EXPERIMENTAL USE OF HYDROGEN TO REDUCE THE CONSUMPTION OF CARBON FUELS IN A COMPRESSION INGNITION ENGINE AND ITS EFFECTS ON PERFORMANCE

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Tyler Brian Stousland

In Partial Fulfillment of the Requirements
for the Degree of
MASTERS OF SCIENCE

Major Department:
Mechanical Engineering

June 2015

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Experimental Use of Hydrogen to Reduce the Consumption of Carbon Fuels in a Compression Ignition Engine and its Effects on Performance

By

Tyler Stousland

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr. Robert Pieri
Chair

Dr. Mariusz Ziejewski

Dr. Scott Pryor

Approved:

11/20/15	Dr. Alan Kallmeyer
Date	Department Chair

ABSTRACT

As part of an effort to find use for electric energy produced by wind turbines, Basin Electric started a program to produce hydrogen through electrolysis. It is not enough to simply produce hydrogen, there needs to be uses for the hydrogen in order to make the project worth pursuing.

Hydrogen can be used to supplement diesel fuel in the combustion process in a compression ignition engine. This research will go over two engines which were tested running different combinations of hydrogen and diesel fuel. The results will show how both engines were able to replace up to 50% of the diesel fuel energy input with hydrogen. This paper will also talk about how the addition of hydrogen affects the combustion process by increasing the peak cylinder pressure by 44% and advancing the peak cylinder pressure by 13° of crank angle.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. Problem

One day it will become uneconomical or impossible to use fossil fuels for the power production needs of humans. With more and more people on the earth the demand for energy will only increase, even with increases in efficiencies, additional energy sources will be needed. If this is the case, new means of power conversion need to be developed. Wind turbines were some of the original power producing structures and are becoming more popular today as interest in technologies to reduce carbon emissions, or “green” technologies, increases. Wind turbines are designed to operate within a certain wind speed and with wind changes the efficiency of the turbine changes [1]. If that energy could be stored, then the power from the wind turbines would be greatly extended.

1.2. Growing Transportation Energy Demands

Carbon fuels are used in the everyday life of most people in the United States and serve a growing role in the rest of the world. Oil has become imperative to the development of a country. Diesel engines are used more in other parts of the world than here in the United States. In Europe almost half of the automobiles sold are diesel fueled. In America, diesel engines have been put into the role of a work engine powering mostly trucks and heavy equipment. Of course there are other uses such as trains and ships, most of which are diesel powered. Finally, there are diesel generators used in places without power or for emergency power backup when it is needed. The work in this paper mostly looks at a heavy duty diesel engine that could be used in agricultural equipment or a heavy transport truck.

India and China are the two fastest growing economies on the planet today. In 2011 General Motors sold one vehicle every 12 seconds in China for a total of 2.55 million vehicles [2]. That is a little bit higher than the just over 2.5 million vehicles sold here in the United States in the same year [3]. According to the British Broadcasting Corporation the number of car drivers in India has doubled in the last ten years [4]. With the number of people on the planet driving in markets that previous had a low demand of oil, prices could go up and supplies could go down. The United States consumes about 22% of the world’s daily oil demand [5]. Compare that with China’s 10% and India’s 4%.

1.3. Changing Engine Regulations Putting Pressure on CI Engines

Government standards are changing for engine emissions. The United States has standards which dictate the amount of hydrocarbons, oxides of nitrogen, particulate matter, carbon monoxide, and smoke an engine is allowed to produce for highway compression ignition engines [6]. These regulations call for a decrease in oxides of nitrogen by more than 90% from engines produces in 2003 to engines produced after 2007. They also call for a decrease in particulate matter by 90% from engines produced in 2006 to engines produced after 2007. Oxides of nitrogen and particulate matter are key areas to focus on for emissions reduction in compression ignition engines.

There are different regulations for non-road engines [7], [8]. These regulations refer to Tiers. Tier 1, 2, and 3, are now being superseded by Tier 4 which comes into effect in 2014. The regulations are split up by engine power ratings. The engines used in these experiments fall into these regulations.

1.4. How Hydrogen Can Be Part of the Solution

Hydrogen is the most abundant element in the universe and could be used to supplement the need for fossil fuels [9]. Depending on the means of production hydrogen can be a renewable resource. Electrolysis powered by wind turbines is one way to get hydrogen as a renewable source from water. At night when the demand for power is low and wind turbines are still producing power, the energy could be used to power the electrolysis process for producing hydrogen. The stored hydrogen could then be used to produce power whenever there is a spike in demand. The hydrogen could also be transported to various locations where energy is needed. This could decrease the need and cost to connect wind turbines to the country’s power grid.

Basin Electric started a project with the idea to use wind turbines to power the electrolysis process to produce hydrogen [10]. The electricity produced by two wind turbines at night, or when power demand is low, can be sent to the electrolyser to produce hydrogen from water. The hydrogen that is produced could then be pressurized, stored, and used wherever and whenever extra energy is needed. As part of the project different uses for this hydrogen were researched. A light duty truck was converted from burning gasoline to burning hydrogen. North Dakota State University worked on converting a diesel tractor to run on a mixture of diesel fuel and hydrogen.

