HYDROGEN INJECTION INTO DIESEL ENGINES FOR FUEL EFFICIENCY IMPROVEMENT

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Declarations

The content of this dissertation is the product of many hours of the authors time spent problem-solving, testing, and summarizing, unless otherwise noted.

Acknowledgements

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Abstract

The purpose of this investigation was to determine whether hydrogen injected into a diesel internal combustion engine has the potential to reduce overall fuel consumption. The most economical means of performing the required tasks was used whenever possible in an attempt to mimic a small off-grid application. The genset was a small 4kW compression ignition diesel. The electrolyzer was an off-the-shelf model designed for automotive applications. It combines hydrogen and oxygen output and is currently found from many manufacturers over the internet. It was found that the H_2/O_2 mixture actually did help conserve fuel by about 18% in a low load case but generally, savings were under 5%. At a higher proportion of generator rated load, fuel consumption was shown to increase with H_2/O_2 injection by up to 5%, thus the H_2/O_2 output must be optimized to achieve any savings. Reasons for this phenomenon are discussed and recommendations for further research are included.

Table of Contents

Table of Figures

Table of Equations

Introduction

Background

Diesel engines have a significant social, environmental, and economic impact that is readily evident to most people on Earth. Food consumed every day by many people today has been produced by the use of diesel fuel. Tractors used to work the soil and harvest crops, irrigation pumps to sustain them, and transport trucks to deliver them, primarily use diesel fuel. With a growing population, minimal options, and dwindling fossil fuel resources, diesel conservation should be a priority or malnutrition may result in many areas.

Fossil fuel combustion releases greenhouse gases and particulates which are harmful to humans and the environment. The rapid rise of CO_2 levels in the atmosphere in recent years is directly attributable to the combustion of fossil fuels[1]. There is evidence that rising CO_2 levels can lead to climate change[1]. On a local scale, particulates from engine exhaust may cause health problems.

No economy is immune to the effect of diesel fuel. Manufacturers use diesel to transport raw materials and finished products as well as to generate electricity. It may be argued that the global economy would cease to function without diesel fuel.

The main contribution of this investigation is to reduce diesel fuel consumption which could have far reaching social, environmental, and economic benefits.

Additionally, this investigation provides the opportunity to encourage development in renewable energy, specifically, integrating hydrogen generation in wind diesel grids.   Hydrogen can be the energy storage that balances the wind output and load fluctuations when coupled with either a fuel cell or diesel generator.   At the same time, hydrogen in renewable energy dominated grids can encourage the transition to hydrogen transport.

If positive results occur, it may be feasible to extend the efficiency gains into all fossil fuel, or biomass combustion equipment such as heaters, cooking equipment, gas turbines, and gasoline/petrol engines.

[1] Hunter, R

Theory

Supplemental hydrogen injection was considered for fuel efficiency improvement for this investigation on account of its beneficial combustion characteristics, ease of use, and economic production. Currently, there exists much debate over the effects of supplemental hydrogen in internal combustion engines. This was another motivator to verify and quantify any efficiency improvements as claimed by some manufacturers[2,3,4,5].

The following summary of hydrogen properties with respect to internal combustion engines (ICEs) is derived from a training module for hydrogen engine technicians prepared by the College of the Desert and presented on the Department of Energy, Energy Efficiency and Renewable Energy (EERE) website[6].

Hydrogen has increased flammability relative to other fuels, meaning that it combusts over a wider range of fuel air mixtures. The advantage to this is that the engine can run leaner (decreases fuel/air compared to ideal stoichiometric ratio). Leaner mixtures yield more complete combustion since there is both a decreased fuel volume to combust in a given time and increased surface area to complete the reaction. Another advantage to lean operation is decreased emissions resulting from lower final combustion temperatures, which helps mitigate the production of nitrogen oxides. Since more oxygen is available, unburned hydrocarbons and carbon monoxide emissions logically decrease as well.

Ignition energy is defined as the energy needed to ignite a fuel. Hydrogen has an ignition energy value an order of magnitude less than that of gasoline. This is another factor that allows leaner mixtures. However, it also means that hydrogen may ignite from "hot spots" on cylinders, resulting in precombustion, potentially causing engine damage.

Hydrogen flames travel closer to the cylinder walls. The College of the Desert report calls this property decreased quenching distance, meaning it is more difficult to quench a hydrogen flame. One issue to manage as a result of this is engine backfiring on account of a partially closed valve.

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2 www.savefuel.ca
3 www.hybridwaterpower.com
4 http://alternativegassolutions.com
5 www.watertogas.com
6 www.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf

Hydrogen has a higher autoignition temperature. This feature is defined as the temperature at which the fuel/air mixture is ignited. It limits the compression ratio since the mixture heats up during compression. The compression ratio $\left(\frac{V_1}{V_2}\right)$ is related to autoignition temperature (T_2) by the following equation:

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

Equation 1: *Temperature compression ratio relation*

T_1 is defined as the absolute initial temperature

γ is the ratio of the specific heats

From this equation it can be seen that higher autoignition temperature allows higher compression ratios. According to the formula for theoretical thermal efficiency, efficiency increases with compression ratio for both the Otto (petrol) and the Diesel Cycles. For the Diesel cycle, the term V_3/V_2 represents the volume ratio for the stage of constant pressure heat addition at the beginning of the power stroke.

$$\eta_{th} = 1 - \frac{1}{\left(\frac{V_1}{V_2}\right)^{\gamma-1}}$$

Equation 2: *Thermal efficiency for Otto Cycle*

$$\eta_{th} = 1 - \frac{1}{\left(\frac{V_1}{V_2}\right)^{\gamma-1}}\left[\frac{\left(\frac{V_3}{V_2}\right)^{\gamma} - 1}{\gamma\left(\frac{V_3}{V_2} - 1\right)}\right]$$

Equation 3: *Thermal Efficiency for Diesel Cycle*[7]

The ratio of specific heats γ for hydrogen is 1.4 and 1.1 for gasoline, indicating that thermal efficiency should be higher using hydrogen fuel instead of gasoline. This is due to the simpler structure of the hydrogen molecule, which makes the combustion reaction more

[7] Moran, MJ, Shapiro, HN

efficient. One drawback to the higher autoignition temperature is that hydrogen is more difficult to ignite in compression ignition engines because higher temperatures are required.

The flame speed of hydrogen at stoichiometric ratios is almost ten times that of gasoline. This allows a closer match to the theoretical thermal efficiency since there are decreased losses to the surroundings.

The diffusivity, or the ability of hydrogen to disperse in air is higher than other fuels. This facilitates formation of a uniform fuel air mixture to give more surface area for the combustion reaction to occur and more even expansion. Furthermore, hydrogen disperses rapidly in the event of a leak, decreasing danger to users.

Another design issue with hydrogen use is its low density, meaning a large volume is required for a competitive range compared to other fuels. The energy density of the fuel air mixture is lower as well since the cylinder volume is restricted.

In addition, the oxygen produced by the electrolyzer and sent to the air intake of the engine may increase fuel efficiency as well. Using pure oxygen instead of air increases the actual combustion products, while reducing the amount of nitrogen in the combustion chamber. Increased nitrogen has a detrimental effect on fuel efficiency and emissions, so is not desired in the combustion intake. Oxygen enriched fuel mixtures tend to burn hotter and faster than standard air mixtures[8], enhancing the effects of hydrogen. It has been noted that industrial process (steel, aluminum, glass manufacture) fuel efficiency improvements can amount to 30-60%[8] by retrofitting air/fuel to oxygen/fuel combustion. The addition of significant quantities of oxygen to the combustion chamber can dramatically increase temperatures. Using small quantities oxygen as a supplement avoids this issue, while potentially yielding some benefits.

