump with a resolution of 0.18mL/min. The pumps head has two rollers, so the water flow had some pulsed component (Figure 10), but much of the flow variation would be attenuated as the water was heated into a gas phase then travelled through 0.5m of copper pipe before reaching the intake air manifold.

Table 8: Water injection error margin.

Load	Injection rate	Pump r/min	Maximum error
9.91kW	340g/h	3.1r/min - 334.8g/h	-1.53%
19.1kW	522g/h	4.8r/min - 518.4g/h	-0.69%

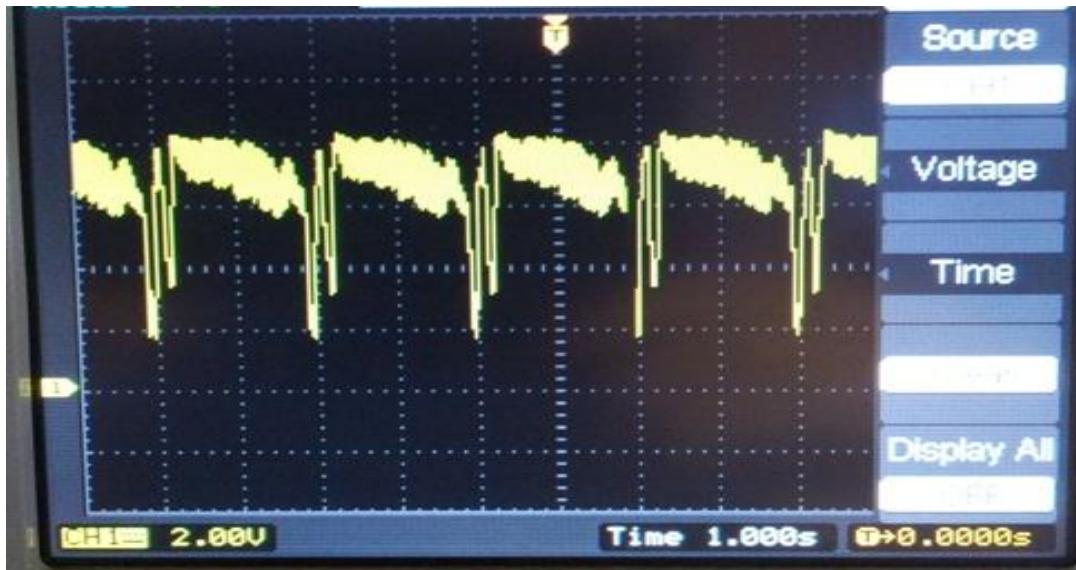


Figure 10: Voltage measurement from a Sensirion SLQ-HC60 flow meter connected to the peristaltic pump.

Table 9: Water system design appraisal.

Water Injection Subsystem Appraisal	
Advantages	Disadvantages
<ul style="list-style-type: none"> • Accurate control over water injection • Good mixing of water and intake air • Relatively long test cycle removing effects of pulses in water injection • Reuse of waste heat energy from exhaust 	<ul style="list-style-type: none"> • Unknown water/steam injection temperature • Possible small reduction of air density due to displacement from water mist and increased air temperature • Water vapour mixing with engine oil • Risk rusting of piston rings if engine not purged of water after test

5.2.4 Diesel Metering System

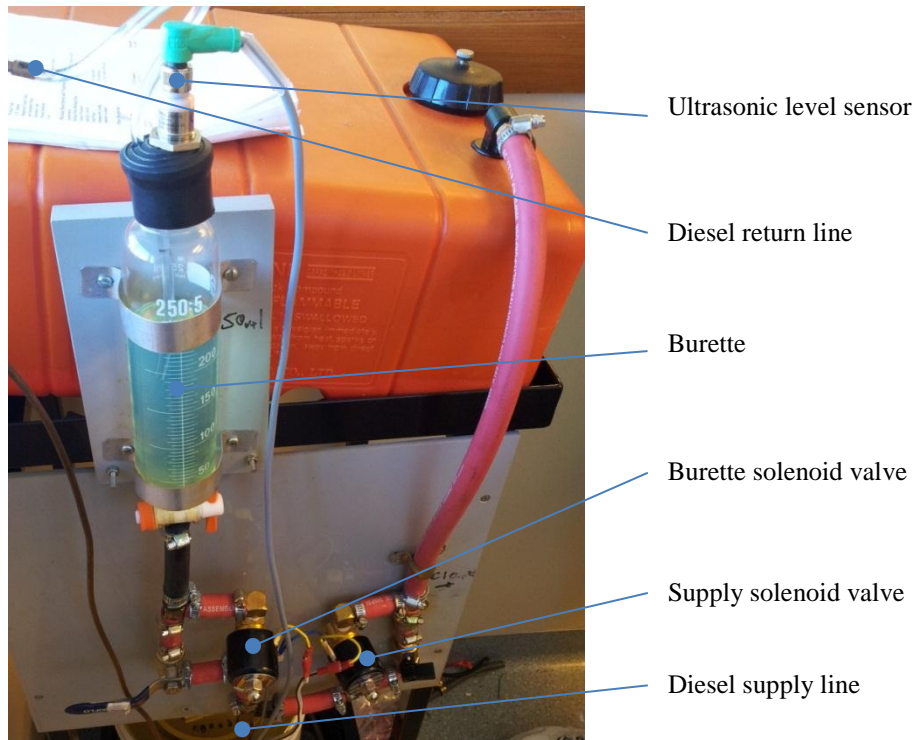


Figure 11: Layout of diesel supply and metering system.

The diesel metering system incorporated an ultrasonic level sensor measuring the change of diesel volume in a burette over time. This system was designed and built because it had potential to be accurate, required minimum modification to the original fuel metering system, and it allowed automation of the experiment. The PLC system monitored the fuel level for both diesel consumption records and high/low limit levels for draining and refilling the burette. The level of the burette was a major controlling factor of the PLC ladder logic. On the rising edge of the burette filling up the bypass or supply valve would close and the engine would draw its fuel from the burette, and the automatic test loop would either start if other conditions were met or would increase the HHO rate to the next level. During the time the burette was being drained, the PLC continually updated the flow rate, until the burette reached the low level set point and the PLC would log fuel consumption versus time, as well as logging the other sensors. The sensor was a *Pepperl+Fuchs UB300-18GM40-I-VI* ultrasonic sensor with a 4-20mA output, and a span of 7200 ADC counts at the PLC's 11bit ADC over the 100g measurement range.

Calibration the diesel system included; measuring the density of the diesel, checking the linearity of the ultrasonic metering system, and calculating the analog-to-mass conversion constant for the output from the ultrasonic sensor. The mass of the diesel was calculated by measuring 100g of water in a measuring cylinder with jewellers scales (resolution of 10mg) marking the level, then measuring the mass of the diesel filled up to the same level. The mass of the diesel was measured at 835kg/m³. The calibration of the peristaltic pump was performed by pumping diesel at 1r/min, the mass flow rate at this speed was the same relative mass flow rate/rpm as other r/min. The mass flow rate was calculated at 1.5g per revolution per r/min. Next the peristaltic pump was used to move the burette level from low too high in 15g increments and check the difference in the analog readings. It was found there was up to 0.92% non-linearity error over the measurement range, but this is most likely due to the human error in pressing the stop watch stop button at the start and end of the 60 second measurement period.

Table 10: Diesel system linearity test results.

Added diesel mass (g)	Start ADC	End ADC	delta ADC	$\frac{dADC}{dMass(g)}$
15	4032	5272	1240	82.67
15	5272	6510	1238	82.53
15	6510	7753	1243	82.87
15	7753	9008	1255	83.67
15	9008	10255	1247	83.13
15	10255	11487	1232	82.13
15	11487	12737	1250	83.33

The resolution of the ultrasonic was adequate for the task, with 100g of diesel equal to a 7200 ADC span. The sensor noise was monitored while the engine was shutdown. It was observed the signal only fluctuated ± 1 ADC units over the measurement range – accounting for 0.013% error. Inaccuracy in fuel measurement was more effected by the burette draining past the low point. After further observation it was found the overshoot could be offset in the. Below are the

calculation performed by the PLC to measure mass flow rate, accounting for refill overshoot.

$$t_{hr} = \frac{t_{ms}}{\frac{ms}{s} \times \frac{s}{hr}} = \frac{t_{ms}}{3.6 \times 10^6} \text{ hrs} \quad (5.1)$$

$$m_d = \frac{l_c - l_s - l_e}{k_d} = \frac{l_c - 3854}{82.904} \text{ g} \quad (5.2)$$

$$\dot{m}_d = \frac{m_d}{t_{hr}} \text{ g/hr} \quad (5.3)$$

Where t_{ms} is PLC counter time [ms]

t_{hr} is diesel drain time [h]

l_s is the measured ADC value when the burette is full

l_c is the real-time measured ADC value of the ultrasonic sensor

l_e is the overshoot ADC magnitude when the burette is refilled

m_d is the mass of diesel consumed [g]

k_d is the constant relating change in ADC value to change in mass

\dot{m}_d is the mass flow rate of diesel [g/h]

5.2.5 PLC Control and Data Logging System

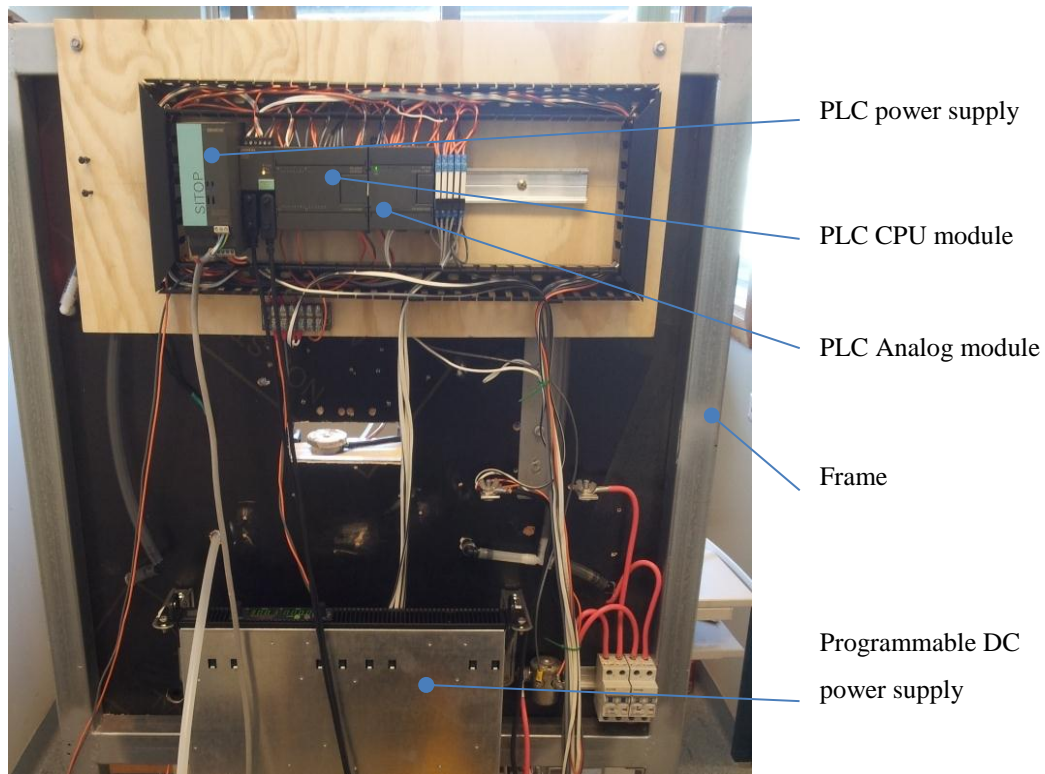


Figure 12: PLC control and data logging system and electrolyser DC power supply.

The experiment was semi-automated with a Siemens S7-200 series PLC system. This included the CPU 224XP and the EM 235 Analog expansion module, both with 11 bit ADC and DAC resolution, a 24V DC power supply and a basic SCADA interface. The reasons for using a PLC system included easy of programming, repeatability, accuracy in control and measurement, flexibility and support. The PLC platform came in handy as the situation changed and the experiment required two major modifications.

Initial PLC Program Design

Initially the HHO tests were to be performed on a smaller 2.4kW Yanmar diesel engine, with the PLC system acting as a closed loop dynamometer controller for five loading schedules as well controlling all other aspects of the experiment. This initial system was designed to have four control variables – HHO at six rates, water

injection at six rates, water electrolyser efficiency at three rates and engine dynamometer load at five levels. This is a total of 540 system states. The goal was to find the greatest fuel reduction from measured data and then optimize BSFC with three dimensional interpolation.

Second PLC Program Design

When the 2.4kW engine became unavailable for any future testing, a new simpler experiment was devised with a larger 39kW Cummins engine that was set up as a generator with three input variables – HHO addition at 60 increments, water injection at six increments, and three engine loads for a total of 1080 system states. Most of the calibrations for the first system could not be used for the final test bed as the diesel, HHO, engine loading and data logging subsystem's had to be rebuilt and new calibrations carried out. Having a PLC system reduced programming overhead in designing the new experiment, as the program was modularized so certain ladder logic modules could be kept from the initial experiment and modified for the new experiment.