The National Renewable Energy Laboratory has partnered with Xcel Energy to build a wind turbine research site near Boulder, Colorado. The site conducts wind turbine related research, including hydrogen production from electrolysis [11]. The goal of the project is to increase efficiencies of renewable production of hydrogen. It focuses on large scale production and storage of hydrogen to compete with coal, oil, and natural gas.

There are two main issues that stand in the way of using hydrogen today. They are production and distribution/storage costs. According to the National Renewable Energy Laboratory most hydrogen produced in the United States comes from steam reforming of natural gas. This process takes natural gas, and uses energy to separate out the hydrogen. A small amount of hydrogen is produced using electrolysis. This process requires large amounts of electricity and for the water to be purified first to prevent contaminants from building up on the electrodes. In addition to only being produced in small quantities, there are only nine commercial hydrogen refueling stations in the United States [12]. The current production and distribution facilities are not able to sustain any large hydrogen demand.

A Secondary Issue is there is little technology which utilizes hydrogen to produce power. Honda recently leased an automobile which uses a hydrogen fuel cell in California called the FCX [13]. General Motors also has an Equinox SUV powered by a hydrogen fuel cell [14]. Other manufacturers produce vehicles which use hydrogen to different degrees but they are all still in the development phase.

An analysis of the base cost for production and distribution sites of a nationwide hydrogen network has been made by M. Melendez and A. Milbrandt at the National Renewable Energy Laboratory [15]. In the paper they explain the estimated cost to be approximately $837 million, based on 2020 demand for hydrogen. This puts a hydrogen station near every major highway in the country with a maximum distance between stations of 100 miles. This analysis was for on highway vehicles, meaning cars and over the road trucks.

A diesel/hydrogen hybrid engine is one way to use hydrogen to produce power. A system can be developed to reduce fossil fuel consumption without any loss in power output compared with normal operation. This system can also be retrofit to current engines in use today, extending their usefulness into the future. This paper will focus on work that has been done on diesel/hydrogen hybrid engines.

Hydrogen does burn clean with its only byproduct being water (H_2O). This means if a system is developed to use hydrogen there will be no carbon emissions emitted into the atmosphere because not carbon fuel is in the combustion chamber. Nitrogen (NO_x) emissions still need to be managed if burning hydrogen with atmospheric air as nitrogen will still be in the combustion chamber.

Hydrogen also has a larger heating value than diesel fuel per unit mass; 142,000 kJ/kg for hydrogen compared with 45,000 kJ/kg for diesel fuel. Hydrogen has over three times the energy per unit mass. The problems arise in obtaining storage for the less dense gaseous hydrogen compared with systems designed for the more dense liquid fuel.

Hydrogen is lighter than air. This could be considered a good thing or a bad thing depending on the point of view taken. It could be bad because of its low density which makes it difficult to store hydrogen in quantities that make it practical for everyday use. It could also be a good thing when looking at fuel leakage. When diesel fuel tanks leak, after an accident or from some other kind of damage, the fuel pools on the ground, this creates a fire threat. This threat will persist until the fuel spill is cleaned up. When a hydrogen fuel tank leaks, because it is lighter than air, the hydrogen gas immediately goes up into the atmosphere and starts to dissipate reducing the long term fire threat.

The flammability range for hydrogen is also larger than diesel fuel. Hydrogen is combustible in air from a concentration range of 4-75%. This gives a lot of options in an engine as far as a lean burn situation is concerned but if there is a contained leak only a small amount of fuel could become a risk.

2. LITERATURE REVIEW

2.1. Dual Fuel Engine Research

Dual fuel systems using diesel fuel is not new [16]. These systems used diesel fuel as an ignition source and an alternative fuel as a supplement. Hsu uses two injectors to deliver fuel to the combustion chamber. One injects a small amount of diesel fuel as an ignition source and the other is a gas injector which injects natural gas as the main fuel. This process known as the “H-process” is capable of running on 100% diesel fuel or a mixture of 95.4% natural gas and 4.6% diesel fuel. Using this system the peak cylinder pressure remains unchanged but emissions are affected. NO_x emissions are cut by 43% and HC are increased by about 530%.

Energy Conversions Inc. [17] is a company that this researcher has worked with personally. They develop engine conversions for locomotives. They take a diesel locomotive and convert it to run on 95% natural gas and 5% diesel fuel. This conversion is done so there is little impact to the operation of the vehicle for the operator. A natural gas line is plumbed into the intake manifold of the engine and is regulated to 860 kPa. There is a piggy back computer which is then plugged into the locomotives engine control module. This piggy back computer then makes changes to diesel injection timing and engine coolant flow rates.

Most hydrogen usage in internal combustion engines has been focused on spark ignited engines. BMW had the Hydrogen 7 for example. The Hydrogen 7 is a BMW 7 series which has been converted to run on gasoline or hydrogen. Additionally the wind to energy project has already converted a Chevrolet Silverado to run on gasoline or hydrogen [9]. Both of these projects use spark ignited engines, this type of research will not be covered in this paper. This paper will focus on compression ignition engines.