Supplemental hydrogen seeks to utilize the advantages of the fuel while minimizing the drawbacks. Due to the increased flammability, ignition energy, flame speed, and diffusivity of hydrogen, it may be possible to decrease overall fuel consumption when used in a gasoline or diesel engine since leaner mixtures can be used and the cycle experiences fewer losses. At the same time, few engine modifications are required, and only water and excess alternator electricity is needed to provide the hydrogen, resulting in a relatively low cost fuel. Factors such

[8] Baukal, Charles E

as higher ignition temperature cannot be fully utilized to increase fuel efficiency since extensive engine modifications would be required to change the compression ratio.

Equipment Description

The main equipment used in this investigation was the diesel fuelled electrical generator and the electrolytic cell. The electrolytic cell separates hydrogen from oxygen in the water molecule. This mixture of hydrogen and oxygen is then sent to the air intake of the diesel generator.

Diesel Generator

The diesel generator was an Amico model AH4000LE, rated power 4000W. A summary of the main technical specifications are shown in the following table.

Rated Frequency	60 Hz
Revolution speed	3600 rpm
Type	Single cylinder, vertical, air-cooled
Bore x stroke (mm)	78 x 64
Displacement	305 cc

Table 1: *Generator Technical Specifications*

The modifications made to the generator to facilitate the test included removal of the fuel tank (for weight measurement), and removal of protective coverings for fuel line routing. A fuel tank cradle was constructed to position the fuel tank close to the engine while enabling the weight of the fuel to be measured. At the same time, this set up mitigated temperature and vibration interference.

Hydrogen/oxygen Electrolytic cell (Hydrogen Generator)

The hydrogen generator was a commercially available unit sold through www.savefuel.ca. Its rated output is .33 L/min at 7-8 Amps current draw, rated for use in 2L, 4 cylinder gasoline engines. The apparatus is equipped with a flashback arrestor between the electrolytic cell and the output (air intake) to prevent ignition sources reaching the cell. The flashback arrestor is simply a container which forces the gas to bubble up through water before exiting to be used in an engine. The actual hydrogen generator consists of two stainless steel threaded electrodes, on which are connected thin plates separated by approximately 0.25 in. The unit is shown pictorially in Figure 1.

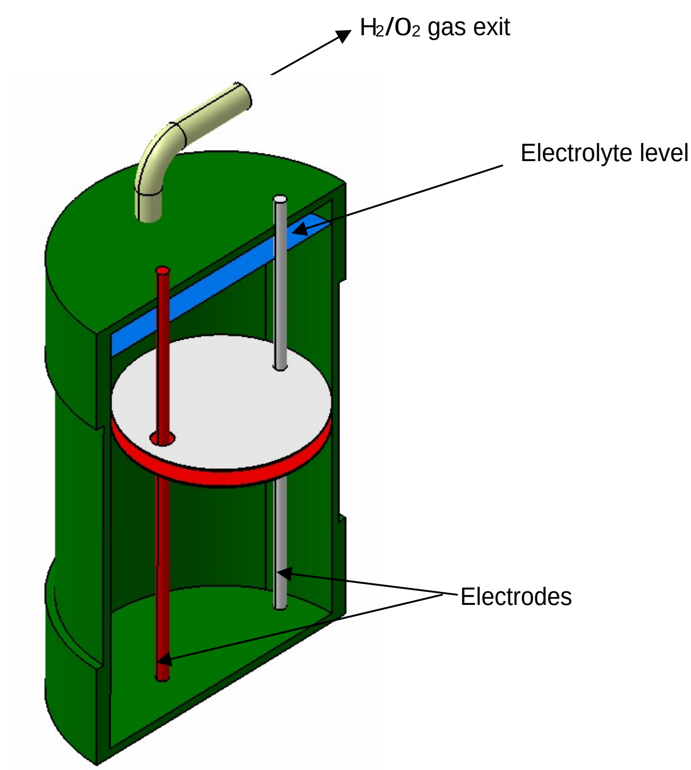

Figure 1: H_2/O_2 generator section cut

This electrolysis method of hydrogen/oxygen production was chosen primarily for its low cost and simple operation, but it is also safer than other forms of hydrogen supply. The H_2/O_2 generator does not store any flammable gas. All gas is sent directly to the air intake of the engine. Purchasing hydrogen in cylinders was an option as well, however, due to safety concerns and handling equipment required, it was not considered. Commercial laboratory quality electrolyzers proved cost prohibitive[9]. Furthermore, this style H_2/O_2 generator is ubiquitous in any search for fuel efficiency improvement products.

The gas is produced at atmospheric pressure and is drawn in by the vaccum in the air intake of the engine. This installation method is suggested by the manufacturer for automobile applications.

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[9] www.hgenerators.com

Power Supply

A power supply was needed to convert the household AC to DC for use by the electrolyzer. The power supply used for the electrolyzer in this experiment was a HYelec HY3020E. The current could be controlled from 0-10A, voltage 0-30V. However, the current and voltage were limited by the internal resistance of the electrolyzer.

Measuring Instruments

The equipment used to take measurements such as weight, time, and current were standard hardware store devices such that the experiment could be most economical.

Loads

The loads used in this experiment are standard forced air convection heaters each with a high and low setting. In addition, an array of lights was constructed for smaller load increments.

Primary Experimental Procedure

The following procedure was used to determine the fuel consumption of the diesel generator with and without the H_2/O_2 injection. It was alternated 10 minutes at a time under the same load and atmospheric conditions to mitigate variations with temperature and provide quicker comparisons.

Purpose

The purpose of this investigation was to determine fuel consumption for the diesel electrical generator at a variety of loads.

Equipment

Timer/Stopwatch	Diesel fuel	Diesel generator	Load measurement (ammeter)
Dump loads (heaters)	Scale	Diesel generator	Container (for fuel)
Fire extinguisher	Thermometer	DC power supply	

Set up

Figure 2: Generator/weight measurement set up

1. Load measurement device connected to genset and load
2. DC power supply connected to electrodes on electrolyzer
3. Scale placed on platform
4. Fuel container filled to safe level
5. Fuel container placed on scale

Procedure

1. Generator started per manufacturer's instructions. Load connected only after exhaust gas temperature leveled off (approximately five minutes).
2. Fuel and tank weight measured together (enter Weight before)
3. Power supply turned on for proper measurement of fuel consumption with H_2/O_2 injection, lit LED indicating proper operation.
4. Connected load 1 and run 2 minutes (if measuring no load fuel consumption omit this step)

5. Zeroed scale to measure fuel consumed in approximately 10 minute span by weighing fuel and tank together (enter Weight after)
6. Connected load 2 and repeated step 3
7. Readings taken as required to fill in the following table
8. Checked exhaust gas temperature over range of loads to determine abnormal operation

Load 1 (A)	Load 2 (A)	Time elapsed (min:s)	Weight before (g)	Weight after (g)

Analysis

From the values in the above table the specific fuel consumption (sfc) was calculated in g/kW$_e$. These values were used as fuel consumption for this generator.