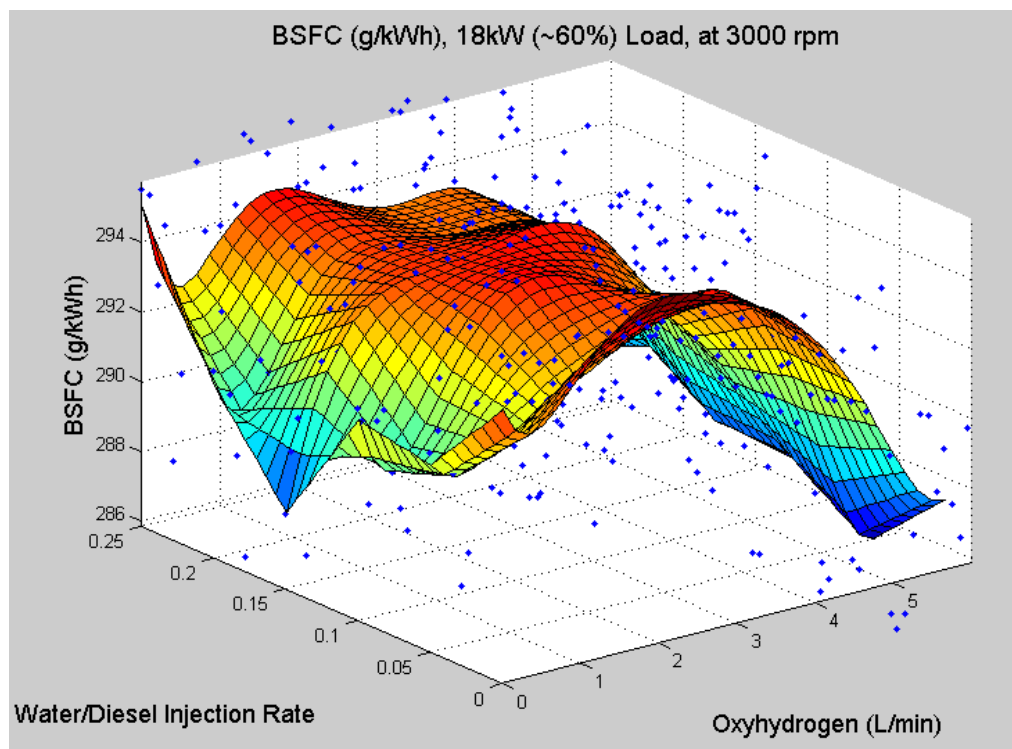


Figure 13: Example of the noise in the diesel readings

Problems with second PLC program design

The MATLAB script for processing the logged data was developed simultaneously with the ladder logic, so the results could be interpreted immediately at the location of the experiment (Appendix H). After running the second experiment design at the 1080 system states, processing of the data revealed several improvements to the test were required. High noise margin, time shift in data from filtering noise, insufficient time to reach steady state in exhaust temperature, generator instability under full load (~28kW generator electrical load) and no apparent fuel savings all necessitated a change in test procedure. The BSFC data had a high margin of noise that required not only filtering in the data sampling phase, but further filtering in the MATLAB script. This introduced a large time shift into the results so the independent variables could not be aligned accurately with the dependant variables of BSFC and engine temperature.

Final PLC Program Structure

The final experiment involved the operator setting engine load and water injection rate manually, then allowing the PLC to step through the HHO injection rates. For each HHO injection rate the engine ran for the time it took to drain 100g of diesel, then the injection volume would increase and another 100g of diesel would be consumed and so forth. After all four volume flow rates of HHO were trialled and engine states logged, the test would conclude and a new load and/or water injection rate would be selected for testing. The new test cycle could only commence after the exhaust gas temperature stabilized to a rate of temperature rise below 3°C/min.

The final method used to test the effects of HHO on diesel consumption and exhaust emission removed the key problems of the initial tests. The initial tests were useful for revealing large changes in fuel consumption and acted as a guide for the final test. The final test method tested the effects of HHO and water injection over the full range but at larger increments and at a much higher measurement resolution. The engine was much more stable in operating temperature and a second stage of filtering was not required. If the diesel measurements were more accurate on a

shorter time base, then the initial PLC program structure would be ideal, as a larger range of HHO volumes and water injection rates could be trialled.

5.2.6 HMI / Text Display

The HMI interface was basic four line LCD with 15 keys for viewing and controlling system variables and states. It was used as a means to start an automated test, manually control inputs, monitor system states, monitor diesel levels, and calibrate all subsystem spanning constants and offsets. The control menu included access to engine loading, HHO production and water injection rate.

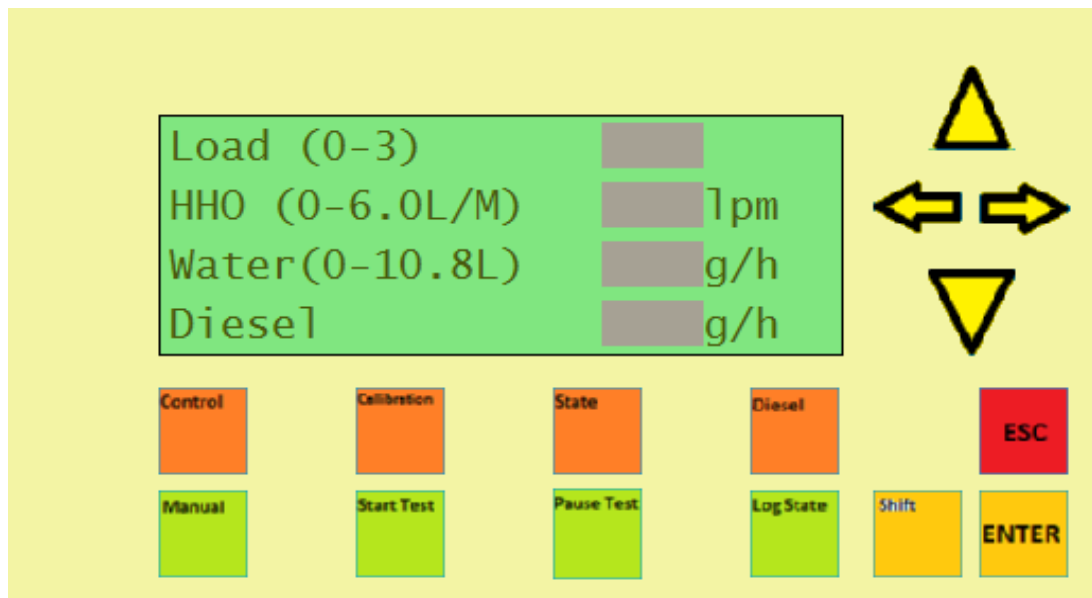


Figure 14: Text display of the control screen

The calibration menu included seven screens with access to modify seven parameters' span and offset constants. Calibration would usually start with a calculation of a span and offset, writing an output/reading an input, comparing the actual value, and then correcting the span or offset until the sensor or device could be accurately controlled or logged. The system state included a non-modifiable view of current operating conditions, with the inputs on one screen, and the measured outputs from the generator on a second and third screen. The diesel system had its own set of screen to monitor limits and current values coming from the ADC readings of the ultrasonic level sensor. This access to the real time ultrasonic ADC data allowed for

quick and efficient calibration or monitoring of linearity, refill limits, span constant, and noise for the ultrasonic level sensor on the diesel burette.



Figure 15: Text display of ultrasonic level sensor real time level and limits.

Data Logging

The Siemen's S7-200 series PLC system was used to log four dependant variables and three independent variables. The four dependant variables included exhaust gas temperature, intake air temperature, relative humidity, and ultrasonic diesel level in the burette. The three control or independent variables included the HHO flow rate, water injection rate and engine load setting (Table 11). The sensors were all filtered at the hardware analog stage, with the value logged being the average of 256 samples and at a sample rate of 2kHz.

Table 11: Sensor and control variable accuracy

Sensor	Interface	Sample interval	Response time	Error margin
EGT TC	4-20mA ADC	5ms	<1s	$\pm 2.15^{\circ}\text{C}$
Intake air temperature	4-20mA ADC	125ms	1s	$\pm 0.54^{\circ}\text{C}$
Relative humidity	4-20mA ADC	125ms	1s	$\pm 5.1\% \text{RH}$
Ultrasonic level	4-20mA ADC	5ms	30ms	$\pm 0.98\%$
HHO injection	2-10V DAC	5ms	N/A	+1% - -7%
Water injection	Manual	5ms	N/A	$\pm 8.3\%$
Generator load	Relay	5ms	N/A	$\pm 0.01\%$

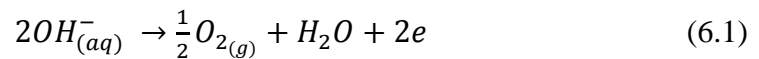
Data download from the PLC to the laptop was performed after each change in load under the final test scheme. Basic analysis of the results could be carried out as the engine was settling between changes in load level to catch any possible trends of interest in the BSFC. The initial data analysis pointed to no gains in fuel economy for the full capacity range of HHO injection (0-6L/min), therefore trialling three rates of HHO injection was enough to prove the effects.

Chapter 6 Conversion Efficiency

6.1 Chemistry

HHO is the stoichiometric mixture of hydrogen and oxygen generated from water electrolysis. Water electrolysis occurs when DC electron current flows from a negative electrode (cathode) to the positive conductor (anode) via an electrolytic solution. Aqueous hydrogen cations H^+ are attracted to the cathode where they accept electrons and form covalent bonds resulting in H_2 gas generation. The hydroxide anions balance the flow of current in the electrolyte solution and are attracted to positive (anode) conductor, where they release electrons to the anode to form water and covalently bonded oxygen gas or O_2 . In this way current is balanced at anode and cathode[13].

Chemical reaction at anode (positive conductor);



Chemical reaction at cathode (negative conductor);



The electrolyte allows current to flow with much lower overpotential and allows much higher conductivity than electrolysis in pure water. Typically strong bases are used as electrolytes – either sodium hydroxide (NaOH) or potassium hydroxide (KOH). The metal cation becomes a spectator ion, whose concentration affects surface potential (voltage) and electrical conductivity. In other words a more concentrated electrolyte solution will require a lower potential to flow the same current as a less concentrated electrolytic solution.

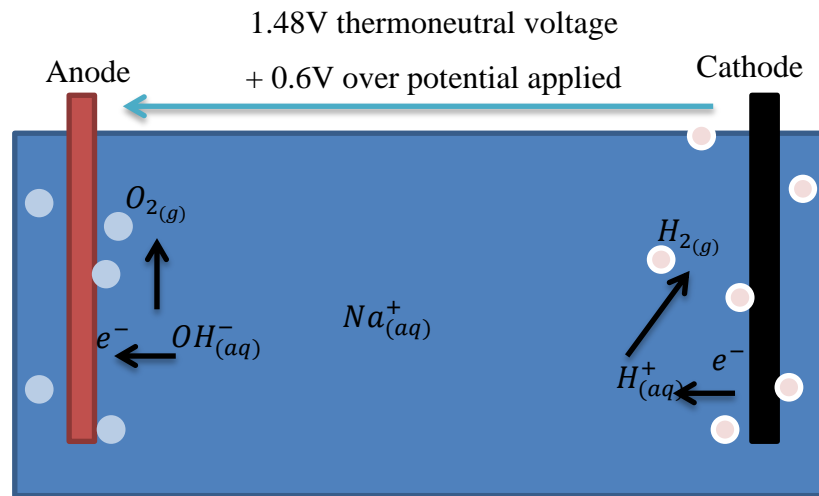


Figure 16: Single cell water electrolysis, showing formation of hydrogen gas at cathode and oxygen gas at anode.

The metal ions from a hydroxide salt in the electrolyte are not consumed during electrolysis as the metal cations are spectator ions. The interactions between the spectator metal cations and the conductor in the electrode is important, because this interaction determines over potential of electrolysis and the life expectancy of the plates. Typically stainless steel or nickel plates are used as the electrodes for water electrolysis because of their ability to resist corrosion.