The majority of the work done with compression ignition engines has been done with hydrogen fumigated into the inlet manifold. The diesel fuel is then directly injected into the cylinder. The following section will discuss others researchers work like this. This is a simple approach to introducing hydrogen into a diesel engine. These tests have all had similar results from substituting a small amount, usually less than 30%, of diesel fuel energy for hydrogen fuel energy.

2.1.1. Adding Small Amounts of Hydrogen

Most research has been done in a laboratory setting adding various mounts of hydrogen. Researchers at Pennsylvania State University looked at small amounts of hydrogen fumigated into the intake manifold of a compression ignition engine to see the effects on emissions and overall engine performance [18]. They used small amounts of hydrogen in two different engines. The first was mounted on a dyno and run with hydrogen accounting for 0, 5, and 10% of the total fuel energy input. They determined that there was no discernible change in engine efficiency. The second engine was installed in a vehicle and run on the urban cycle on a chassis dyno with the same hydrogen input. In this test they found that engine efficiency went down 1%. These researchers found significant changes to engine performance when hydrogen is added to the intake charge of a compressions ignition engine.

Adding small amounts of hydrogen can have a positive effect on diesel combustion. Researchers at Jadavpur University in India saw a thermal efficiency rise between, 2-4%, when adding hydrogen [19]. Their engine was run at different loading conditions with a constant hydrogen injection rate. They found that without using exhaust gas regeneration engine efficiency rose but so did NO_x emissions. When running with exhaust gas regeneration engine efficiency decreased but there was no effect on NO_x emissions. For all experiments the exhaust gas temperature was higher than running on diesel alone.

Researchers have also experimented with running different amounts of hydrogen at different loads. The result of this is that during lower loads the hydrogen accounts for a higher percentage of the total energy input than at higher loads [20][21]. With this work hydrogen was run for the entire load range from 0-100% engine load. At 0% engine load hydrogen accounted for 38% of total energy and at 100% engine load hydrogen accounted for 13% of total energy input. At these levels of hydrogen the researchers found no adverse effects when burning the hydrogen diesel mixture.

Similar results have also been achieved by researchers at West Virginia University. They used a large displacement 10800 cubic centimeter Cummins diesel engine. There tests resulted with 31% energy from hydrogen at 70% load and 77% energy from hydrogen at 15% load [22]. They also observed a substantial increase in peak cylinder pressure and a 23% shorter combustion period at 70% load. At the 15% loading condition adding large amounts of hydrogen actually lowered the cylinder peak pressure and heat release rates, decreasing overall engine efficiency. The same group looked at NO_x emissions as hydrogen energy was increased. They determined that as more hydrogen was added NO_x emissions increased [23].

When looking at engine emissions specifically researchers have found that adding hydrogen can change the ratios of the different exhaust gases. Researchers at Pennsylvania State University tested small percentages of hydrogen, 0-15% energy from hydrogen, in a small 2,500 cubic centimeter 4 cylinder diesel engine. They observed that the ratio of NO to NO2 changed as higher amounts of hydrogen were added to the intake air charge. As the percentage of hydrogen went up more NO2 was produced and less NO was produced [24]. They also observed at lower engine speeds particulate matter emissions increased as hydrogen was increased but at higher engine speeds particulate matter decreased as hydrogen was increased. Carbon emissions such as CO and CO2 both decreased regardless of testing conditions as hydrogen was increased.

2.1.2. Issues Which Arise from Adding Large Amounts Hydrogen

So far in this paper researchers have been adding more hydrogen at lower loads and less hydrogen at higher loads. Adding more hydrogen at higher loads starts to create issues that need to be addressed. For example engine knock has been seen by researchers at Czestochowa University of Technology [25]. They introduced hydrogen into compression ignition engine based on an energy balance from 0-25% total energy from hydrogen. They determined below 17% the engine ran smoothly with little difference to normal operation. Above this point however engine knock started to occur. They observed that when more hydrogen was added the ignition delay was decreased and peak cylinder pressure rose.

The engine noise is a common result among researchers when adding a certain amount of diesel fuel. One way to reduce the engine noise is to delay the engine timing [26]. For their experiment hydrogen was injected into the intake manifold of a single cylinder research diesel engine. The same engine noise was encountered and the peak pressure inside the cylinder rose with adding increased amounts of hydrogen. In the experiments hydrogen was responsible for up to 50% of the total heat release. To reduce engine noise the researchers delayed the injection timing of the diesel fuel. They found that this decreased engine noise but if the injection timing was delay too much it was difficult to obtain auto ignition of the fuel mixture.

There are a few problems that need to be addressed when using duel fuels in a combustion engine. Diesel fuel's auto ignition temperature is much lower that of hydrogen's and its rate of combustion is less as well. For most of the work hydrogen is injected into the intake manifold. This gives the hydrogen time to mix with the air to create a close to homogeneous mixture. Then the mixture enters the cylinder during the intake stroke. The compression stroke then heats the air hydrogen mixture above the auto ignition temperature of diesel fuel. Near the end of the compression stroke diesel fuel is injected into the cylinder. The diesel fuel is injected before top dead center (TDC) so that it has time to vaporize and mix with the air in the cylinder. Once the diesel is mixed it ignites and starts to burn.