Sources of Error

Current measurement ±0.1A (multiplied by two for two loads connected load > 13.5A)

Weight ±1g

Time ±1s

Human factors

Calculated nominal sources of error (example assuming 10 minute elapsed time):

$$\%Error_{sfc} = \frac{\left(\dfrac{Measured\ weight + 1g}{\{Measured\ current - .1A\} \times 120V \times \{Measured\ time - 1s\}\left(\dfrac{3600s}{hr}\right)} \right) - Nominal\ calculated}{Nominal\ calculated} \times 100\%$$

Equation 3: *Percent error for measurements*

A sample of test values was taken and the percent error resulting from the equipment ranged between and 1.60%-2.22%. Human factors are more difficult to quantify but include the manual timing and weight measurement, rather than an automatic control system.

Early Findings

The engine/generator was found to react slowly and inconsistently with variability of the load. Thus, in the interest of reasonable results with the economical use of fuel, a secondary procedure was developed whereby the load remained constant and the H_2/O_2 input varied.

Secondary Experimental Procedure

It was determined from the early findings that an optimized amount of gas would be useful to find for a variety of loads.

Purpose

To determine the optimum amount of H_2/O_2 gas to use for a variety of loads

Equipment

Same as Primary Experimental Procedure

Set up

Same as Primary Experimental Procedure

Procedure

1. Generator started per manufacturer's instructions. Load connected only after exhaust gas temperature leveled off (or five minutes).
2. Fuel and tank weight measured together (entered Weight before).
3. Connected load 1 and run 2 minutes (if measuring no load fuel consumption this step omitted).
4. Power supply (10W) turned on for measurement of fuel consumption with H_2/O_2 injection Lit LED checked to ensure operation.
5. Zeroed scale to measure fuel consumed in approximately 10 minute span by weighing fuel and tank together (entered Weight after).
6. Recorded readings as required to fill in the following table).
7. Increased DC power by 10W.

8. Repeated step 3-8 up to 50W DC power (omitted 4).
9. Connected load 2 and repeated step 3.
10. Checked exhaust gas temperature over range of loads to determine abnormal operation.

Power to Electrolyzer (W)	Load 1 (A)	Load 2 (A)	Time elapsed (Min:s)	Weight before (g)	Weight after (g)

Analysis

From the values in the above table the specific fuel consumption (sfc) trends were determined for a set electrolyzer power to find the optimum H_2/O_2 gas for the load supplied by the genset.

Results

Early results were plagued by inaccuracies brought upon by equipment and human factors. Wherever economically viable, the instruments were upgraded to reduce these errors. This included a new scale which did not shut off automatically, thereby reducing the human impact on the results since it no longer was necessary to remove and replace the fuel tank on the scale. Also, the ammeter was replaced as it became inoperative during test. The test setup was altered since it was found that even small increases in the scale temperature produced very large distortions in the weight measurements. Where results formed a repeatable pattern, they are presented in this report. In some cases, the results were inconclusive, even erratic. The reason for this may be due to the operation of the engine during the initial 20 hour break-in period. During this period, engine components, and to a lesser extent, electrical generator equipment wears to standard operational level. For example, bearings and cylinder walls become smoother as imperfections in material and/or manufacturing are evened out with friction between parts.

The final results presented are from the testing of the genset which occurred after the 20 hour break in period. They are used since they are generally more conservative and the temperature interference has been eliminated.

Data are presented in percent fuel savings versus electrolyzer power to determine the optimal electrolyzer input for maximum gain. The percent fuel savings is calculated relative to the baseline (no H_2/O_2 injection) case using SFC. In equation form as follows:

$$\%\ fuel\ savings = \frac{SFC_{Baseline} - SFC_{H_2/O_2\ Injection}}{SFC_{Baseline}} \times 100\%$$

Equation 4: *Calculation of percent fuel savings*

Another interesting concept to determine was the "Process Efficiency". The process efficiency for the purposes of this investigation is defined as the ratio of the energy input to the electrolyzer to the energy offset by H_2/O_2 injection. It was assumed that the energy content of the diesel fuel was 38.6 MJ/L and the density was 846 g/L[10] . The energy flows were related by the following equations:

$$E_{saved} = \left(SFC_{Baseline} - SFC_{H_2/O_2\ Injection}\right) P_{AC} \Delta t \left[38.6 \frac{MJ}{L}\right] \left\{\frac{L}{846g}\right\} \left(\frac{1000Wh}{3.6MJ}\right)$$

$$E_{used} = P_{DC} \Delta t$$

$$\text{Process efficiency} = \frac{E_{saved}}{E_{used}}$$

Equation 5: *Process Efficiency calculations*

In fact, the Process Efficiency plot for a 20A load case showed a profound reduction in fuel consumption compared to the energy input to the electrolyzer as shown in Figure 3. This led to an investigation to determine the source of the interference. The value of almost 700% process efficiency was deemed over expected limits. It was found that a 20-25°C increase in the scale temperature resulted in an error of more than 40% in the weight measured. This was found by measuring baseline fuel consumption at the beginning and the end of the test. These values are shown in Table 2.

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[10] PEC522 Notes-Energy 2000 – National Energy Policy Paper. DPIE, 1988

DC Power W	% fuel savings	Process efficiency (%)
0 (beginning)	0	0
0 (end)	44.28	Undefined
9.72	43.69	694.64
20.24	42.01	320.76
30	46.63	240.78
40.15	41.00	158.20
49.61	34.34	107.24

Table 2: *Values derived from 20 Amp load test (includes temperature interference)*

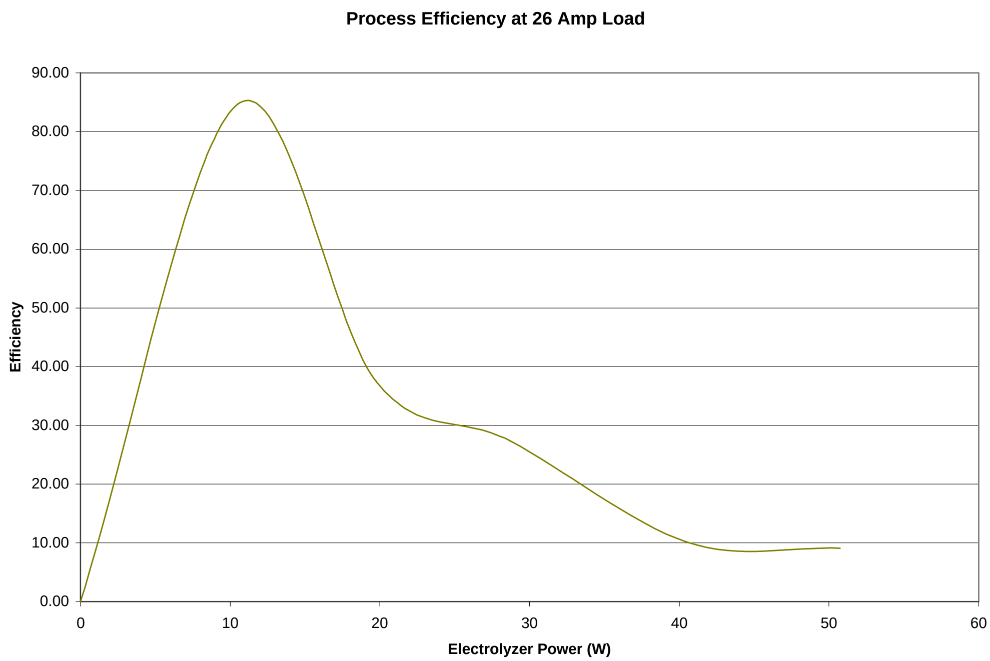

Figure 3: Process Efficiency at 20 Amp Load with Temperature interference

Optimization Phase

During the optimization phase, it was noted that generally the H_2/O_2 injection had a positive effect on fuel efficiency at low loads while gradually decreasing to a negative effect at high loads. Unfortunately, load cases were limited to 10A, 14A, 20A, 23A, due to the limited dump loads and time restrictions. In all, five hours out of a total 35 hours of test data was deemed valid, after discounting temperature interference, instrument failures, and process modifications. At the 35 hour point the engine began operating too erratically and often failing to operate at all such that no valid data could be derived from it. Unfortunately there was insufficient time for troubleshooting and repair, so testing was halted.