6.2 Energy Efficiency

The thermodynamic and electrical efficiency of electrolysis decreases with increasing cell potential V_{cell} . The thermoneutral voltage potential E_{tn} across the anode to cathode is 1.48V, and the electrolyser efficiency $\eta_{thermal}$ is given by;

$$\eta_{thermal}(\%) = \frac{E_{tn}}{V_{cell}} \times 100 = \frac{1.48}{V_{cell}} \times 100\% \quad (6.3)$$

Where V_{tn} is the thermoneutral voltage of electrolysis [V]

V_{cell} is the externally applied cell voltage [V]

The current required to generate 1L/h of HHO from a single cell can be calculated using Faradays first law of electrolysis;

$$\text{Volume, } V = \left(\frac{1}{3} O_2 + \frac{2}{3} H_2 \right) \times 10^{-3} = 0.001 \text{ m}^3 \text{ of HHO}$$

$$\text{Faradays constant, } F = 96485.31 \frac{A \cdot s}{mol}$$

$$\text{Pressure, } p = 101325 \text{ Pa}$$

$$\text{Number of excess electrons, } z = \frac{1}{\frac{1}{2} + \frac{1}{4}} = \frac{4}{3} \text{ electrons}$$

$$\text{Ideal gas constant, } R = 8.3145 \frac{J}{g \cdot K}$$

$$\text{Temperature, } T = 298.15 \text{ K}$$

$$\text{Time, } s = 3600 \text{ s}$$

$$\text{Current, } I_F = \frac{V \cdot F \cdot p \cdot z}{R \cdot T \cdot t} \tag{6.4}$$

$$= \frac{0.001 \cdot 96485.31 \cdot 101325 \cdot \frac{4}{3}}{8.3145 \cdot 298.15 \cdot 3600}$$

$$= 1.4602 \text{ A L}^{-1} \text{ hr}^{-1}$$

A 100% current efficient cell will require 1.46A of current per hour to produce 1L of HHO. The product of the thermoneutral voltage and current required to produce 1L of HHO will give the energy required to produce 1L of HHO at 100% efficiency[14].

$$E_{100\%} = I_F \times E_{tn} = 1.4602 \times 1.48 \quad (6.5)$$

$$= 2.161 \text{ Wh/L or } 7.79 \text{ kJ/L}$$

Comparing this energy value with the energy in the equivalent volume of hydrogen (2/3 litre) at the lower heating value (LHV_{H_2}) of 120MJ/kg;

$$E_{H_2} = \frac{p \cdot V_{H_2} \cdot MW_{H_2} \cdot LHV_{H_2}}{R \cdot T} \quad (6.6)$$

$$= \frac{101325 \cdot \frac{2}{3} \times 10^{-3} \cdot 2.016 \cdot 120 \times 10^3}{8.3145 \cdot 298.15}$$

$$= 7.69 \text{ J STP}$$

This means it takes 2.163Wh/L at standard temperature and pressure (STP) to produce HHO at 100% efficiency. Knowing the power efficiency is more useful than voltage efficiency because system efficiencies can be calculated almost directly. The energy required to crack hydrogen from water is the same as the LHV energy of the equivalent volume of tank hydrogen.

6.3 Typical Energy Losses

A voltage overpotential of typically 0.6V above the 1.48V thermoneutral voltage is required for any significant current to flow at STP[13]. This is due to a low reaction rate, the activation energy barrier, electrical resistance of the electrolyte and electrodes, and bubble formation[13].

Cell potentials in on-board water electrolyzers are a compromise between voltage of the alternator charging system and the cell potential required to generate sufficient current flow. So in the case of a 13.8V charging system, six series cells are used to

divide the potential down to $V_{cell} = \frac{13.8(V)}{6 Cell} = 2.3V$ per electrolyser cell. In terms of voltage efficiency, these electrolysers are less than $\eta_{thermal} = \frac{1.48}{2.3} = 64\%$ efficient, if the cell is operating a 100% current efficiency. The net electrical conversion efficiency of the electrolysis system used ranged from $\eta_{HHO} = 50.6\%$ to 55% (Table 2), this includes losses from the switch mode DC supply, but not the generator.

The conversion efficiency of diesel into 3 phase electrical power by the diesel engine and generator was calculated from the corrected baseline fuel consumption measurements. At 30% and 55% engine load the BSFC was 352g/kWh and 272g/kWh respectively. If diesel has an energy content of $E_d = 45.6 kJ/g$ [15] then the efficiency of the generator set $\eta_{generator}$ would be;

$$\eta_{generator} = \frac{\text{Electrical energy output}}{bsfc \times \text{diesel energy}} = \frac{3.6 \times 10^6}{bsfc \times 45.6 \times 10^3} \quad (6.7)$$

$$\eta_{generator}(30\% \text{ load}) = \frac{3.6 \times 10^6}{351.7 \times 45.6 \times 10^3} = 22.4\%$$

$$\eta_{generator}(55\% \text{ load}) = \frac{3.6 \times 10^6}{272.3 \times 45.6 \times 10^3} = 29.0\%$$

The net efficiency of the generator and electrolyser systems to convert diesel into HHO can be calculated by taking the product of the generator and electrolyser system efficiencies.

Table 12: Net efficiency of HHO production for different engine loads and HHO flow rates.

HHO	η_{HHO}	$\eta_{net} = \eta_{HHO} \cdot \eta_{generator}$	
		30% engine load	55% engine load
2L/min	50.6%	11.4%	14.7%
4L/min	55.0%	12.5%	16.0%
6L/min	54.6%	12.6%	15.8%

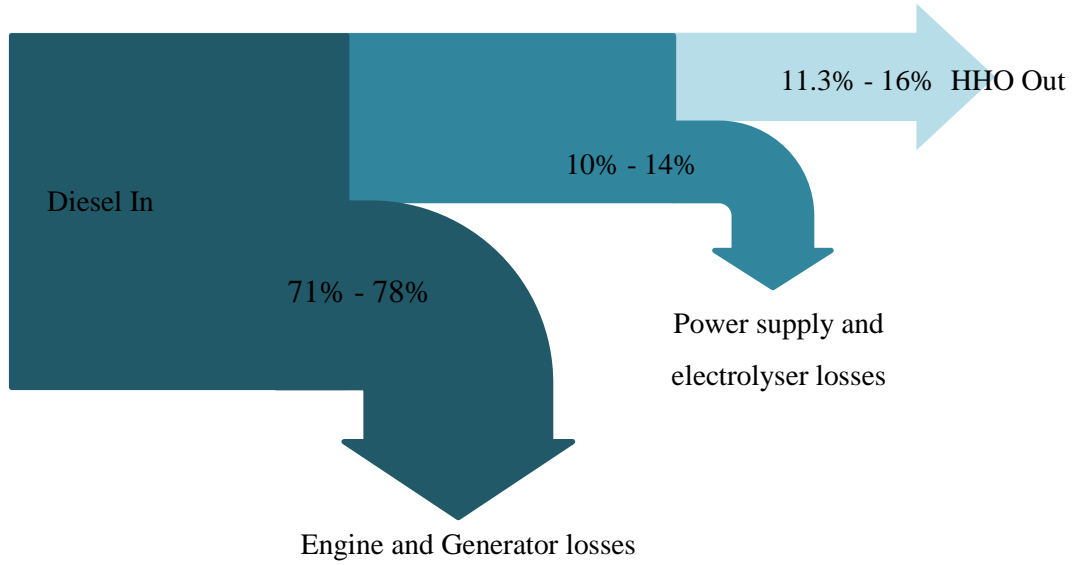


Figure 17: Diesel to on-board HHO conversion efficiency diagram, depending on engine load and HHO injection rate.

Measuring the magnitude of reduction of diesel consumption due to externally produced and supplied HHO will allow the break even on-board electrolyser efficiency to be calculated. This is achieved by calculating the diesel energy saved for a given injection rate of HHO.

$$E_{break\ even} = \frac{\Delta\dot{m}_D \cdot E_d}{3600 \cdot \dot{V}_{HHO}} = \frac{\Delta\dot{m}_D \cdot 45.6 \times 10^3}{3.6 \times 10^3 \cdot \dot{V}_{HHO}} (Wh/L) \quad (6.7)$$

From the break even energy per litre of HHO produced a required net electrolysis efficiency can be calculated for comparison of the current recorded system efficiency, to see if it is possible to reduce diesel consumption with on-board HHO injection, and to quantify the additive or fuel mode effect of HHO in a diesel generator. This analysis will be performed in section 7.4 Specific Fuel Consumption.

Chapter 7 Results

7.1 Data processing

Initially the data was processed in MATLAB, where the power was corrected to the environmental conditions and contour plots of BSFC as a function of HHO and water injection rates, over a grid of 1080 data points. After it was found that the fuel system required a larger time base in the diesel sampling to improve accuracy of the results, a test scheme with only four system states per run was implemented and the results interpreted using Microsoft Excel.

7.2 Power Correction

The engines load during the test consisted of a three phase 28kW generator connected to two levels of resistive loads; 9.91kW and 19.1kW. These loads were controlled from the PLC's digital outputs. The power supplied by the generator to the load was measured with a Fluke 43B power quality analyser, measuring the 'a' phase current and voltage. The ambient air and humidity conditions were not controlled in the testing of the engine, so the relative power output had to be corrected to account for the falling humidity with the rising temperature of the air as the test carried on.

The dry air pressure p_d was calculated by removing the partial pressure of water p_w which was a function of the air pressure p_a , temperature T_c and relative humidity ϕ . The ambient air pressure was assumed a constant 1018hPa – taken from the USQ weather station, and the relative humidity and temperature were logged during testing.

$$p_d = p_a - \frac{\phi \cdot e^{77.345 + 0.0057T_c - \frac{7235}{T_c}}}{T_c^{8.2}} \quad (7.1)$$

Where p_a is air pressure [Pa]

ϕ is relative humidity

T_c is the air temperature [K]

Power correction to account for changing atmospheric condition was achieved by SAE J1349 formula;

$$cf = 1.180 * \left(\left(\frac{99 \times 10^3}{p_d} \right) \cdot \sqrt{\frac{T_c}{298}} \right) - 0.18 \quad (7.2)$$

During testing at the 10kW electrical load, the correction reduced the generators indicated power in the range of 97% to 98.4%. The negative power offsets in Figure 18 and Figure 19 were due to the atmospheric water reducing the relative concentration of oxygen in the air. The rise in corrected power as the test commenced resulted from the reduction of air humidity due to the rising air temperature caused by the heat released from the operation of the generator. These power corrections were important for presenting fuel economy results as they provide a means to correct fuel consumption for the changing ambient conditions.

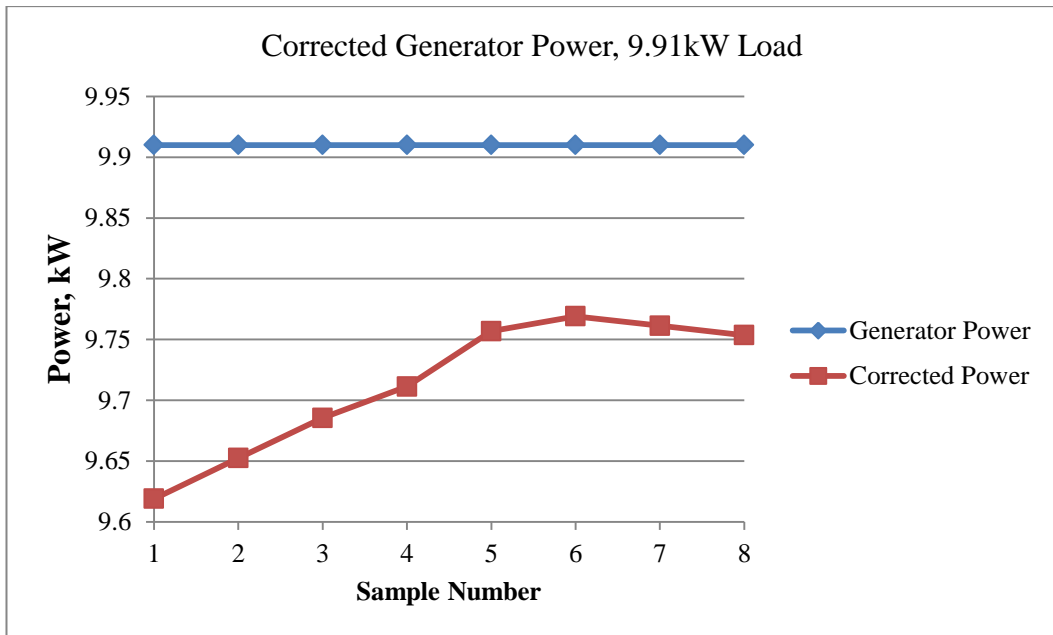


Figure 18: Power correction applied to the 9.91kW electrical load.

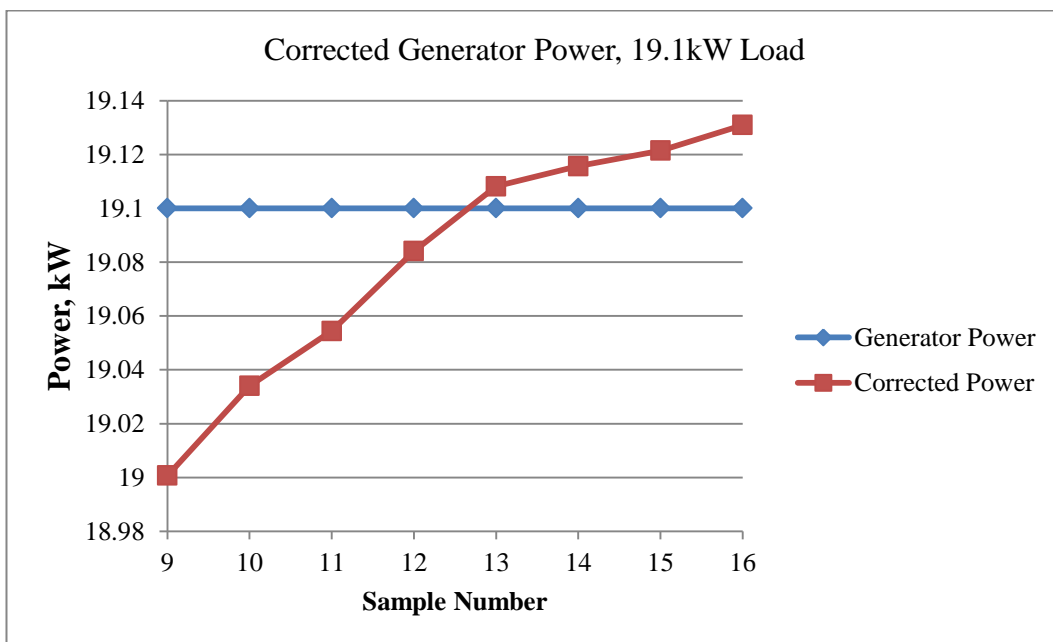


Figure 19: Power correction applied to the 19.1kW electrical load.