The laminar burning velocity for hydrogen at 3 MPa and 350C is 6 m/s [27]. This is about 43 times faster than diesel fuel which burns at 0.14 m/s at 4.5 MPa and 527C [28]. Temperature affects burning velocity more than pressure for hydrogen. These two reference points are not at the same conditions but as you increase the burn temperature of hydrogen the burning velocity increases [27]. If the burning temperature of hydrogen was increased to the same as the diesel fuel in the conditions above the laminar burning velocity would be faster than sited above. The diesel fuel is still necessary for combustion though as the auto ignition temperature of hydrogen is 585 C [29], over twice as high as diesel fuel [28]. These temperatures would be difficult to achieve with current diesel engines.

2.2. Experimental Work Done at NDSU to Maximize Hydrogen Energy Input

Work done at North Dakota State University was started with work done by a grad student, Austin Decker [30]. His work included the first test with the 4 cylinder CAT engine. A simple injection system was used to pipe hydrogen gas from high pressure cylinders into the intake manifold of the engine, after the turbo. Using this injection setup hydrogen consumption was calculated from a reduction in the air intake into the engine. This work was the baseline for the work done in this report.

The test runs for this work were chosen to be at similar speeds and power outputs for comparison purposes. Austin chose to perform tests at two different power outputs and 3 different speeds. His results showed a replacement of up to 60% of the total energy with hydrogen. Further work needed to be done to verify these findings as there was no way of verifying the hydrogen flow rates in those experiments.

This report includes more tests with the 4 cylinder CAT engine as well as similar tests on a 4 cylinder Kubota engine. These experiments had more instrumentation including a hydrogen mass flow meter and an in cylinder pressure sensor to record the pressure inside the cylinder as the fuel mixtures burn. It will be shown that the results in this report are similar to the results obtained by Austin. Hydrogen makes up to 50% of the total energy input and there is an increase in cylinder pressure. Cylinder pressure rise is consistent with work done by other researchers discussed earlier in this report. The Kubota testing was done to compare results across different manufacturers. The results will be used to see any effects of engine design in the addition of hydrogen to the combustion process.

2.3. Problem Statement and Objectives

The main problem of investigation for this report is maximizing hydrogen input. What is the maximum amount of hydrogen that can be injected into a diesel engine and still have the engine operate as originally designed? A Caterpillar and Kubota diesel engines were retro fit to run on a combination of diesel fuel and hydrogen gas. The goal of this research is to see how much of the combustion energy for the dual fuel operation can come from hydrogen without having adverse effects on engine operation and efficiency.

Previous work has not gone much higher than around 30% energy from hydrogen. Once this percentage is exceeded engine efficiency goes down. It is hypothesized that the fuel is igniting and burning before it is intended to create uneven and undesirable cylinder pressures. This report will investigate these pressure curves to see what their effect is on the combustion process. Engine efficiencies and engine emissions are also of interest and will be investigated.

Chapter 5 will discuss the modifications needed to make an engine run on both diesel fuel and hydrogen. Chapter 6 will cover the setup, equipment used, and procedures for the experiments. Chapter 7 will show the results and discussions of what was learned from the experiments covered in chapter 6, this includes the efficiency calculations and in cylinder pressure curves. Finally chapter 8 will conclude the paper, discussing what was learned. It will also suggest future work and discuss subsequent research which has been done at North Dakota State University.

3. ENGINE MODIFICATIONS

3.1. Summary of Engine Background and Modifications

A Caterpillar 3054C, 4 cylinder 4000 cc engine, from a backhoe was used for testing. It produces 75 kW and 374 N-m of torque when run normally on diesel fuel. It was installed in the engines lab around 2006 and was not used for research but as part of a class to teach engineers how to perform an engine dynamometer test. It is now used only for this hydrogen research. Figure 1 shows the engine mounted on engine stands in the engines lab at NDSU.

Figure 1. 4000 cc CAT Research Engine Setup in Lab

The engine is about 4-6 years old and is almost fully mechanically controlled. The governor is mechanical and is made to maintain engine speed by adjusting fuel injected into the engine. The throttle is mechanically controlled with a cable. The high pressure injection system, controlled by the injector pump, is mechanical with direct gear drive to the crankshaft. The only things that are electric on the engine are the starter and an electric fuel cutoff solenoid. The solenoid shuts off fuel delivery if it does not receive a constant voltage signal, and is used as a safety kill switch.

The engine was bolted to engine stands and mounted to an isolation pad in the engine dynamometer lab. This room was built to test a variety of different engines owned by the university. The list includes a 4000 cc Perkins diesel from CAT, a 6600 cc diesel from CAT, and a 2000 cc Kabota. Engines are mounted on one of two isolation pads and the exhaust is plumbed to an exhaust vent in the ceiling. Engine cooling is performed by a water to water heat exchanger sized to each engine.