10 Ampere Load

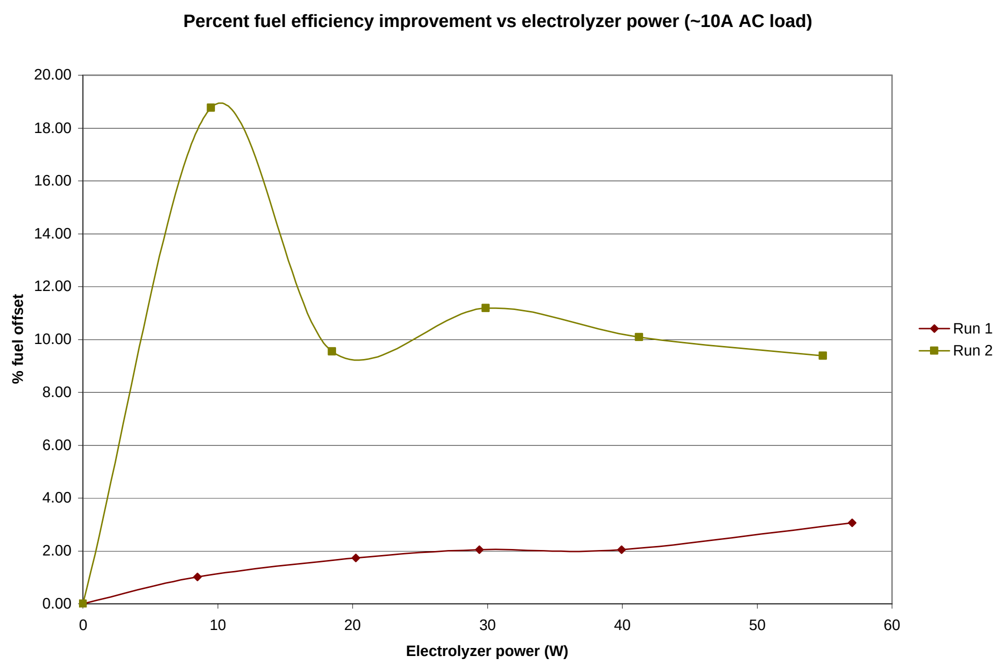

Figure 4: 10 Amp Load - Optimization

As seen from Figure 4 (Run 2), the point where the fuel is offset most significantly is at approximately 10 WDC. At that point 18.79% of the diesel fuel is offset by the addition of supplemental H_2/O_2. It is also important to note the large variability from Run 1 to Run 2. Since runs were performed on different days, atmospheric conditions may have produced this discrepancy. Run 1 and 2 both showed positive results. Higher air fuel ratios mean that the combustion temperatures are lower (shown by decreased exhaust gas temperature of around 100°C from high to low load), as a result, the combustion may not be complete. This fact is evidenced by the greater specific fuel consumption of the engine under low load conditions. The baseline SFC is presented for reference in Figure 12. The increased efficiency may be because the H_2/O_2 increased the flame speed and decreased the ignition temperature of the mixture for more complete combustion.

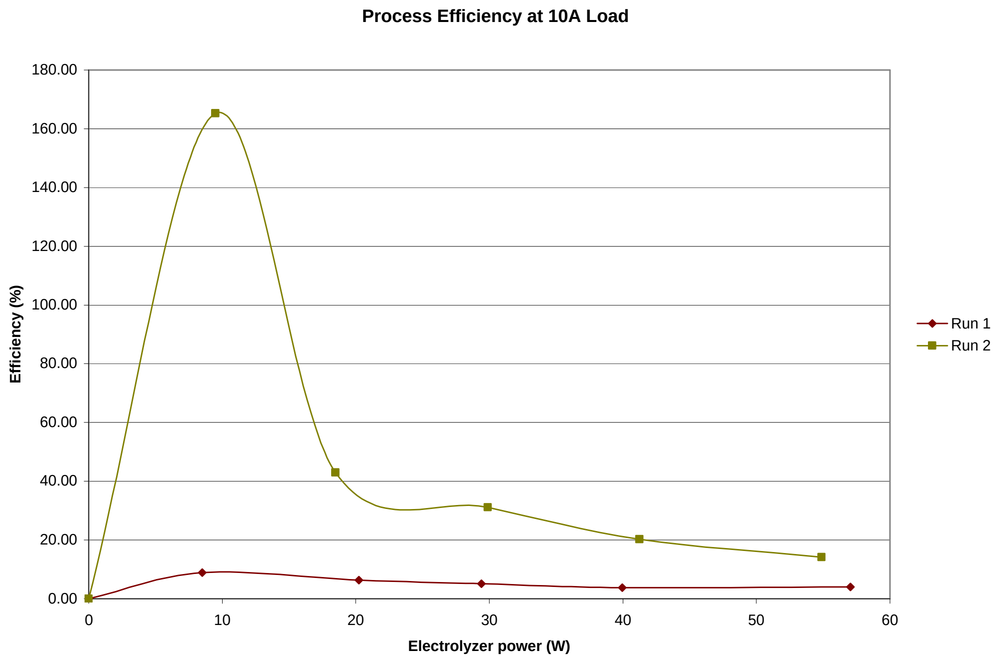

Figure 5: Process Efficiency at 10A Load

From Figure 5 it can be seen that the optimal process efficiency peaks above 100%. This is an important design consideration since at those conditions, it actually increased overall efficiency to have a diesel genset running an electrolyzer to inject H_2/O_2 back into the engine. At values less than 100%, yet still greater than 0%, it may only be logical to use an electrolyzer as a dump load. The leveling out of the efficiency curve shows that added H_2/O_2 still provided some benefit, but with diminishing returns on input energy.