7.3 Engine Loading

The engine was loaded by supplying power from the generator at two rates, 9.91kW and 19.1kW. The generator was rated to 28kW and the engine for 39kW, both at 1500r/min. The loading of the engine was of main interest, so equation (7.3) converts the electrical load on the generator to a percentage engine loading:

$$\text{Engine load} = \frac{P}{\eta \cdot P_G} \times 100 \quad (7.3)$$

$$\text{Load 1} = \frac{P_1}{\eta_1 \cdot P_G} \times 100 = \frac{9.91}{0.85 \times 38.78} \times 100 = 30.1\%$$

$$\text{Load 2} = \frac{P_2}{\eta_2 \cdot P_G} \times 100 = \frac{19.1}{0.9 \times 38.78} \times 100 = 54.7\%$$

Where P is the three phase electrical load [kW]

η is the efficiency of the generator for the given load

P_G is the rated power of the diesel prime mover [kW]

The maximum engine loading was only around 54.7%, however engines are usually load to around 80% of their rating. The fuel consumption results discussed in the next section indicate HHO was less effective with the higher 54.7% engine loading compared to at 30%, so at 80% engine loading the potential for HHO to reduce fuel consumption may be even further diminished.

7.4 Specific Fuel Consumption

HHO on-demand did not reduce diesel consumption in any of the rates at either load trialled. As the rate of HHO production increased so did the energy required to run the electrolyser, resulting in a net loss. Increased fuel consumption almost linearly increased with an increase in HHO injection. Only with 10% water injection at 30% engine load and no HHO, was a 2.5% reduction in fuel consumption recorded (Figure 21).

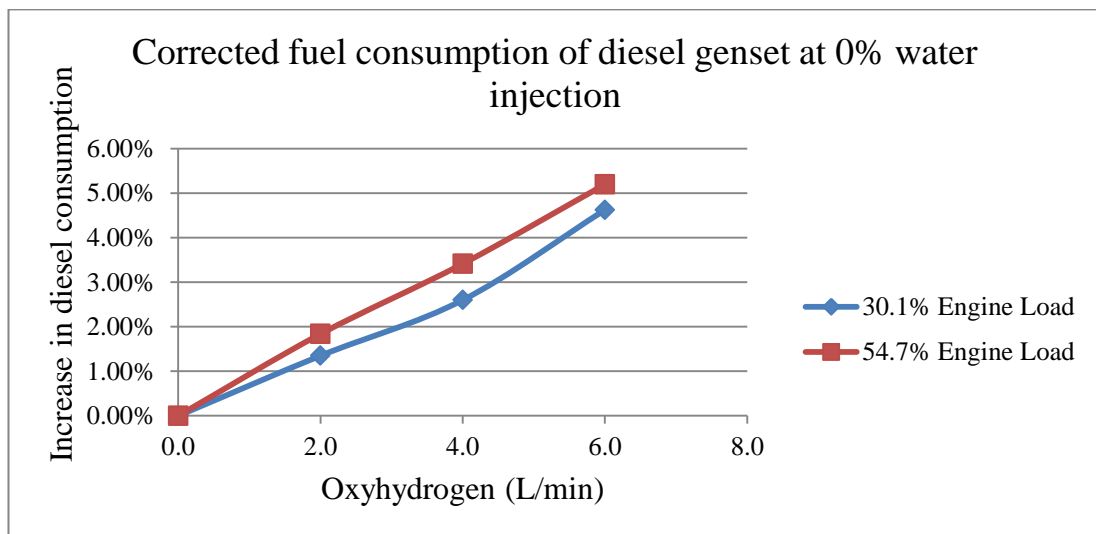


Figure 20: Effect of HHO injection with 0% additional water injection

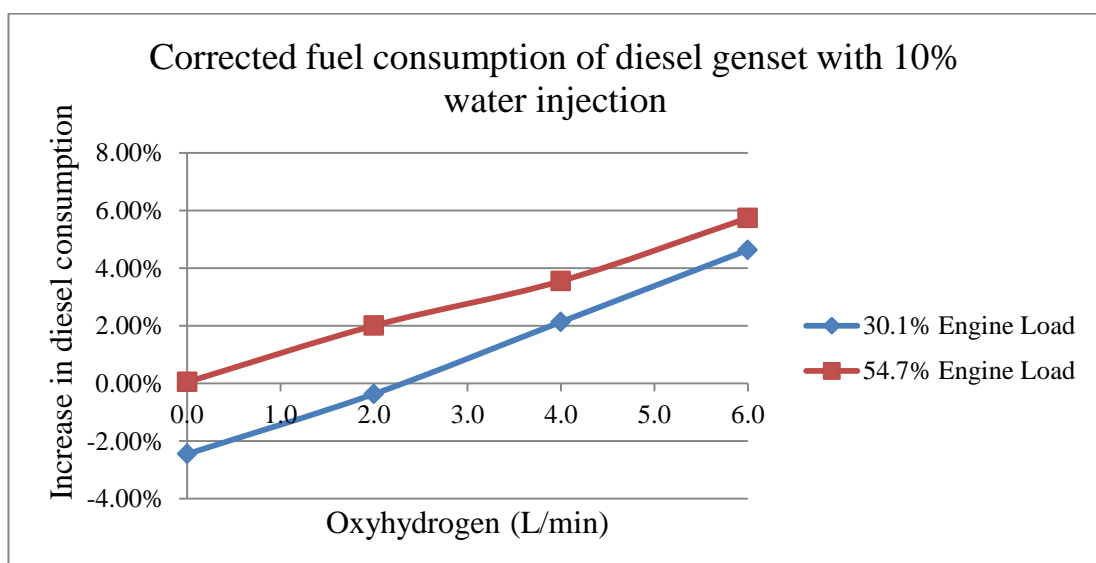


Figure 21: Effect of HHO injection with 10% additional water injection

A clear linear correlation between HHO injection rates and diesel consumption can be observed in Figure 20 and Figure 21. Seeing there was no net reduction in diesel consumption, the next area of interest is to quantitatively compare the performance of HHO against diesel as a fuel in terms of the diesel generators ability to convert the fuel energy into useful work. Another area of interest would be to assess the required production energy and net efficiency per litre of on-board HHO produced to break even with fuel consumption. This will allow an assessment of whether or not fuel saving can be obtained with a more efficient electrolyser.

Figure 22 shows a comparison between the measure and break even efficiency of HHO production when the losses of the engine, generator, power supply and electrolyser are considered. As mentioned earlier the real life conversion efficiencies are in the order of 11-16%, and to be able to break even the net efficiency of the HHO production would have to be 73% to 84%. This is impossible to reach, because the generator has an efficiency of 22% at the 9.91kW load. So even if the electrolyser and DC power supply were 100% efficient, HHO would still increase diesel consumption.

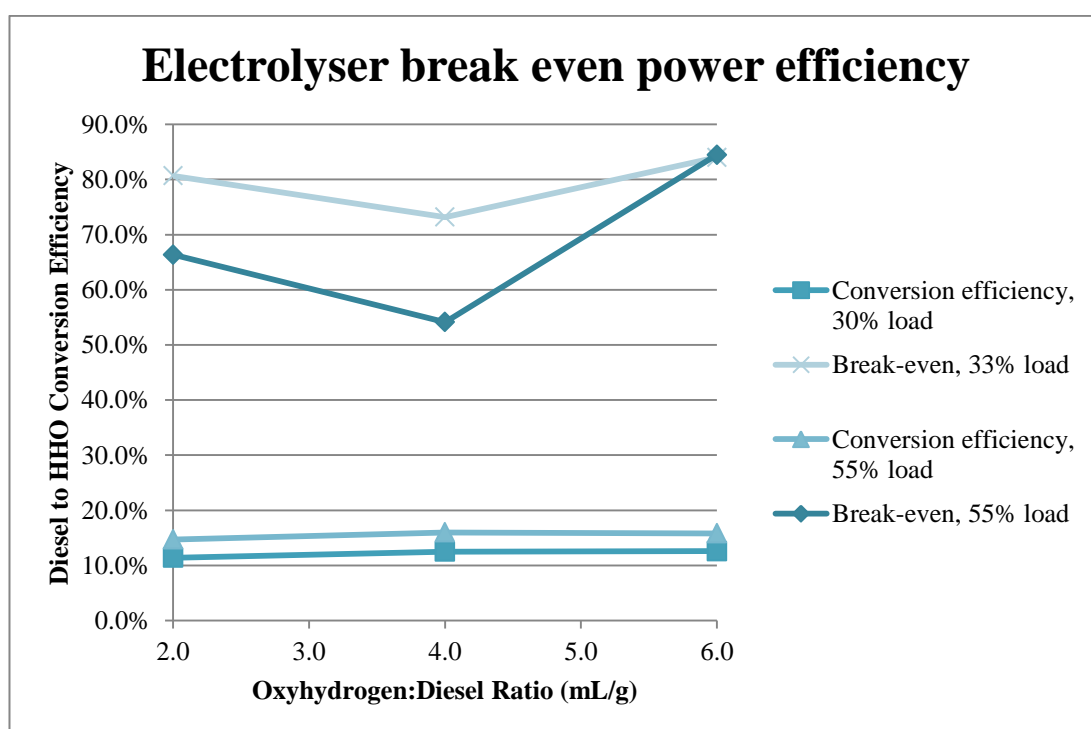


Figure 22: Comparison of measure and break even energy efficiency for on board electrolysis.

HHO production and injection from an external power source allow an analysis of the effectiveness for HHO to act as a fuel replacement or as an additive. The coefficient of performance of HHO as a fuel compared to diesel as a fuel for a given engine load could be calculated by taking the quotient of the reduction of diesel energy due to HHO addition by the input HHO energy.

$$COP_{HHO} = \frac{\Delta\dot{m}_D \cdot E_D}{t \cdot \dot{V}_{HHO} \cdot E_{HHO}} = \frac{\Delta\dot{m}_D \cdot 45.6 \times 10^3}{60 \cdot \dot{V}_{HHO} \cdot 7.79 \times 10^3} \quad (7.4)$$

Where $\Delta\dot{m}_D$ is change in diesel mass flow rate due to HHO addition [g/h]

E_D is energy content of diesel [J/g]

t is number of minutes per hour [min]

\dot{V}_{HHO} is volumetric flow rate of HHO [L/min]

E_{HHO} is the energy in HHO [J/L]

Table 13: Coefficient of performance of HHO as an additive, compared to diesel. In brackets is the COP HHO needs to recover production losses and not increase diesel consumption.

HHO	COP_{HHO} , (<i>COP for break even</i>)	
	30% engine load	55% engine load
2L/min	1.24 (8.77)	1.51 (6.8)
4L/min	1.37 (8)	1.85 (6.25)
6L/min	1.19 (7.94)	1.18 (6.33)

From the measured data it is apparent HHO addition had an additive effect much lower than what would be required to recover losses of producing the gas on-board. The highest coefficient of performance of 1.85 was measured at 55% load and 4L/min of HHO with no water injection, but under those conditions the required

COP of HHO as an additive would be 6.25. The break even COP is taken as the inverse of the on-board conversion efficiency of diesel energy into HHO energy (Table 12).

7.5 Exhaust Emissions

This section will focus on the effects of HHO and water injection on oxides of nitrogen (NO_x) emissions. NO_x are highly reactive gasses found in exhaust emissions of internal combustion engines created from the high peak temperatures generated during the combustion stroke. NO_x gases contribute to smog, greenhouse emissions and acid rain, and react with other chemicals forming toxic compounds dangerous to human and plant life. For these reasons maximum limits on NO_x emissions are continually being reduced, and to meet these limits technologies that reduce NO_x emissions are continually being developed [16, 17].

Emission testing on the diesel generator set was performed with the same rates of oxyhydrogen and water injection as the BSFC tests. The main difference with the emissions test included only running externally powered electrolysis for the HHO production, and the time base for each system state was reduced from 100g fuel consumption to a 75g fuel consumption period. The gas analyser was a CODA, it sampled CO , CO_2 and NO_x on a 187ms time base. The time at each load level was around 75s and 52s for the 9.91kW and 19.1kW loads respectively, allowing between 400 and 290 exhaust emission samples. The last half of each set of samples were averaged to yield the results outlined in this section.

HHO and water injection reduced NO_x between 1.3% and 11.8% due to water and or HHO injection. At 30% engine load NO_x was most affected by HHO injection, when combined with water injection there was a total reduction of 11.8% NO_x emissions (Figure 23).