To eliminate the effect of the coolant flow rates through the engine the thermostat on the engine was jacked fully open. The coolant flow rate through the engine would then remain constant for all testing and the cooling of the engine would be controlled by the amount of water flowing through the water to water heat exchanger.

Hydrogen needed to be injected into the intake of the engine at so the intake manifold needed to be modified. Figure 2 below shows a simple flow schematic for the hydrogen delivery system made to introduce hydrogen into the intake of the engine. The decision was made to inject the hydrogen after the turbo to increase turbulence and reduce risk of backfire in the engine intake. The theory is the incoming air would keep the hydrogen away from the turbo, the turbo being the hottest place on the engine. During engine operation the hot side of the turbo can reach temperatures greater than 480 C°.

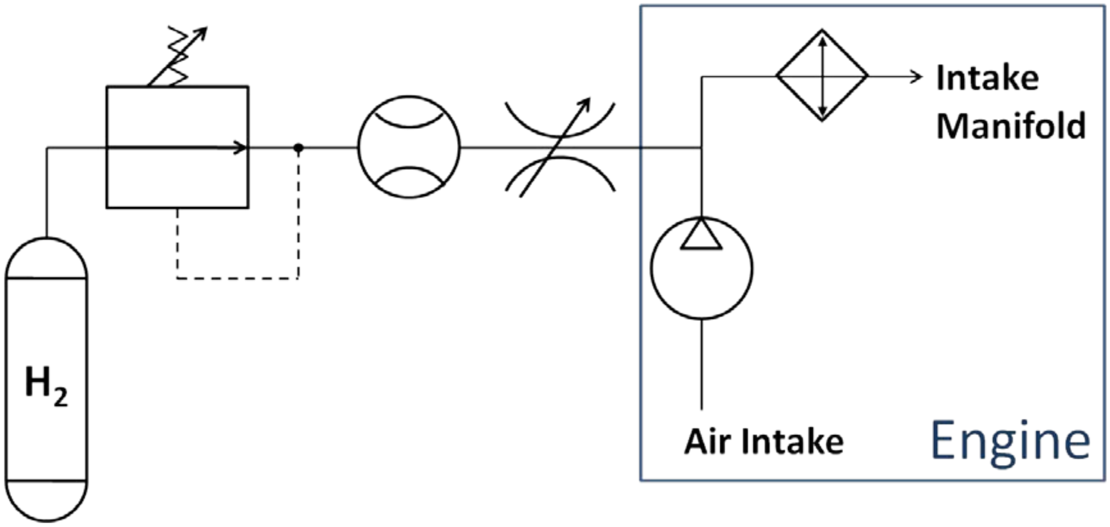

Figure 2. Hydrogen Plumbing System Schematic from Storage to Intake Manifold

The hydrogen used for testing is stored in a standard storage tank at 13,800 kPa. For lab testing the tank is mounted away from the engine, but in practice the tank would be mounted on the vehicle. A pressure regulator restricts output hydrogen pressure to 550 kPa to protect the downstream mass flow meter from damage due to high pressure. This pressure was also chosen to be high enough to keep air, compressed from the turbo charger, from flowing up into the hydrogen line yet low enough for safe operation. Turbo compressor output pressure during tests is never over 138 kPa and maximum output pressure is less than 276 kPa. After the hydrogen passes through the pressure regulator, it enters the hydrogen mass flow meter.

The mass flow meter is a thermal instrument used to record the mass of hydrogen entering the engine. A full explanation of the hydrogen mass flow meter will be given in the experimental setup section of this report. Next there is a variable flow needle valve used to control the amount of hydrogen entering the engine. After the control valve, the hydrogen enters the intake and begins to mix with air in the intake. The hydrogen/air mixture then passes through the intercooler and into the cylinder bank. Figure 3 shows the location of the hydrogen infusion point on the engine. The black line entering the intake just above the red hose connecting the turbo to the intercooler is the hydrogen infusion line.

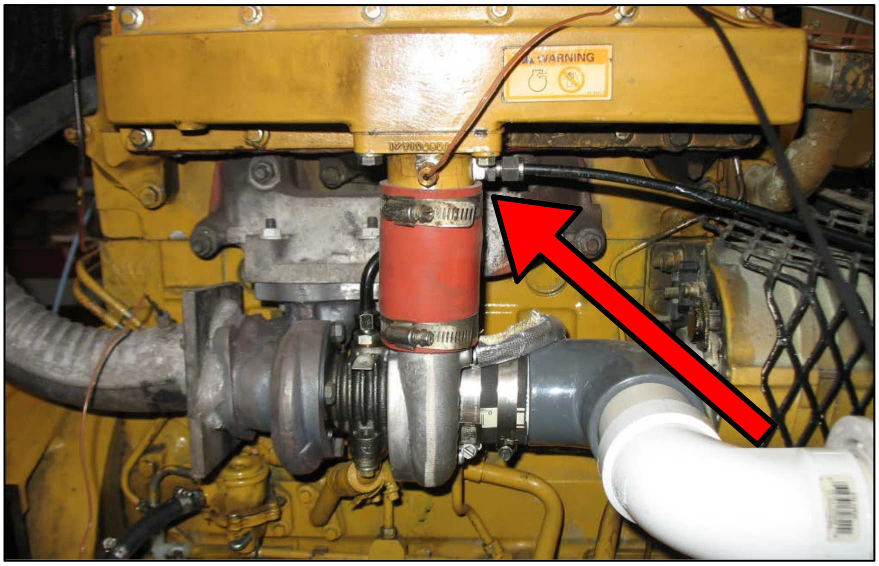

Figure 3. The Plumbing Connection for where the Hydrogen Enters the Intake Manifold