14 Ampere Load

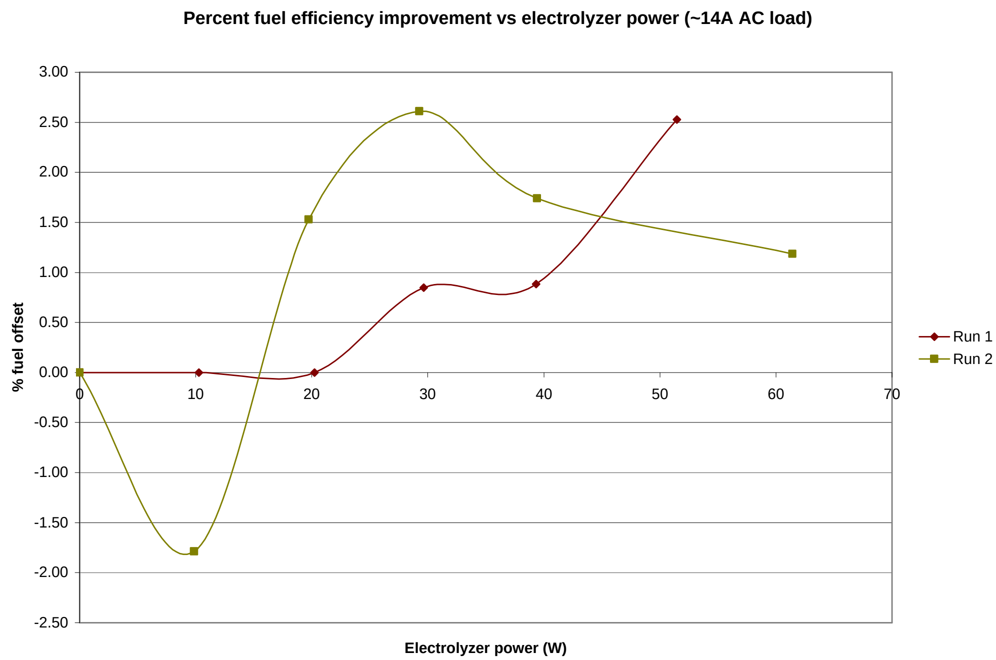

Figure 6: 14 Amp load – Optimization

It can be seen from Figure 6 that the values were very close to the range of sources of error (1.60-2.22%), but there are some interesting points. The peak efficiency occurs when the electrolyzer is set to 30 W DC. This may be as a result of the greater amount of fuel that wasinvolved in the combustion reaction, making it more complex and slower. Thus more H_2/O_2 was needed to provide any benefit such as increasing flame speed. One important trend, when compared to Figure 4, to note is that the relationship between fuel consumption and optimal H_2/O_2 injection is not linear. That is, for an increase in fuel consumption of 13% the optimal electrolyzer power required increases 300% or more. It could be that the actual optimum requires increasing electrolyzer power even further as shown by the upward trend of Run 1.

The process efficiency curve (Figure 7), as expected, complements Figure 6, but it is important to note that the curve never rises over 8%. As a result, with the equipment in this investigation, the electrolyzer would only be operated as a dump load. However, if low H_2/O_2 inputs were avoided, efficiency improvements are possible.

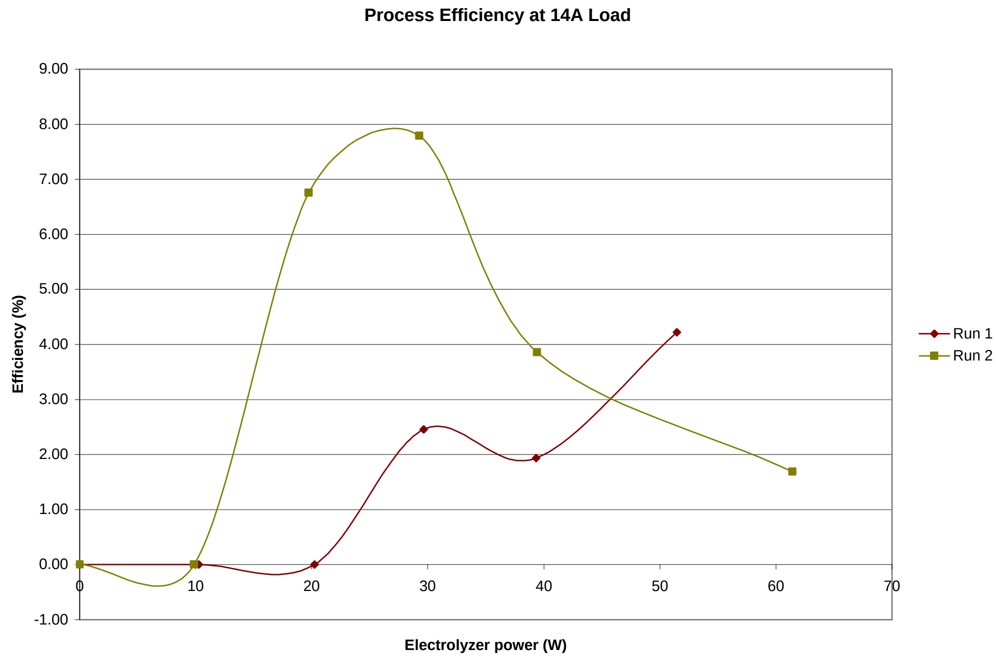

Figure 7: Process Efficiency at 14A Load

20 Ampere Load

The following plot at the 20 A load condition shows general efficiency improvements over the baseline case but shows some indication that the optimum H_2/O_2 output may be beyond the capability of the power supply circuit. The reason for this suspicion is the non linear relationship between H_2/O_2 output and fuel consumption as shown in the 14 A load case and the pattern of both 10 A and 14 A load case, stable efficiency except for the relatively pronounced optimum point, which is missing in Figure 8.

The optimum process efficiency plot from Figure 9 emphasizes the steady results shown in Figure 8. Since the same efficiency (within 1.5%) improvement was found over the range of electrolyzer power tested the maximum process efficiency occurs at the lowest input power (10 W).

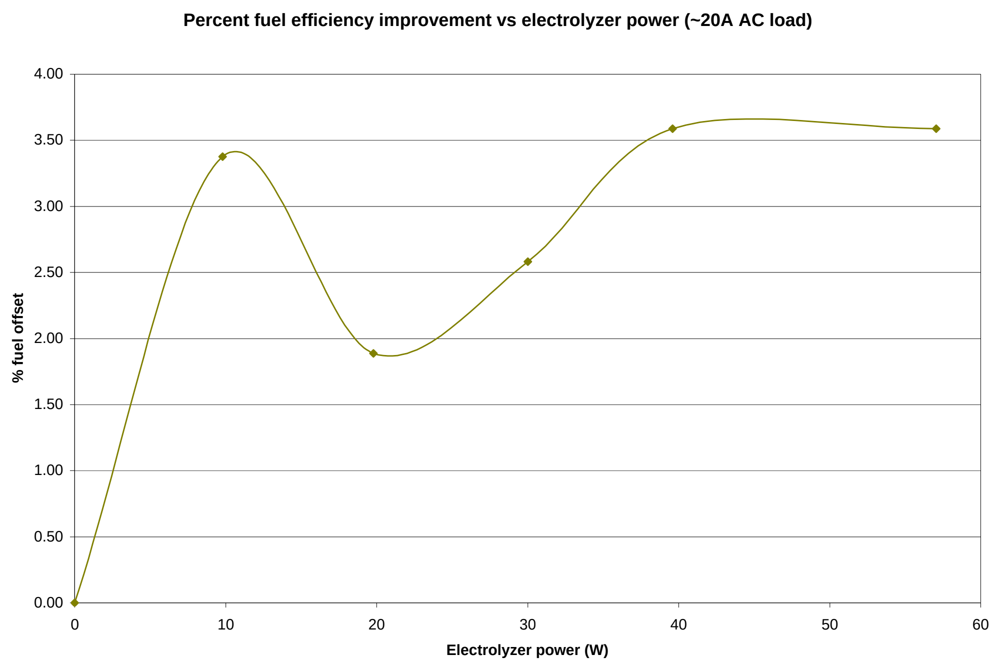

Figure 8: 20 Amp load – Optimization

Figure 9: Process Efficiency at 20 A Load

23 Ampere Load

The largest load tested (23 A) proved to be the breaking point in efficiency improvements. It was noted that efficiency improvements were not realized. While the decreases in efficiency noted were not large, it is important to avoid operating a system in this mode for extended periods. However, it can also be noted that the curve begins an upward trend at higher electrolyzer power that might reveal a positive optimum point with a higher DC power supply capacity. If time allowed, it would be interesting to explore this by modifying the circuit to increase amperage to the electrolyzer. It was decided not to present the process efficiency plot as it was entirely negative.