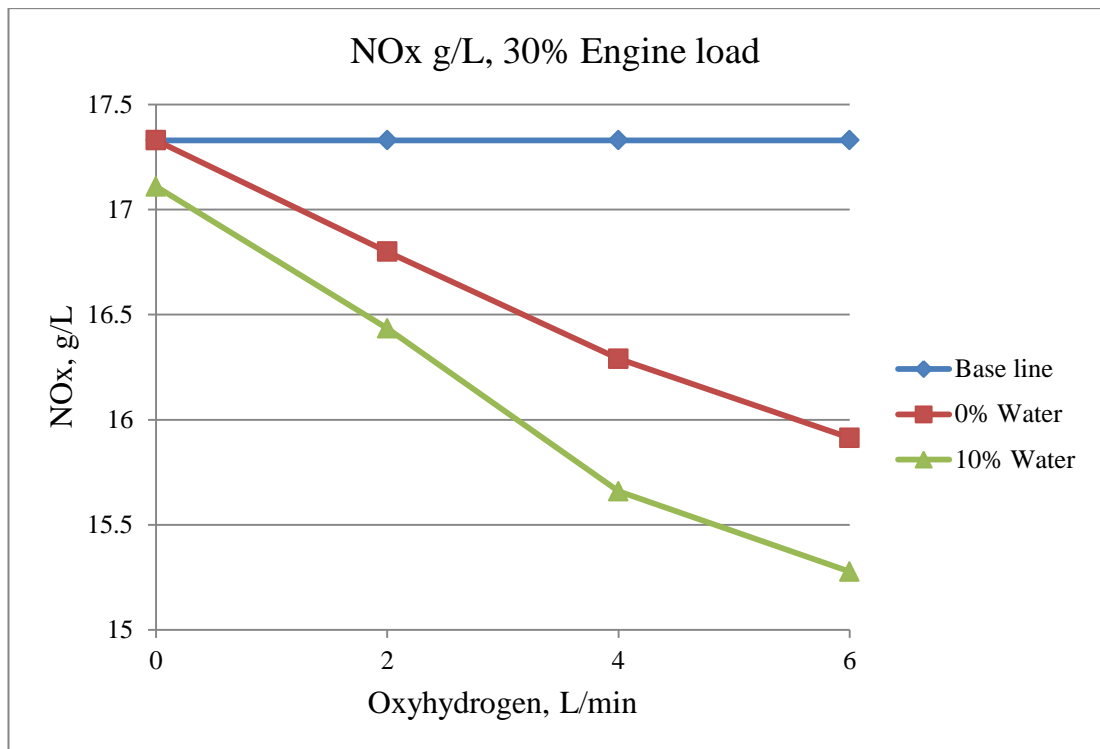


Figure 23: The effects of HHO and water injection on NOx at 30% engine load.

Water injection played the dominant role in NOx reduction at the 55% or 19.1kW engine load (Figure 24). HHO probably caused a larger reduction of NOx at 30% engine load than at 55% load because of the higher relative ratio of HHO addition. The opposite would normally be expected due to the faster combustion and higher HHV of hydrogen compared to diesel. In this experiment there was no moisture removal from the HHO coming from the electrolyzers. The water vapour or mist contained in the HHO was not filtered, so as to replicate on-board HHO system widely available. During the initial BSFC testing, a desiccant water removal stage was implemented. It had no obvious effect on changing fuel consumption, so it was removed for the final test. This allowed a closer replication of on-board HHO systems and also allowed observation of any unusual results that could indicate the presence of Rydberg clusters [18].

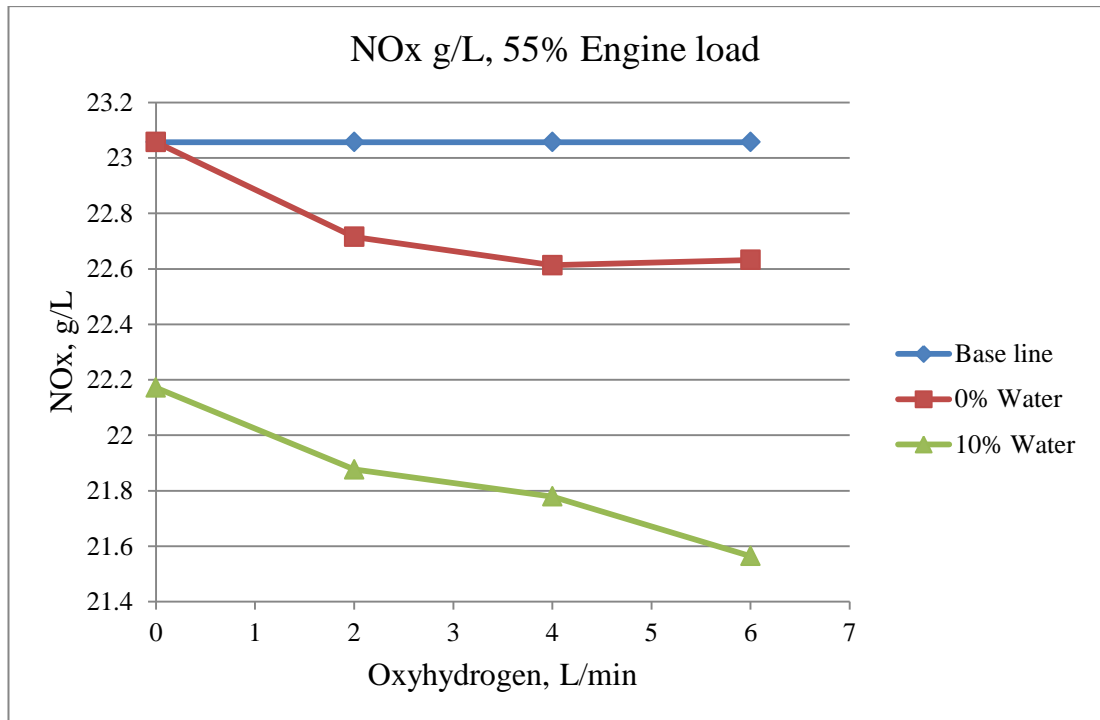


Figure 24: The effects of HHO and water injection on NOx at 55% engine load.

In the literature reviewed in Chapter 2, both hydrogen and HHO injection increased NOx, but in this experiment NOx decreased with increasing rates of HHO injection. The difference between those experiments and this one was twofold. Firstly the water electrolyser did not have a moisture removal stage – so the HHO may have contained a portion of water vapour and or mist, reducing the peak in-cylinder temperatures. Secondly HHO addition was at lower rates in this experiment than the experiments from the literature review. For example Bari and Esmail [2] injected up to seven times more HHO than the maximum used in this experiment, based on the assumption of the volumetric flow rate correction discussed in chapter 2. The small engine experiments with tank hydrogen involved 20 and 32L/min of hydrogen [6, 7] – that is 5-8 times more hydrogen and in an engine with an order of magnitude smaller displacement than the test engine used for this experiment.

Chapter 8 Future Research Recommendations

Future research opportunities that could extend the findings of this research paper definitely exist. Most diesel generators are turbo charged, and loaded at higher percentages than the loads used in this test. The effects of HHO addition and water injection in a turbo diesel engine under a wider range of generator loads would be of interest. Other areas of interest in terms of diesel engines would include testing the effects of HHO on truck and mining equipment engines, within the normal engine speed and load conditions that they are subject to. The effects of on-board HHO injection could be trialled for typical engine load and speed cycles that spark ignition engines are subject to in road vehicles.

Another area of research potential stemming from this research would be to develop methods for increasing the energy in the HHO gas via plasma electrolysis, or via high voltage resonant electrolysis, or any other method, and then test the effects of these altered states of HHO on internal combustion engines to see if fuel economy could be raised. This research project has only shown that on-board HHO addition is ineffective for reducing diesel consumption on a light to medium loaded naturally aspirated diesel generator. This inability for on-board HHO addition to reduce fuel consumption cannot be inferred to other types of internal combustion engines, or speed load cycles until it is tested.

It is important in future research of on-board HHO addition to; state the power efficiency of the electrolyser, have properly calibrated flow control and measurement for HHO, and have HHO production rates that leave a reasonably large portion of the engines power to do useful work. If the research is aimed at determining the ability for HHO to reduce fuel consumption in an engine, then the HHO should be produced by the engines power, especially for road transport (unless the external electrical supply could be feasibly carried).

Chapter 9 Project Conclusion

9.1 On-board HHO Addition Research Gap

Literature review of small rates of tank hydrogen or HHO addition in diesel engines and generators agreed on a reduction of diesel consumption. However the reductions in diesel consumption were not enough to overcome the typical production losses when generating on-board HHO. The claims of small rates of on-board HHO addition to reduce diesel consumption in a generator were based on a purely theoretical stance of producing HHO at 100% efficiency (Chapter 2). The literature review revealed the need for experimental testing and validation of an on-board electrolyser system on a diesel generator, since this is one major area where the claims of fuel saving are made.

9.2 On-board HHO's Effect on Diesel Consumption

The experiment included the addition of 0-6L/min of HHO produced from an on-board electrolyser into a diesel generator at 30% and 55% of the 3.9L engines rating. The experiment was run with and without 10% water/diesel injection ratio to test whether water injection could have alleviated potential NO_x exhaust emission, should a reduction in diesel consumption be possible. The results conclusively showed that diesel consumption linearly increases with increasing on board HHO addition – up to a 5.2% increase in diesel consumption with 6L/min at 55% engine loading. The coefficient of performance of HHO compared to diesel as a fuel was measured at 1.19 to 1.85, but HHO required a COP of 6.33 to 8.77 to break even with the losses of production. Water injection in conjunction with HHO addition slightly increased diesel consumption, most likely due to reduced combustion temperatures.

9.3 HHO's Effect on NOx Exhaust Emissions

Oxides of nitrogen (NO_x) emissions were reduced up to 11.8% and 6.5% at 30% and 50% loads respectively from 6L/min HHO and 10% water addition with an externally powered electrolyser. At the lighter 30% engine load 70% of the NOx reduction was as a result of the HHO injection, the remaining 30% reduction due to water injection. At the increased 55% engine load, water injection was the main contributor to NOx reduction. HHO was only responsible for 28% of the NOx reduction. HHO did not increase NOx most likely due to the small gaseous and liquid water content of the gas, and because the electrolyser was powered externally for the emissions test. A moisture removal stage in the water electrolyser system was omitted from the experiment to better replicate 'fuel saving' HHO generators that this experiment was aimed at validating.

9.4 Financial Analysis

No financial feasibility studies were conducted for on-board HHO injection because HHO increased fuel consumption for all rates of injection for the 3.9L 28kW Cummins diesel generator set. Even if the water electrolyser and the DC power supply were 100% efficient, HHO's COP as an additive would be negated by the mechanical losses of the generator.

Appendix A: Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project

Project Specification

FOR: **RICK CAMERON**
TOPIC: EFFECTS OF HHO GAS AND STEAM INJECTION IN A DIESEL GENERATOR USING AN ON-BOARD ELECTROLYZER

SUPERVISORS: Dr. Leslie Bowtell (Electrical)
Dr. Paul Baker (Mechanical)

ENROLMENT: ENG 4111 – S1 2012
ENG 40112 – S2 2012

PROJECT AIM: This project seeks to quantify the effects on net brake specific fuel consumption (BSFC) and exhaust emissions, specifically NO_x and particulates, for a compression ignition generator. Various ratios of HHO will be trialled and the system will take into account the water electrolyser losses as an added load on the generator in overall efficiency calculations.

PROGRAMME: Issue A, 30th February 2012

1. Obtain base line BSFC and exhaust emissions data for a test diesel engine running at 3000rpm and different loads for comparative analysis – the same conditions a diesel generator would typically operate at.
2. Experimentally verify whether a diesel engine running at constant speed and different loads can have a net gain in efficiency if small ratios of HHO ($\leq 5\%$ of base line diesel fuel usage) is injected into the air intake of the engine. Taking into account the added load of a typical HHO water electrolyser on the engine under test.
3. Develop a PLC system to control engine load and HHO injection ratios automatically in terms of a percentage of the base line fuel usage to aid repeatability.
4. Produce a SCADA HMI to display the real time experimental data.

As time permits

5. Develop a method of data logging BSFC and exhaust emissions when the engine is running the tests described in specifications (1) and (2) above.
6. Evaluate additional measures to improve fuel economy of the diesel generator, specifically water mist injection in conjunction with HHO injection.