The effects of hydrogen cooling the intake air charge were not a concern as the hydrogen was stored at room temperature and the flow rates were low enough that the pressure drop did not create any hydrogen cooling problems. The engine intercooler is used to regulate the incoming air charge before entering the engine cylinders. During the tests run for this report the temperature of the air/hydrogen charge after the intercooler varies by only a few degrees over the entire experiment.

The fuel system was changed as well. The return line was rerouted and plumbed back into the fuel supply line just before the fuel transfer pump on the engine. This was done because the lab was only equipped with one diesel flow meter so it did not have the capability to subtract the return line from the supply line to determine to total fuel consumption. The diesel flow meter was midway from the diesel fuel cell and the engine so it would measure only fuel leaving the fuel cell thus measuring diesel fuel consumption.

Finally, the engine head was removed so a hole could be drilled in it for the installation of a cylinder pressure sensor. No major changes were made to the engine to perform this installation, only a fuel supply line needed to be rerouted. The installation of this sensor will be talked about in more detail later in this paper.

To give a reference point for the pressure traces produced by the in cylinder pressure sensor, an additional tachometer sensor was installed on the rear housing of the engine near the flywheel. An inductive tachometer sensor was taken from a triumph engine and mounted on the cover plate over the flywheel. A bolt was then screwed into the flywheel as a pickup for the sensor. This bolt was already in use as a balance in the flywheel so balancing the flywheel was not an issue.

3.2. Expected Outcomes and Reasons for Engine Changes

The expected outcomes with these modifications are to run a diesel engine on a combination of diesel fuel and hydrogen using current engine technology and keeping the cost of the conversion as low as possible. Dual fuel injectors were not considered for a number of reasons including, added cost and complexity. The idea was to keep the conversion simple so that people could convert their diesel engines to run as a hybrid without spending too much money. The goal is to prove that an engine can be converted and run efficiently on a combination of diesel fuel and hydrogen.

4. EXPERIMENTAL SETUP

4.1. Hydrogen Safety

Inside the lab hydrogen safety was a top priority. All experiments were done with at least two lab technicians present. A hydrogen detector was installed on the ceiling of the lab directly above the engines. The detector had a built in alarm as well as the capability to output a signal to a shut off switch. Hydrogen is flammable in air in concentrations as low as 4% [29]. The first warning alarm was set to go off at 1% hydrogen concentration. This alarm turned on a yellow warning light to indicate rising hydrogen concentrations. At 2% the warning light changed to red and a horn sounded.

During all experiments an exhaust fan in the ceiling was used to vent any fumes inside the lab to the outside of the building. This prevented any buildup of hydrogen gas or any other fumes. In addition to the exhaust fan an emergency fuel shutoff switch was install to cut fuel to the engine in the case of an emergency.

Hydrogen plumbing was either stainless steel pipe or hose compatible with hydrogen. The stainless steel was used from the storage tank to the pressure regulator and through the hydrogen mass flow meter. Both the pressure regulator and the hydrogen mass flow meter are rated for use with hydrogen. The pressure regulator lowered the pressure to 550 kPa. This pressure was chosen as a safe working pressure as it was low enough for use with the equipment yet high enough so that air was not pushed back up the hydrogen supply line.

Hydrogen storage cylinders were kept upright in locked storage racks on the exterior of the lab building. These racks were fenced in and protected by concrete bollards. The storage of this gas was in accordance with the Los Alamos National Laboratory hydrogen gas safety guide [29]. All areas inside the lab and outside on the storage unit were marked with hydrogen warning signage.

4.2. Dynamometer with Data Acquisition

The DYNO-mite dynamometer was purchased and installed at the same time the university received the CAT engine. It replaced an old blue electric dynamometer that used to be in the engines lab. The DYNO-mite is a water brake dynamometer consisting of a rotor and a stator. This dynamometer is used to monitor and transmit engine torque, and speed to the data acquisition box.

Figure 4 below shows the rotor and stator of the dynamometer drum. The piece being held is the rotor which spins with the engine. The part sitting on the bench is one piece of the housing. The two housing pieces sandwich the rotor and enclose the system.

Figure 4. Inside View of the Water Brake Dynamometer

The system uses the resistance of the water to transfer the load through a brace, not pictured. The bottom of the brace is fixed to the water drum, while the top is fixed to the engine's flywheel housing. When a load is applied, the brace compresses. A strain gauge is located on the outside of the brace to record the load as a voltage in the computer. Engine speed is monitored by an inductive instrument. A piece of steel is fixed in the rotor and a sensor is mounted in the stator housing. Because the dynamometer rotor is rigidly connected to the crankshaft, the speed of the rotor is also the speed of the engine.