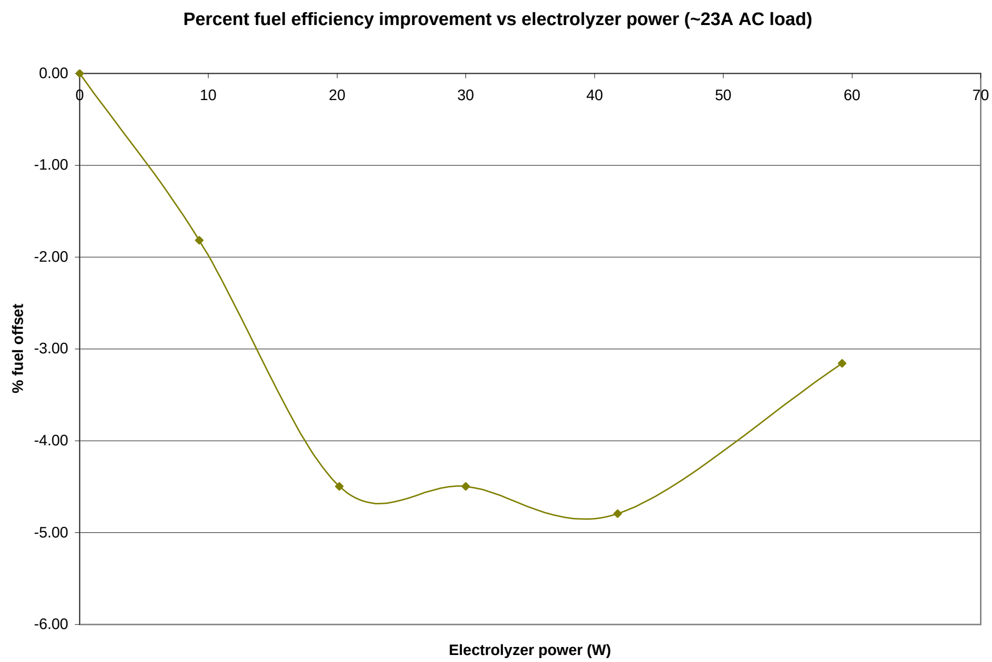

Figure 10: 23 Amp load – Optimization

It was originally thought that the reason for the rise in fuel consumption was due to the decreased air fuel ratio at high loads. The air fuel ratio is defined as the proportion of the mass of air to the mass of fuel used in the combustion reaction. As the amount of fuel injected into the cylinder is increased, it requires a greater amount of air for complete combustion. Since hydrogen is much less dense than air, it may have displaced the combustion air thus leaning the air/fuel mixture. The H_2/O_2 gas may have recombined to form water and was thus not used for combustion of the fuel. More fuel would be automatically injected to compensate for the lean mixture while still meeting the load. For a diesel engine, the air/fuel ratio is variable with loading, atmospheric conditions, and engine design. The following assumptions were made to approximate the air fuel ratio for the Amico diesel engine used in this experiment.

- Each intake stroke is restricted to the rated displacement of the engine (305 cc)
- Constant speed of 3600 rpm (from manufacturer's specifications)
- Density of air 1.225 kg/m^3 (standard Temperature and pressure at sea level)

$$\frac{305cm^3}{4rev}\left(3600\frac{rev}{\min}\right)\left[\frac{1m^3}{1x10^6\,cm^3}\right]\left\{1.225\frac{kg}{m^3}\right\}\left[\frac{1000g}{1kg}\right]=336.26\frac{g}{\min}$$

Equation 6: *Air usage of Amico engine*

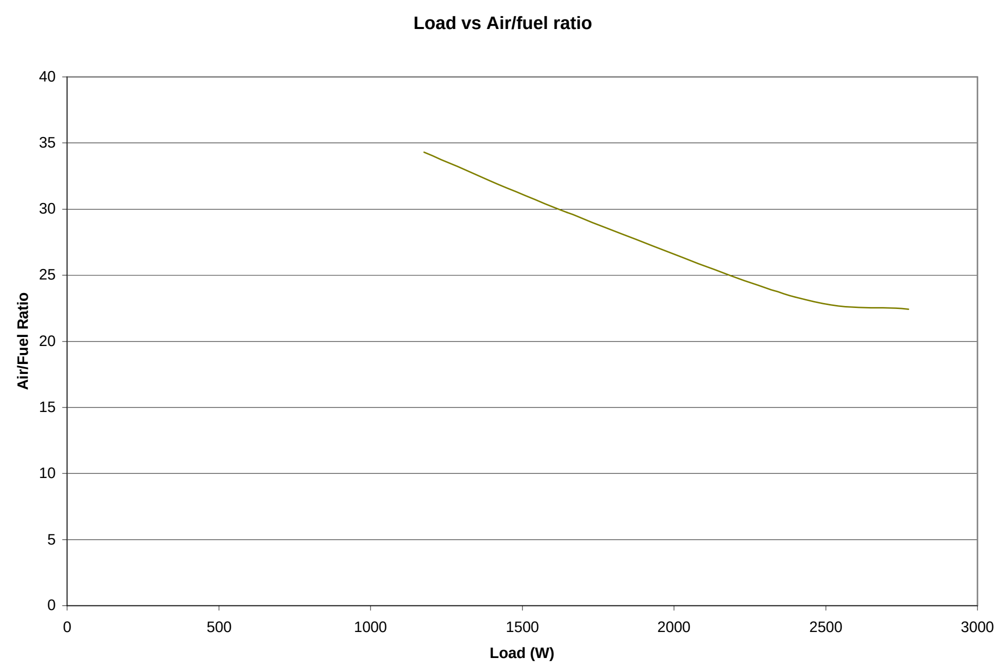

Figure 11: Approximation of air fuel ratio for Amico engine

It can be seen from Figure 11 that air fuel ratio increased with load from approximately 34:1 at 10 A load to 22:1 at 23 A load. The volume of air displaced by H_2/O_2 was calculated using the following procedure:

The power supply was set to maximum (9.4A, 5.7V) and connected to the electrolyzer for 2.534 hours. The weight of water converted to H_2/O_2 gas was 13 grams. The volume of hydrogen was calculated using the following method:

Known:

$$\rho_{Hydrogen}=0.090\ g/L$$

$$\rho_{Oxygen}=1.429\ g/L$$

$$2H_2O \rightarrow 2H_2 + O_2$$

Equation 7: *Electrolysis reagents*

2 mole H_2O =36 g

2 mole H_2=4 g=MM_{H2}

1 mole O_2=32g=MM_{O2}

Assumed gases exist as diatomic molecules

$$\dot{m}_{H_2} = \left(\dot{m}_{H_2O}\right)\left[\frac{MM_{H_2}}{MM_{O_2}}\right]$$

$$\dot{m}_{H_2O} = \frac{13g}{2.534hr} = 5.13\frac{g}{hr}$$

$$\dot{m}_{H_2} = 0.641\frac{g}{hr}$$

$$\dot{m}_{O_2} = 5.130 - 0.641 = 4.489\frac{g}{hr}$$

$$\dot{v}_{H_2} = \frac{\dot{m}_{H_2}}{\rho_{H_2}} = 7.134\frac{L}{hr}$$

$$\dot{v}_{O_2} = 3.141\frac{L}{hr}$$

Equation 8: *Calculation of volumetric flows of electrolyzer*

This indicates that the H_2/O_2 was displacing 10.275 L/hr of combustion air. Since the engine consumes about 275 L/min of combustion air, it can be assumed that the supplemental H_2/O_2 has a negligible effect due to volume displacement. There are no external signs of precombustion at the higher loads, but exhaust gas temperatures are certainly higher (160°C at idle, 300°C at high loads) so that may contribute somewhat to the decreased efficiency. Precombustion may occur when the H_2/O_2 mixture experiences a sufficient temperature increase to combust. Since the mixture has a low autoignition temperature, it may burn when injected to a hotter cylinder before the fuel is even injected. As a result of the uncertainty surrounding the operation at high loads with H_2/O_2 injection, more research is needed.