AGREED:

Student: _____ Supervisors: _____,
Date: _____, _____

Appendix B: Experiment HAZOP

HAZOP STUDY RECORD SHEET						DATE:	
SYSTEM: HHO UNIT, FUEL MEASUREMENT SYSTEM P&ID DWG No: -		PROJECT: RICK'S HHO ENGINE SYSTEM. PRESENT:		PAGE: 7 of		REV NO: 1	
CHAIRMAN: P. Baker		SECRETARY:		REV DATE: 5/6/2012		BY	
No.	GUIDE WORD	POSSIBLE CAUSES	CONSEQUENCES	EXISTING SAFEGUARDS	RISK	ACTION REQUIRED	DONE
1.	High Flow.	NOT POSSIBLE.	---				
	High Level.	OVER FILL BEAKER	DIESEL SPILL.	RELIES ON PROCEDURES		SPILL KIT. ON HAND. # EYE WASH BOTTLE. - ADDITIONAL ULTRASONIC LEVEL DETECTOR.	BRETT.
2.	Low Level.	SUCK AIR THROUGH PIPES.	ENGINE STOPS (NEEDS PRIMING)	PROCEDURES.		INTRODUCE AUTOMATIC T.P. PREVENT.	RICK.
	Low Flow.	FAULTY VALVE (PARTIAL VACUUM)	ENGINE STOPS	PROCEDURES		INTRODUCE CONTROL SYSTEM LOCK	
3.	Low Flow or Empty	LOW PRESSURE BUBBLING ON TANK GLASS RUN OUT OF FUEL (EMPTY FUEL TANK)	ENGINE STOPS (NEEDS PRIMING)	" "		---	
4.	Reverse Flow	---	---	PROCEDURES.		---	

RICK = Frequency x Severity ie. FREQUENCY : High = H, Medium = M, Low = L., SEVERITY: Extreme = E, Severe = S, Moderate = M, Insignificant = I

HAZOP STUDY RECORD SHEET

SYSTEM:		PROJECT:			DATE:			
P&ID DWG No:		PRESENT:			PAGE: 2 of			
CHAIRMAN:		SECRETARY:			REV NO:			
P. Baker		P. Baker			REV DATE:			
No.	GUIDE WORD	POSSIBLE CAUSES	CONSEQUENCES	EXISTING SAFEGUARDS	RISK	ACTION REQUIRED	BY	DONE
5.	High Pressure.	---	---	---	---	---	---	---
	High Temp (SPILL)	FUEL + DIESEL SPILL + IGNITION SOURCE = FIRE	DESTROY ROOM.	SMOKE DETECTOR. ENGINE THERMAL OVERLOAD. PROCEDURAL. + EXHAUST FAN. IF FUEL DOES SPILL FROM BEAKER, NEAR NO IGNITION SOURCES.	LOW PROB.	LOOK AT REPAIRING COPPER LINES SUBJECT TO VIBRATION.	BRETT	
	Low Temp.	---	---	---	---	---	---	---
	IMPURITIES	BLOCKED FILTERS. BACTERIA IN DIESEL.	FLOW STOPS (ENGINE STOPS).	PROCEDURES / MAINTENANCE.	---	---	---	---
	CHANGES REACTIONS	CONDENSATE BUILDS UP IN OIL IN TANK	CONTAMINATED OIL.	OIL CHANGE AFTER TESTS.	---	---	BRETT	

RISK = Frequency x Severity ie. FREQUENCY : High = H, Medium = M, Low = L., SEVERITY: Extreme = E, Severe = S, Moderate = M, Insignificant = I

HAZOP STUDY RECORD SHEET

SYSTEM: ELECTROLYZER (AHO)		PROJECT: AHO/ENGINE SYSTEM -			DATE:	
PAID DWG No:		PRESENT:			PAGE: 3 of	
CHAIR: P. Baker		SECRETARY:			REV NO:	
POSSIBLE CAUSES		CONSEQUENCES			REV DATE:	
GUIDE WORD	EXISTING SAFEGUARDS	RISK	ACTION REQUIRED	BY	DONE	
1. HIGH FLOW.	ELECTRICAL CURRENT TO CELLS.	BANK -	FUSED, FOLD BACK LIMITED POWER SUPPLY.	Low	-	-
HIGH LEVEL.	ELECTROLYTE LEVEL IN CELLS - SPILLS WHEN FILLING.	EXPLOSIVE TO CAUSTIC SOLUTION.	PROCEDURES/PPE.	MED.	WELD PPE - GLOVES, FACE MASK, GLOVES, EX WASHA BOTTLE.	BRETT
LOW LEVEL OR FLOW.	IN CELLS.	REDUCES CURRENT & GAS PRODUCTION.	N/A - INTRINSICALLY SAFE.	Low.	- WORK INSTRUCTION REQUIRED.	ROCK
ZERO FLOW OR EMPTY.	-	-	-	-	-	-
REVERSE ENGINE STOPS.	SHUTS OFF CELLS.	INTRINSICALLY SAFE	ENGINE INTERLOCKED WITH CELLS.	Low.	-	-
REVERSE FLOW.	H ₂ BURNS BACK - FLAME ARRESTER.	-	FITTED WITH FLAME ARRESTER.	Low	-	-

RISK = Frequency x Severity ie. FREQUENCY : High = H, Medium = M, Low = L., SEVERITY: Extreme = E, Severe = S, Moderate = M, Insignificant = I

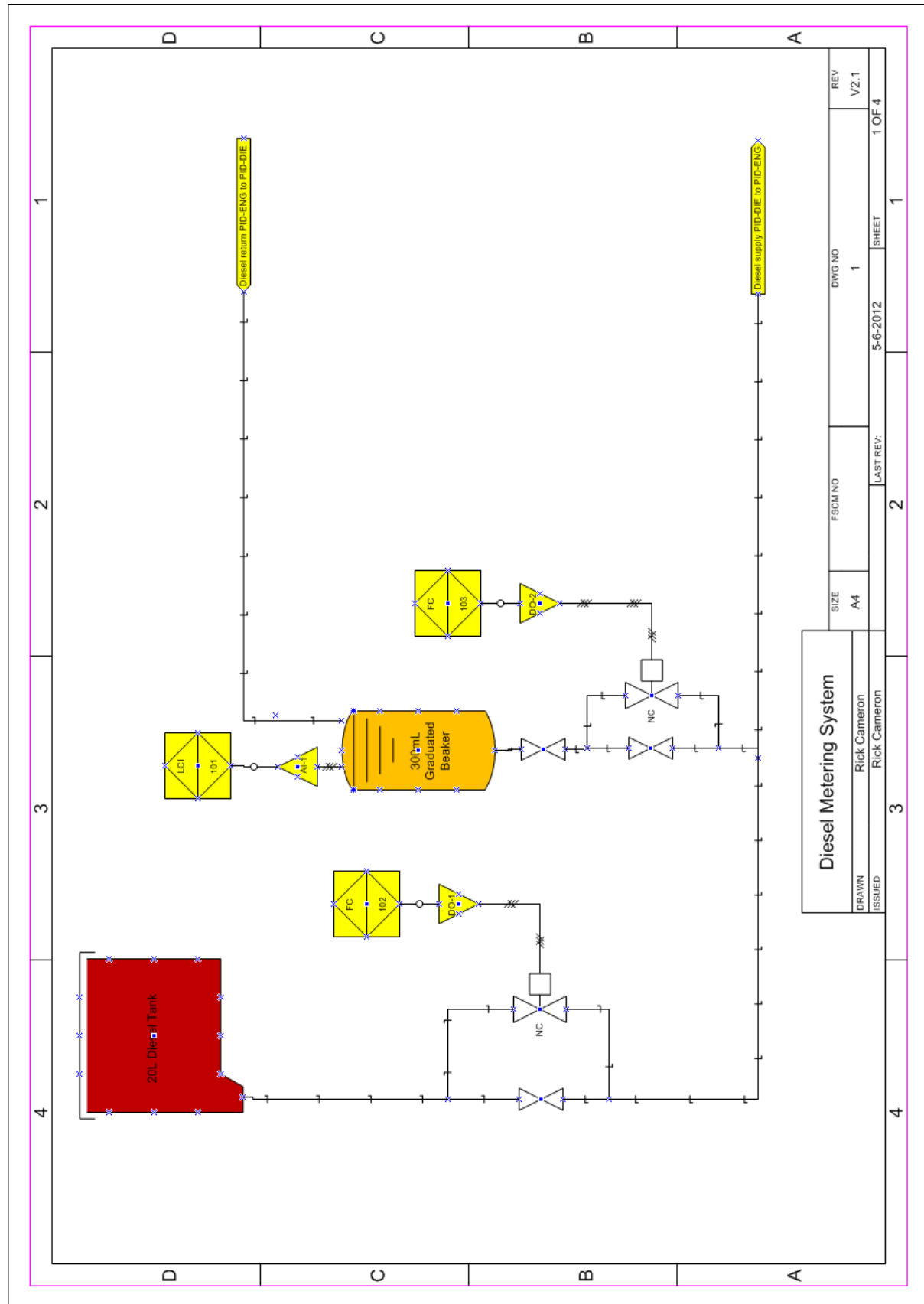
HAZOP STUDY RECORD SHEET

SYSTEM: H ₂ O CELLS.		PROJECT:-		DATE:				
DWG No:		PRESENT:		PAGE: 5 of				
CHAIRMAN: P. Baker		SECRETARY:		REV NO: REV DATE:				
No.	GUIDE WORD	POSSIBLE CAUSES	CONSEQUENCES	EXISTING SAFEGUARDS	RISK	ACTION REQUIRED	BY	DONE
	CHANGE IN CONC. IN CELL.	REDUCTION IN WATER LEVEL.	INCREASE IN CONC. OF NaCl.	CONSTANT MONITORING LEVEL OF ELECTROLYTE LEVEL IN CELLS	Low	INCLUDE IN PROCEDURES	RICK-	
	TESTING	CALIBRATION OF UNIT PRIOR TO USE.	-	-	-	-	-	
	ELECT. CLASSIFICATION	INCORRECTLY RATED FOR EXPLOSIVE, CLASS I AREA.	EXP EXPLOSION.	ROOM PURGED ATMOSPHERE DESIGNED FOR PELV (PROTECTED WITH LOW VOLTAGE)	Low	ENSURE PURGE AIR IS ON DURING. WHEN CELLS ARE ENERGISED. PROCEDURES.	RICK-	
	INSTRUMENTS NEAR CELLS.	LOSS OF CONTAMINANT. SINK.	-	CONCENTRATION OF H ₂ IS BELOW LEL.	Low	ENSURE ELECTRICAL ISOLATION SOURCES. ISOLATED FROM CELLS. LOCK AT PHASING INTO ENCLOSURE. ENSURE PURGING SYSTEM OPERATING. BOP.	RICK-	

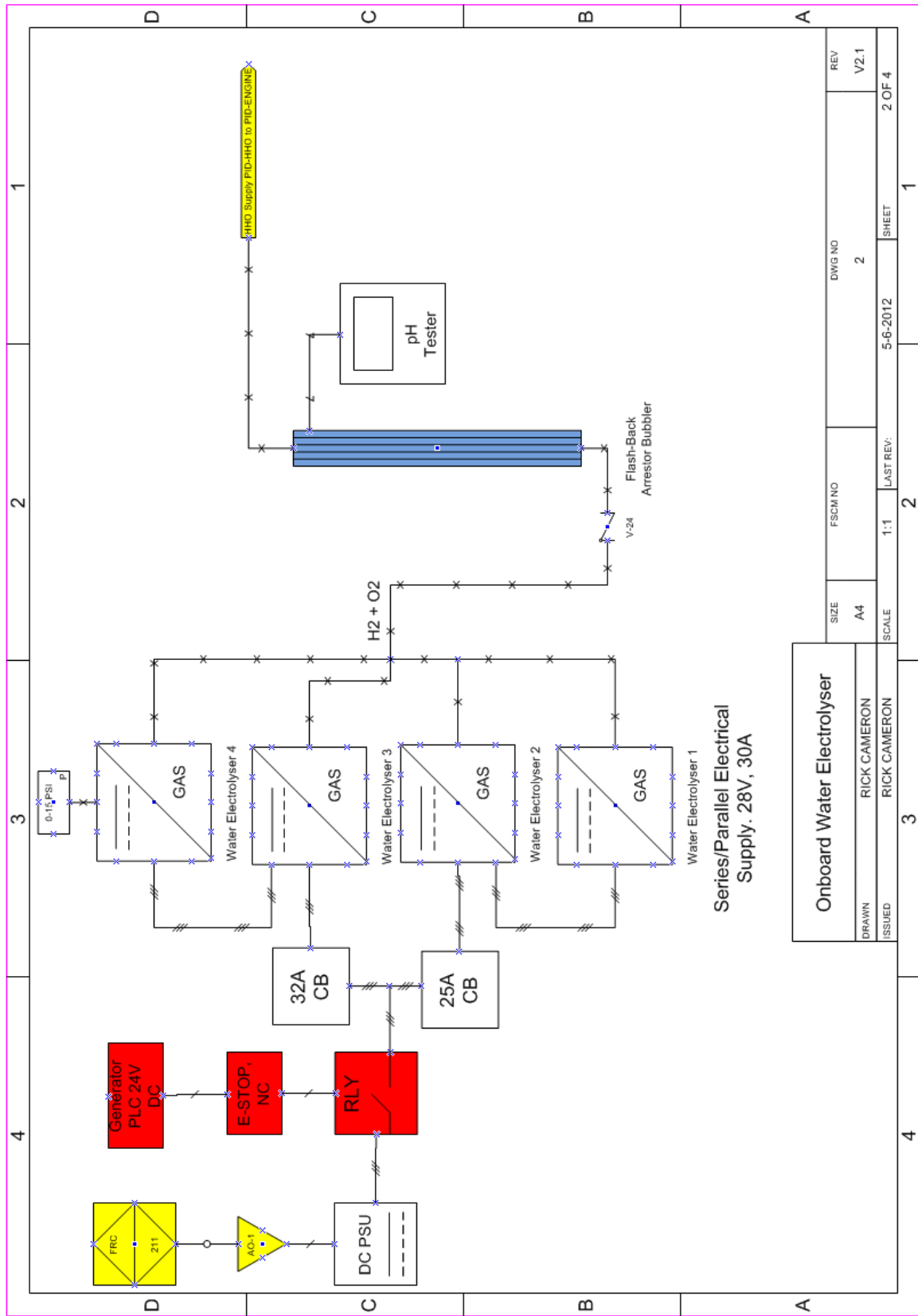
RISK = Frequency x Severity ie. FREQUENCY : High = H, Medium = M, Low = L., SEVERITY: Extreme = E, Severe = S, Moderate = M, Insignificant = I

FULLY ATTENDED OPERATION
WITH 2 PEOPLE IN ATTENDANCE.