Figure 5 shows the rotor and stator assembly mounted on the engine with the strain gauge brace (blue piece).

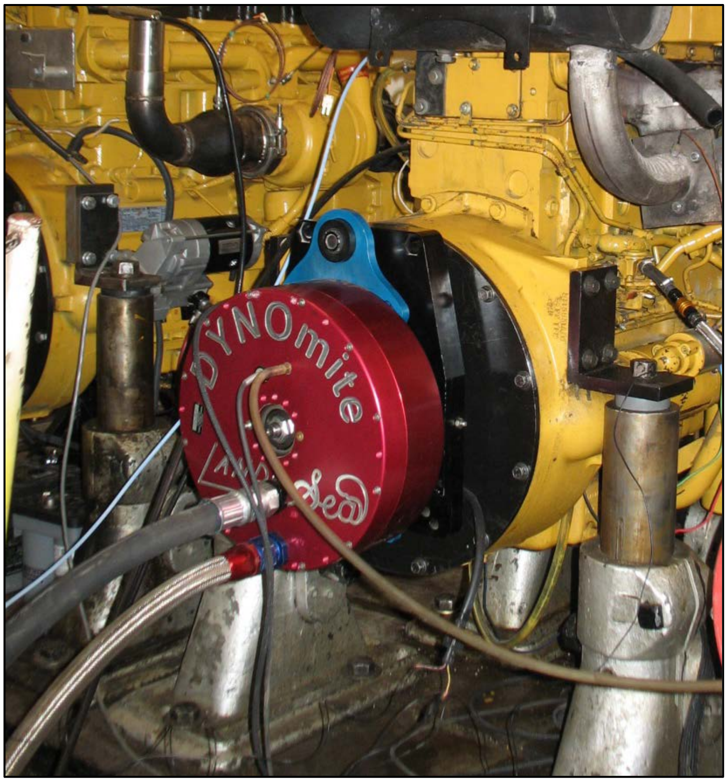

Figure 5. Dynamometer Mounted on CAT Engine

With the torque and speed of the engine recorded, the software then calculates the power output of the engine with the equation

$$P = 2\pi * \frac{\tau * n}{60 * 1000} \tag{1}$$

Where P is kW, τ is engine torque (Nm), and n is engine speed (rpm).

The dynamometer is calibrated by securing a beam to the rotor housing that extends off to the side and hanging a known weight at a known distance from the center to create 135.58 N-m of torque. Multiply the vertical force times the horizontal distance to get torque; if the dynamometer reads a different number, then it needs to be recalibrated. Figure 6 shows the setup for calibrating the dynamometer.

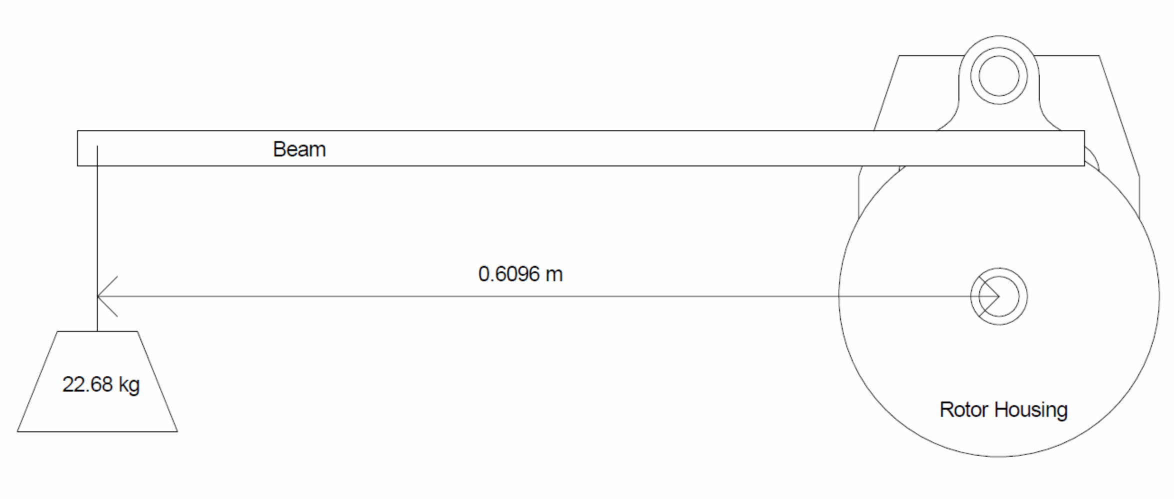

Figure 6. Dynamometer Calibration Setup

The data acquisition module receives all the various sensor inputs and sends the data to the computer to be displayed and recorded. Other sensor input such as diesel fuel flow rates, intake air flow rates, inlet manifold pressure, coolant temperature, intake air temperatures before and after the intercooler, exhaust temperature after the turbo, and atmospheric conditions outside the engine are all recorded through the data acquisition module.