Discussion

Significance of Results

Any neutral party results from testing these H_2/O_2 generators are significant since there is very little verified evidence available. In fact, during the course of this experiment a single report was found originating from a third party[15], unfortunately only the abstract was available. The bulk of information available remains on manufacturers' or "tinkerers'" websites and can be discounted as claims and lacking detail for proper system integration (eg. process efficiency). Despite the challenges of working with a small engine to produce reliable results, there was some evidence derived from this experiment to support the use of supplemental H_2/O_2 injection to reduce fuel consumption in some cases. For comparison, Umpqua Energy, an Oregon company uses the same principle for its H_2/O_2 generators, stating expected fuel savings to be in the 3-12% in transport applications[11]. Canadian Hydrogen Eenergy Company guarantees a 10% savings[12]. Assuming a 10% increase in fuel economy for diesel applications, the resulting fuel savings would amount to 451800 barrels of diesel fuel per day in the United States alone (based on EIA consumption estimates for diesel fuel)[13]. Also, the technology has the potential to decrease emissions based on Umpqua Energy claims as shown in Table 3:

Emission	Percent Reduction
NO_x	Up to 60
Carbon Monoxide	Up to 100
Hydrocarbons	Up to 100
Particulates	Up to 95

[11] www.umpquaenergy.com
[12] www.chechfi.ca
[13] http://tonto.eia.doe.gov/dnav/pet/pet_sum_sndw_dcns_nws_w.htm (Energy Information Administration)

Opacity (Smoke)	Up to 70

Table 3: *Claimed emission reductions with H_2/O_2 injection*[11]

Thus the addition of H_2/O_2 gas has the potential to provide additional benefits even if efficiency gains are marginal. The significance of this is that it eliminates a potential drawback of H_2/O_2 injection such that the device may be used in additional applications for its additional benefits rather than simply where commercially logical.

Another significant finding was the pronounced improvement in diesel efficiency at low load factors with H_2/O_2 injection. Load factor is the proportion of the rated load of the generator (4kW) in this case. Increasing fuel economy in the low load regime makes the technology more applicable in wind diesel grids. For example, the Denham wind diesel grid[14] incorporated low load diesels to support the grid frequency while wind energy is high since it is too variable to provide the expected power quality. At the same time, the diesel generator is able to follow the load. If operated at low load in an efficient manner, a larger proportion of electricity is available for spinning reserve without bringing an additional generator online. The low load diesels were specially designed such that maintenance problems arising from operation at low load were mitigated, with added cost. In theory, with supplemental H_2/O_2 injection the improved combustion characteristics and increased efficiency may make it possible to use a standard diesel to accomplish the same task. The following plot derived from the results of this experiment show the potential effectiveness of H_2/O_2 injection at lower loads, it can be noted by the expanding gap between the baseline and H_2/O_2 injected SFC values below 30% rated capacity.

[14] PEC520: Case Studies of Renewable Energy Systems notes or http://www.verveenergy.com.au/mainContent/sustainableEnergy/OurPortfolio/Denham_Wind_Farm.html

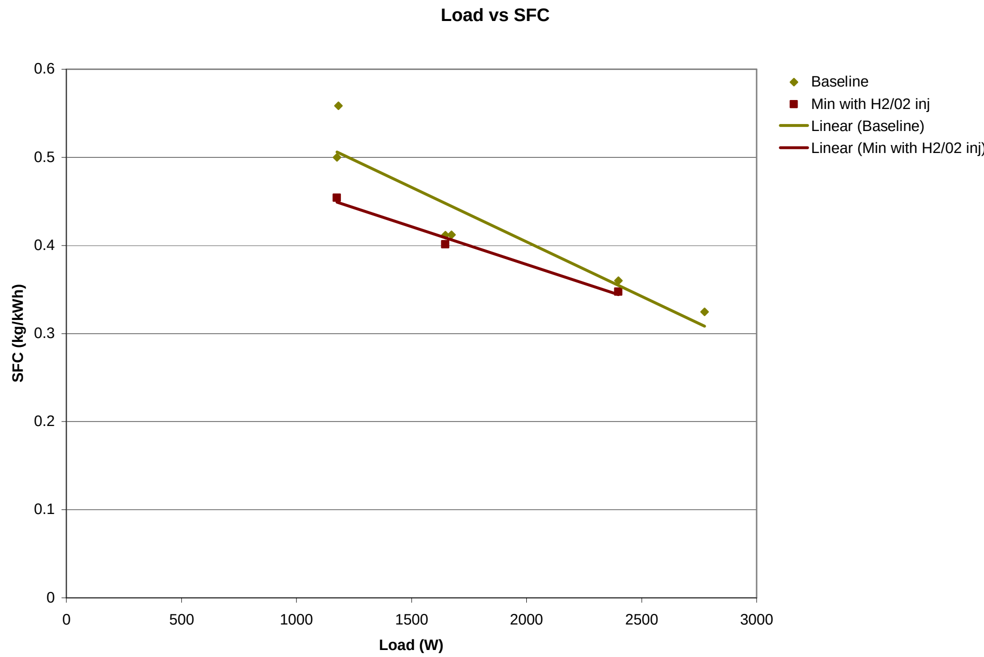

Figure 12: Comparison of Baseline and Minimum H_2/O_2 injected SFC

An additional factor in the adoption of supplemental H_2/O_2, as in the Denham case, could be the elimination of dump loads such as boilers while maintaining the wind penetration level. The boiler could be replaced by an electrolyzer so that during periods of high winds, hydrogen fuel is created from the excess energy. Although, additional cost and safety issues arise when hydrogen and oxygen are separated and stored. There would exist the opportunity to use the hydrogen for transport, as in fuel cells, or other uses where economically viable. According to Levene, J. Kroposki, B. Sverdrup, G, hydrogen produced by wind energy can be cost competitive with petroleum fuel. Hydrogen produced at point of use is currently estimated to be $5.55US/kg (2006 figures) in the short term and $2.27US/kg in the long term. One kilogram of hydrogen is about equivalent in energy to 1 gallon of gasoline (currently $3.29US/gal in the Seattle area).

The advantages of supplemental hydrogen injection could be extended to small SAPS (Stand Alone Power Supplies) incorporating wind turbines and diesel generators. The components of the supplemental H_2/O_2 electrolyzer are inexpensive and simple enough that one can be custom made for any application. The electrolyzer uses DC, traditionally output from wind turbines directly, thus avoiding power losses and cost of additional power conditioning equipment. The opportunity to increase wind penetration in wind diesel with H_2/O_2 injection shows some promise, but further investigation is required.