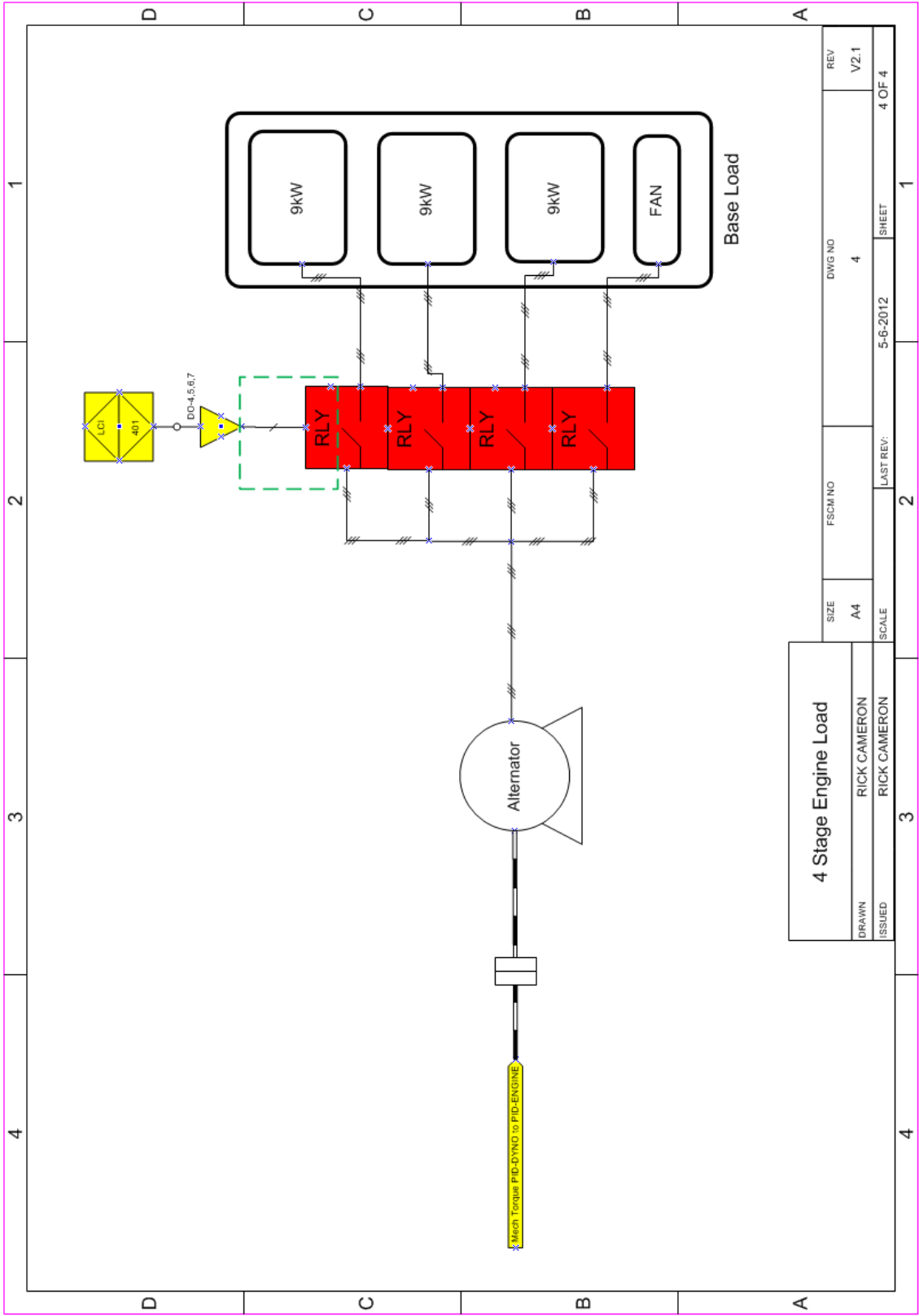
Appendix C: Experiment P&ID



Diesel Metering System	
DRAWN	Rick Cameron
ISSUED	Rick Cameron



Onboard Water Electrolyser		SIZE	FSCM NO	DWG NO	REV
DRAWN	RICK CAMERON	A4		2	V2.1
ISSUED	RICK CAMERON	SCALE	1:1	LAST REV:	5-6-2012
				SHEET	2 OF 4



4 Stage Engine Load		SIZE	FSCM NO	DWG NO	REV
DRAWN	RICK CAMERON	A4		4	V2.1
ISSUED	RICK CAMERON	SCALE	LAST REV	SHEET	4 OF 4
			5-6-2012	1	

Appendix E: Mid-Semester Schedule for New Experiment

ENG4111 Research Project Part 1, 2012 Semester 1

Task/Activity	Sem 1, Week 15		Sem 1, Exams week 1		Break, week 1 (25-29 June)		Break, week 2 (2-6 July)		Break, week 3 (9-13 July)			
	Thurs 7/6	Fri 8/7	Thurs 14/6	Fri 15/6	Tuesday	Wednesday	Thursday	Friday	Monday	Tuesday	Wednesday	Thursday
Design manifold mods, get clearance												
Get steel from w/shop for manifolds												
Setup levels sensor mounting												
Change diesel valves over												
Order manifold parts												
Install ultrasonic level sensor												
Develop Automated test structure												
Break test into s/ware modules												
Diesel PLC module												
HHO PLC module												
H2O PLC module												
Test Loop structure												
Logging s/ware module												
Wire up PLC to HHO Gen												
Develop basic SCADA Control												
Write test procedure												
Build manifolds												
Safety interlock and E-stop tests												
HHO H/ware build												
Calibrate Diesel, HHO, water, air, exhaust												
PLC to engine electrical load wiring												
Fluke power analyzer connection and test												
H2O connection to manifold												
Full system dry test(no engine)												
Full system trouble shooting												
Full system engine test												
MATLAB Optimization of results												
Final test												

Appendix F: Logged Data – Fuel Consumption

On-board HHO Test						
HHO (L/min)	Load (kW)	Diesel (g/h)	EGT (C)	Water Injection	Relative humidity	IAT (K)
0.0	9.91	3430.0	216.7	0%	16.1	297.4
2.0	9.91	3488.4	223.3	0%	13.3	299.3
4.0	9.91	3543.5	229.7	0%	11.8	301.1
6.0	9.91	3623.1	236.4	0%	11.0	302.4
0.0	9.91	3393.9	228.0	10%	9.6	304.8
2.0	9.91	3470.8	231.3	10%	9.0	305.5
4.0	9.91	3555.0	234.5	10%	9.3	305.1
6.0	9.91	3639.0	238.6	10%	9.0	304.8
0.0	19.1	5173.5	324.5	0%	6.0	310.6
2.0	19.1	5277.8	329.3	0%	5.5	311.6
4.0	19.1	5365.3	335.8	0%	5.0	312.3
6.0	19.1	5466.3	342.5	0%	4.9	313.1
0.0	19.1	5205.3	332.2	10%	4.4	313.9
2.0	19.1	5309.3	335.2	10%	4.1	314.2
4.0	19.1	5391.4	339.4	10%	4.2	314.3
6.0	19.1	5507.9	345.0	10%	4.3	314.5

External Supplied HHO Test						
HHO (L/min)	Load (kW)	Diesel (g/h)	EGT (K)	Water Injection	Relative humidity	IAT (K)
0.0	9.91	3423.5	225.9	0%	8.6	303.9
2.0	9.91	3407.4	227.7	0%	8.0	305.3
4.0	9.91	3385.4	229.3	0%	7.6	306.5
6.0	9.91	3372.9	230.3	0%	6.9	307.3
0.0	9.91	3412.6	230.4	10%	6.8	307.6
2.0	9.91	3417.6	230.3	10%	7.3	306.8
4.0	9.91	3405.9	229.7	10%	7.3	306.8
6.0	9.91	3399.6	229.9	10%	7.4	307.0
0.0	19.1	5198.2	326.0	0%	4.4	313.4
2.0	19.1	5184.4	327.6	0%	3.5	315.3
4.0	19.1	5157.0	330.4	0%	2.9	317.3
6.0	19.1	5165.8	332.8	0%	3.0	317.8
0.0	19.1	5237.6	333.5	10%	3.0	317.0
2.0	19.1	5229.8	334.0	10%	3.3	316.8
4.0	19.1	5212.6	333.7	10%	3.1	317.0
6.0	19.1	5206.1	334.0	10%	3.3	317.0

Appendix G: Logged Data – Exhaust Emissions

Exhaust Emissions Data (Averaged)								
Load (kW)	Water	HHO (L/min)	CO(g/L)	O2(g/L)	NOx(g/L)	AFR(--)	LDA(--)	Eff(%)
9.91	0%	0	5.6	5728.1	17.33	47.4	3.3	99.6
9.91	0%	2	4.8	5724.0	16.80	47.4	3.3	99.6
9.91	0%	4	4.9	5773.7	16.29	47.7	3.3	99.6
9.91	0%	6	5.8	5783.5	15.91	47.7	3.3	99.5
9.91	10%	0	5.5	5723.8	17.11	47.4	3.3	99.6
9.91	10%	2	5.7	5723.4	16.43	47.4	3.3	99.5
9.91	10%	4	4.9	5789.2	15.66	47.8	3.3	99.6
9.91	10%	6	5.4	5796.0	15.28	47.8	3.3	99.5
19.1	0%	0	6.3	2578.5	23.06	29.3	2.0	99.6
19.1	0%	2	6.3	2614.3	22.72	29.5	2.0	99.6
19.1	0%	4	6.3	2619.8	22.61	29.6	2.0	99.6
19.1	0%	6	6.2	2621.1	22.63	29.6	2.0	99.6
19.1	10%	0	6.3	2546.4	22.17	29.1	2.0	99.6
19.1	10%	2	5.6	2553.9	21.88	29.2	2.0	99.6
19.1	10%	4	5.8	2562.9	21.78	29.2	2.0	99.6
19.1	10%	6	5.7	2563.0	21.56	29.2	2.0	99.6

Appendix H: MATLAB Script for Processing PLC Data

This MATLAB script extracted raw data from the PLC's logged .csv file and generated surface and contour plots of BSFC and exhaust temperature over the range of HHO addition and water injection rates. This allowed data to be analysed at the time and location of the experiment in the initial stages.

```
% main.m

% Created: Rick Cameron, 2012
% What it does:
% Processes raw data logged with a Siemens S7-200 PLC system from a
30kW
% diesel genset test contour plots showing the effects of varying
rates of
% HHO and water mist injection on brake specific fuel consumption of
% a diesel engine.

% Requirements:
% CSV file from PLC containing logged data
% Barometric pressure in kPa
% active electrical power data from generator

clc; clear;
close all

diesel_col = 1;
egt_col = 2;
HHO_col = 4;
water_col = 5;
load_col = 6;

%% Import logged data from PLC
importfile();

%%Correct the power and BSFC to ambient conditions
T = data(:,7)+273.15; %dry bulb air temperature in kelvin
R_humidity = data(:,8)./100; %relative humidity 0-1
% pressure of water, hPa
pp_water = R_humidity .* (exp(77.345+0.0057.*T-
7235./T)./(T.^8.2.*100));
dry_air_pressure = 1019.0 - pp_water; % dry air pressure, hPa
% SAE J1349 formula for power correction factor
cf = 1.18.*((990./dry_air_pressure).*sqrt(T./298))-0.18;
p = polyfit([1,2,3],[9.91,19.1,28],3); %convert load 1,2,3 with
power function
% Use logged data from EDM1 power meter if available, in kW
corrected_power = cf.*polyval(p,data(:,load_col));
% Convert fuel consumption into BSFC
data(:,diesel_col) = data(:,diesel_col)./(data(:,load_col)*9);

max_hho = max(data(:,HHO_col));
water_max = max(data(:,water_col));
water_step = unique(data(:,water_col));
```

```

water_step = water_step(2);

%% Extract load 1 data
% Find the rows where the load = 1 by looking in column 6
[r,c]=find(data(:,load_col)==1);
load_1_data = data(r,:); % Save the data block

% Inner loop:
% Find the rows where there is 0 HHO production
[r0,c]=find(load_1_data(:,HHO_col)==0);
base_1_data = load_1_data(r0,:); %Save baseline data rows separately
load_1_data(r0,:)=[]; % Now remove base line rows

% Inner inner loop: Average base line fuel consumption data
j=1;
for h=0:water_step:water_max
% find rows with defined injection rate
[r,c]=find(base_1_data(:,water_col)==(round(h*100)/100));
r=r(1:5);
Average_base1(j,:) = mean(base_1_data(r,:));
n = find(load_1_data(:,water_col)==(round(h*100)/100));
load_1_data = insertrows(load_1_data, Average_base1(j,:), n(end));
j=j+1;
end

%% Extract load 2 data
% Find the rows where the load = 1 by looking in column 6
[r,c]=find(data(:,load_col)==2);
load_2_data = data(r,:); % Save the data block

% Find the rows where there is 0 HHO production
[r0,c]=find(load_2_data(:,HHO_col)==0);
base_2_data = load_2_data(r0,:);
load_2_data(r0,:)=[];

j=1;
for h=0:water_step:water_max
[r,c]=find(base_2_data(:,water_col)==(round(h*100)/100));
r=r(1:3);
Average_base2(j,:) = mean(base_2_data(r,:));
n = find(load_2_data(:,water_col)==(round(h*100)/100));
load_2_data = insertrows(load_2_data, Average_base2(j,:), n(end));
j=j+1;
end

%% Extract load 3 data
% Find the rows where the load = 3 by looking in column 6
[r,c]=find(data(:,load_col)==3);
load_3_data = data(r,:); % Save the data block

```

```

% Find the rows where there is 0 HHO production
[r0,c]=find(load_3_data(:,HHO_col)==0);
base_3_data = load_3_data(r0,:);
load_3_data(r0,:)=[];

j=1;
for h=0:water_step:water_max
[r,c]=find(base_3_data(:,water_col)==(round(h*100)/100));
r=r(1:3);
Average_base3(j,:) = mean(base_3_data(r,:));
n = find(load_3_data(:,water_col)==(round(h*100)/100));
load_3_data = insertrows(load_3_data, Average_base3(j,:), n(end));
j=j+1;
end

%% General set up for surface and contour plots
scrn_size = get(0, 'ScreenSize');
scrn_init_loc = scrn_size + [20 50 -600 -250];
scrn_offset = [150 0 0 0];
k=0;
screen_current = scrn_init_loc + k.*scrn_offset;
plot_res = 36;

% Equal increments between min and max sampled HHO
xlin = linspace(0,max_hho,plot_res);
% Equal increments between min and max sampled water
ylin = linspace(0,water_max,6);
ylinfine = linspace(0,water_max,plot_res);
%2d row and column matrices of HHO and water rates
[X,Y] = meshgrid(xlin,ylin);
%2d row and column matrices of HHO and water rates
[X1,Y1] = meshgrid(xlin,ylinfine);

% Sampled data
% Smooth the noise from the SFC data for the interpolated surface
plots.
j = 1;
z1 = load_1_data(:,diesel_col); %SFC
z2 = load_2_data(:,diesel_col); %SFC
z3 = load_3_data(:,diesel_col); %SFC
for h = 0:water_step:water_max
[r,c] =
find((round(load_1_data(:,water_col)*100)/100)==(round(h*100)/100));
% z1(r,1) = medfilt1(load_1_data(r,1),5);
z_egt1(r,1) = medfilt1(load_1_data(r,egt_col),5);
% Polynomial curve fitting option
z1(r,1) = polyval(polyfit(load_1_data(r,HHO_col),...
load_1_data(r,diesel_col),6),load_1_data(r,HHO_col));

[r,c] =
find((round(load_2_data(:,water_col)*100)/100)==(round(h*100)/100));
% z2(r,1) = medfilt1(load_2_data(r,1),5);
z_egt2(r,1) = medfilt1(load_2_data(r,egt_col),5);
z2(r,1) = polyval(polyfit(load_2_data(r,HHO_col),...
load_2_data(r,diesel_col),6),load_2_data(r,HHO_col));

```

```

[r,c] =
find((round(load_3_data(:,water_col)*100)/100)==(round(h*100)/100));
% z3(r,1) = medfilt1(load_3_data(r,1),5);
z_egt3(r,1) = medfilt1(load_3_data(r,egt_col),5);
z3(r,1) = polyval(polyfit(load_3_data(r,HHO_col),...
    load_3_data(r,diesel_col),6),load_3_data(r,HHO_col));

j = j+1;
end

% HHO rate extraction
x1 = load_1_data(:,HHO_col);
x2 = load_2_data(:,HHO_col);
x3 = load_3_data(:,HHO_col);
% Water/diesel rate extraction
y1 = load_1_data(:,water_col);
y2 = load_2_data(:,water_col);
y3 = load_3_data(:,water_col);
% Construct interpolant function for BSFC
F1 = TriScatteredInterp(x1, y1, z1);
F2 = TriScatteredInterp(x2, y2, z2);
F3 = TriScatteredInterp(x3, y3, z3);
% Construct interpolant function for EGT
F_egt1 = TriScatteredInterp(x1, y1, z_egt1);
F_egt2 = TriScatteredInterp(x2, y2, z_egt2);
F_egt3 = TriScatteredInterp(x3, y3, z_egt3);
%Evaluate the interpolant at loactions X1 and Y1.
Z1 = F1(X,Y);
Z2 = F2(X,Y);
Z3 = F3(X,Y);
Z_egt1 = F_egt1(X,Y);
Z_egt2 = F_egt2(X,Y);
Z_egt3 = F_egt3(X,Y);
Z1 = interp2(X,Y,Z1,X1,Y1,'linear');
Z2 = interp2(X,Y,Z2,X1,Y1,'linear');
Z3 = interp2(X,Y,Z3,X1,Y1,'linear');
Z_egt1 = interp2(X,Y,Z_egt1,X1,Y1,'spline');
Z_egt2 = interp2(X,Y,Z_egt2,X1,Y1,'spline');
Z_egt3 = interp2(X,Y,Z_egt3,X1,Y1,'spline');

base_1_BSFC = base_1_data(end,1) * ones(plot_res,plot_res);
base_2_BSFC = base_2_data(end,1) * ones(plot_res,plot_res);
base_3_BSFC = base_3_data(end,1) * ones(plot_res,plot_res);

%% Load 1: 3D graph for non-uniform and noisy data
figure;
set(gcf,'Position',screen_current);
[C,b] = contourf(X1,Y1,Z1,linspace(floor(min(min(Z1/10)))*10,...
    ceil(max(max(Z1/10)))*10,21));
text_handle = clabel(C,b);
title('BSFC (g/kWh), 9.91kW (30%) Load, at 1500 rpm','FontSize',14);
xlabel('Oxyhydrogen (L/min)','FontSize',13);
ylabel('Water/Diesel Injection Rate','FontSize',13);
saveas(gcf, 'bsfc_1_contour.jpg')

figure;
set(gcf,'Position',screen_current);
[C,b] =
contourf(X1,Y1,Z_egt1,linspace(floor(min(min(Z_egt1/10)))*10,...
    ceil(max(max(Z_egt1/10)))*10,11));

```

```

text_handle = clabel(C,b);
title('Exhaust Temperature (C), 9kW (~30%) Load, at 3000
rpm', 'FontSize',14);
xlabel('Oxyhydrogen (L/min)', 'FontSize',13);
ylabel('Water/Diesel Injection Rate', 'FontSize',13);
saveas(gcf , 'egt_1_contour.jpg');

figure;
set(gcf, 'Position', screen_current);
axis([0 6 0 0.5])
surf(X1,Y1,Z1); % interpolated
axis tight;
% hold on
% mesh(X1,Y1,base_1_BSFC);
hold on;
plot3(x1,y1,load_1_data(:,diesel_col), '.', 'MarkerSize',13)
title('BSFC (g/kWh), 9.91kW (30%) Load, at 1500 rpm', 'FontSize',14);
xlabel('Oxyhydrogen (L/min)', 'FontSize',13);
ylabel('Water/Diesel Injection Rate', 'FontSize',13);
zlabel('BSFC (g/kWh)', 'FontSize',13);
saveas(gcf , 'bsfc_1_surf.jpg')

k = k+1;
screen_current = scrn_init_loc + k*scrn_offset;
% End load 1

%% Load 2: 3D graph for non-uniform data

figure;
set(gcf, 'Position', screen_current);
%axis([0 6 0 0.5])
[C,b] = contourf(X1,Y1,Z2,linspace(floor(min(min(Z2/10)))*10,...
    ceil(max(max(Z2/10)))*10,21));
text_handle = clabel(C,b);
title('BSFC (g/kWh), 19.1kW (58%) Load, at 1500 rpm', 'FontSize',14);
xlabel('Oxyhydrogen (L/min)', 'FontSize',13);
ylabel('Water/Diesel Injection Rate', 'FontSize',13);
saveas(gcf , 'bsfc_2_contour.jpg')

figure;
set(gcf, 'Position', screen_current);
[C,b] =
contourf(X1,Y1,Z_egt2,linspace(floor(min(min(Z_egt2/10)))*10,...
    ceil(max(max(Z_egt2/10)))*10,11));
text_handle = clabel(C,b);
title('Exhaust Temperature (C), 19.1kW (58%) Load, at 1500
rpm', 'FontSize',14);
xlabel('Oxyhydrogen (L/min)', 'FontSize',13);
ylabel('Water/Diesel Injection Rate', 'FontSize',13);
saveas(gcf , 'egt_2_contour.jpg');

figure;
set(gcf, 'Position', screen_current);
axis([0 6 0 0.5])
surf(X1,Y1,Z2); % interpolated
axis tight; hold on
% mesh(X1,Y1,base_2_BSFC);
% hold on;

```

```

plot3(x2,y2,load_2_data(:,diesel_col),'.','MarkerSize',13)
title('BSFC (g/kWh), 19.1kW (58%) Load, at 1500 rpm','FontSize',14);
xlabel('Oxyhydrogen (L/min)','FontSize',13);
ylabel('Water/Diesel Injection Rate','FontSize',13);
zlabel('BSFC (g/kWh)','FontSize',13);
saveas(gcf , 'bsfc_2_surf.jpg')

k = k+1;
screen_current = scrn_init_loc + k*scrn_offset;
% End load 2

%% Load 3: 3D graph for non-uniform data

figure;
set(gcf, 'Position', screen_current);
[C,b] = contourf(X1,Y1,Z3,linspace(floor(min(min(Z3/10)))*10,...
    ceil(max(max(Z3/10)))*10,21));
text_handle = clabel(C,b);
title('BSFC (g/kWh), 28kW (~90%) Load, at 3000 rpm','FontSize',14);
xlabel('Oxyhydrogen (L/min)','FontSize',13);
ylabel('Water/Diesel Injection Rate','FontSize',13);
saveas(gcf , 'bsfc_3_contour.jpg')

figure;
set(gcf, 'Position', screen_current);
[C,b] =
contourf(X1,Y1,Z_egt3,linspace(floor(min(min(Z_egt3/10)))*10,...
    ceil(max(max(Z_egt3/10)))*10,11));
text_handle = clabel(C,b);
title('Exhaust Temperature (C), 27kW (~90%) Load, at 3000
rpm','FontSize',14);
xlabel('Oxyhydrogen (L/min)','FontSize',13);
ylabel('Water/Diesel Injection Rate','FontSize',13);
saveas(gcf , 'egt_3_contour.jpg');

figure;
set(gcf, 'Position', screen_current);
axis([0 6 0 0.5])
surf(X1,Y1,Z3); % interpolated
axis tight; hold on
% mesh(X1,Y1,base_3_BSFC);
% hold on;
plot3(x3,y3,load_3_data(:,diesel_col),'.','MarkerSize',13)
title('BSFC (g/kWh), 28kW (~90%) Load, at 3000 rpm','FontSize',14);
xlabel('Oxyhydrogen (L/min)','FontSize',13);
ylabel('Water/Diesel Injection Rate','FontSize',13);
zlabel('BSFC (g/kWh)','FontSize',13);
saveas(gcf , 'bsfc_3_surf.jpg')

k = k+1;
screen_current = scrn_init_loc + k*scrn_offset;
% End load 3
% clc
%% Print to Command Window results
base_BSFC(1) = base_1_data(end,1);
base_BSFC(2) = base_2_data(end,1);
base_BSFC(3) = base_3_data(end,1);
lowest_BSFC(1) = min(min(Z1));
lowest_BSFC(2) = min(min(Z2));
lowest_BSFC(3) = min(min(Z3));

```

```

[r1,c1] = find(Z1 == min(min(Z1)));
[r2,c2] = find(Z2 == min(min(Z2)));
[r3,c3] = find(Z3 == min(min(Z3)));
Opt_HHO_vol(1) = X1(1,c1);
Opt_HHO_vol(2) = X1(1,c2);
Opt_HHO_vol(3) = X1(1,c3);
%LPM of HHO produced/ kg hr^-1 diesel consumed
Opt_HHO_rate = Opt_HHO_vol ./ [9 18 27];
Opt_H2O_rate(1) = Y1(r1,1);
Opt_H2O_rate(2) = Y1(r2,1);
Opt_H2O_rate(3) = Y1(r3,1);
BSFC_reduction = 100.*(1-lowest_BSFC./base_BSFC);

for i=1:3
fprintf('\n%1.0kW Load (%2.2g%%):\n',i*9,i*30)
fprintf('Base line BSFC: %5.4g g/kWh\n',base_BSFC(i))
fprintf('Optimized BSFC: %5.4g g/kWh\n', lowest_BSFC(i))
fprintf('Optimized HHO/diesel volume: %3.3g L/min\n',Opt_HHO_vol(i))
fprintf('Optimized HHO/diesel ratio: %3.3g
(L/min)/(g/Hr)\n',Opt_HHO_rate(i))
fprintf('Optimized water mist/diesel ratio: %4.3g
(g/Hr)/(g/Hr)\n',Opt_H2O_rate(i))
fprintf('Expected reduction in fuel consumption:
%3.3g%\n',BSFC_reduction(i))
end
save('main_test_data')

```


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