Limitations

Unfortunately, very little published data exists to support or refute the findings from this investigation. One such report supporting the findings in this experiment, a PhD thesis from the University of Tasmania, did find that:

> "The research particularly established that vitiation and enrichment effectiveness was only realised at low rather than high loads indicating that hydrogen achieved more than diesel mass substitutions"[15]

This statement does support the evidence found in this investigation; however, this was using an indirect injection engine with pure hydrogen, and quantitative results were unavailable. As a result of the limited amount of complementary data, the scope is limited to this engine and H_2/O_2 electrolyzer under the prevailing conditions in the location tested. There are claims of 10% fuel efficiency[11,12] increases with the same technology in comparable situations. Further research is required to verify the effects of H_2/O_2 injection in a variety of conditions for other sizes and types of internal combustion engines for the technology to become more widely adopted. As noted in the results, the technology may end up being limited to transport or other (eg. off-grid) applications where the electricity used for the electrolyzer would otherwise be wasted.

Achievements

Despite the many frustrations experienced over the course of this experiment, overall, it was beneficial. Many previous assumptions were displaced with first hand knowledge. For example, originally exhaust gas temperatures were assumed to be relatively constant, and higher. It was found that the temperature varied by 140°C. Through problem solving and testing, hands-on knowledge of electrical generating equipment, test instrumentation, process improvement and diesel engines was gained. Through theoretical research, more was learned about the diesel cycle, particularly in comparison to the Otto cycle. In addition, some positive

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[15] Hafez, HA

fuel efficiency improvements were found under certain load conditions. Particularly, the results here were found to merit investigation for the potential application in wind diesel grids. Another important achievement of this experiment is in expanding the body of knowledge on the subject of H_2/O_2 supplementation. In sum, many of the learning objectives of the experiment were achieved even though hydrogen injection may not be the panacea for fuel efficiency under all conditions.

Conclusion

The injection of H_2/O_2 gases into the diesel in this investigation did show some promise of fuel efficiency improvement. It was found that savings of over 18% were possible with this technology, at low load conditions, in the situation tested. However, as the load increased, the savings were reduced, and gradually, the fuel consumption actually increased with H_2/O_2 injection. Consequently, the system incorporating H_2/O_2 must be carefully designed to discontinue injection before it causes detrimental effects. The technology does have a potential application in wind diesel grids such as Denham or small SAPS to decrease fuel consumption and increase wind penetration with integrated system control. It could readily be adapted to transport applications if the vehicle tends to be lightly loaded. Fuel efficiency improvement is an important issue since fossil fuels are a non-renewable resource. Additionally, using water to offset fossil fuels promotes energy independence, since it is a compound that can be found anywhere there are humans. The amount of water used would not risk any supply as it is extremely low consumption.

While this experiment did not test emissions from the engine, Hafez, HA[15] states:

> "Contrary to the common belief, green house gases, nitrogen oxides, hydrocarbons and opacity substances do not coincidently all increase and/or decrease. Indeed, this experiment demonstrated that although the diesel-hydrogen nitrogen monoxide (NO) wet-emissions at all injection rates were partially lower than the diesel baseline, carbon oxides, hydrocarbon emissions, opacity (N) and absorption coefficients (k) were higher. In other words, a measure taken to limit the harm done to human health can increase the damage to the environment and vice versa."

Thus, emissions control is not a significant advantage to H_2/O_2 injection.

In remote, developing areas, where diesel fuel is used for many applications such as backup electrical power, water pumping for irrigation and drinking, and transportation, fuel savings could result in a higher quality of life as greater financial resources are made available for education and healthcare.

The experiment succeeded in enhancing the field of knowledge in general, and for the author. In addition, it was shown that H_2/O_2 injection into diesel engines can provide fuel savings, but more research is necessary to broader the application of this technology.

Opportunities

There are many opportunities for further research in the field of H_2/O_2 injection and fuel efficiency improvement. First of all, an expansion of the scope into other internal combustion engines would be extremely useful. Unfortunately, the experiment was limited to loads above 25% of the rated capacity of the genset, yet the Denham wind diesel grid operated the gensets down to 7%. Any following research should include the load regime between 0-25% of rated load.

It would be interesting to determine the effects of hydrogen and oxygen injected separately, as there is some evidence that either may have its benefits.

While more complicated, injecting pressurized hydrogen at the same time as the fuel, may have the potential for increased fuel savings over a broader load range. Pressurized oxygen is not recommended to be injected into an internal combustion engine since excess heat resulting in engine damage is probable.

Lessons Learned

It is possible that the most valuable portion of this experiment is the provision of lessons learned as well as some encouragement to carry on with further experiments in this field. These are presented to save the researcher who continues the study of H_2/O_2 injection for fuel efficiency improvement as much time and money as possible.

Firstly, it is recommended that a larger, higher quality engine be used, incorporating multiple cylinders, to better simulate the aggregate effects of the H_2/O_2 injection. With the small, single cylinder engine, it is not immediately scaleable to multiple cylinder engines, due to air intake variables. Thus, an experiment using a multiple cylinder engine would be more useful. The engine used in this experiment was an inexpensive model, thus it provided a source of frustration in cases when it would not operate. If a flow meter is used, it is more difficult to find one that measures the minute fuel flows consumed by the Amico. So the greater fuel consumption could supply more accurate results. Also, if possible, the engine should be only minimally modified. The test setup should be suited to the engine, not the other way around. Invariably, fuel lines will be impossible to find replacements, for example. A higher quality engine is more likely to yield consistent results. Unfortunately the Amico was unstable, as shown by the difference in Run1 and 2 in Figure 4 and Figure 5.

In hindsight, a gasoline/petrol engine would have been preferred over a diesel for this experiment. They are cheaper to buy, more prolific, and currently the fuel is less expensive. An additional benefit is the provision of a DC circuit while the engine is running. This is possible with diesel engines as well, but not with the Amico model in this experiment. It is worth checking if there is a DC circuit since that would make the power supply to the electrolyzer much easier to integrate. It was learned after the purchase of the Amico about the lack of DC supply, as a result, an additional component had to be purchased to convert household AC to DC. In addition, much of the focus in the marketing of H_2/O_2 generators is for gasoline applications. Gasoline is inherently less efficient than diesel due its lower compression ratio so it may be that higher gains are possible with spark ignition engines.

The design and construction of the H_2/O_2 generator simple and inexpensive, so it would be worthwhile to construct one custom made for the application. Ideally, this would produce a H_2/O_2 generator with known electrical consumption versus output characteristics, suited to the engine. Likely, constructing a custom made H_2/O_2 generator would be less expensive as well.

With greater resources, it would be beneficial to incorporate more advanced sensors such as flow meters for fuel consumption and H_2/O_2 output, temperature sensors for exhaust gas and cylinders, and an automatic test control system. The control system could vary the load and take instantaneous reactions of the engine to H_2/O_2 input as well as averaging the data. Instantaneous measurements were impossible with the setup in this experiment, but may prove interesting. Also, a diesel engine is not a welcome neighbour for noise and toxic emissions, thus it would be advantageous to avoid manual data taking, when possible. At the same time, greater precision would reduce sources of error. Wasted time due to failed instruments would be mitigated.

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