Air flow and fuel flow are both recorded using turbines. The speed of the turbine is translated into a flow rate. The diesel fuel meter is not very accurate below 8.7 liters per hour and a lot of the readings for these experiments are taken in this region. This meter is not ideal but it is the only one on hand and a new one was not in the budget. A 0-689.4 kPa pressure gauge installed in the intake manifold after the intercooler is used to monitor the output pressure of the turbo. This pressure sensor is a 0-5 volt diaphragm sensor. A weather station, included with the DYNO-mite dynamometer is used to record ambient temperatures and atmospheric pressures in the room. All thermal couples on the engine are K type and all are recorded through the dynamometer. They are mounted right after the turbo compressor in the intake where the hydrogen is injected, right after the engine intercooler, in the engine’s water jacket (coolant loop), and in the exhaust after the turbo. The location of the thermal couples will help so see the effects of adding the hydrogen to the intake and exhaust.

All the data is transferred from the data acquisition equipment to a desktop computer running proprietary software which comes with the DYNO-mite. Figure 7 shows the display on the control panel.

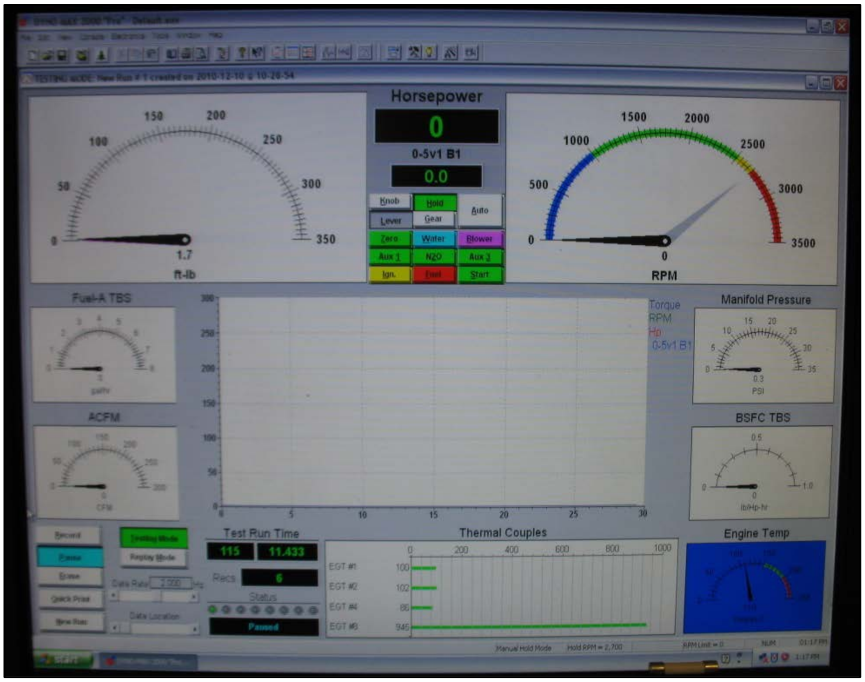

Figure 7. Real Time Computer Data Display

4.3. Hydrogen Mass Flow Meter

The mass flow meter for hydrogen is a Fox Thermal Instruments model 10A calibrated for hydrogen flow. It is an older model, but it does have the functionality to output a signal so it can sync up with the dynamometer data.

There are two probes that stick out into the hydrogen flow; one of the probes is held at a constant temperature and the other absorbs heat from the hydrogen flowing past. The transfer of heat is proportional to the amount of mass flowing in the pipe. The power required to keep the probe at a constant temperature can then be converted into a mass flow rate. The output can be adjusted, but is setup to display standard cubic feet per minute. The number is then converted to a mass flow rate given standard conditions are 70°F and 1 atm using the following equation.

$$\dot{m} = \left[\frac{Q*P*\left(\frac{144\ in^2}{ft^2}\right)}{R*T}\right]*\left(\frac{60\ min}{hr}\right) \qquad (2)$$

Where m is the mass flow rate in (lbm/hr), Q is the volumetric flow rate in (ft^3/min), P is the pressure in (lbf/in^2), R is the ideal gas constant with units (lbf-ft/lbm R), and T is the temperature in (R).

The meter was sized by taking the normal diesel fuel flow for the engine and converting that to an energy flow rate. Then 90% of that rate was converted into a hydrogen mass flow rate. This was the hydrogen mass flow rate that the meter would need to be capable of measuring. The reason a thermal mass flow meter was chosen was because this meter was very accurate at lower flow rates, but still capable of measuring higher flow rates in future work.

4.4. In Cylinder Pressure Sensor

The in cylinder pressure sensor is from Optrand. It is a 0-3000 psi optical sensor. It works by reflecting light off a diaphragm which is deformed by the pressure inside the cylinder. The reflected light then travels through a fiber optic cable to a processor that outputs a 0-5 volt signal.

The sensor is designed to be installed through the water jacket on the engine. Engine coolant can then be used to cool the sensor from the heat generated inside the cylinder. Figure 8 shows the insertion end of the pressure sensor. Note the three o-rings designed to seal the sensor. The end of the sensor is designed to be a metal on metal seal with the cylinder and torqued to a specific spec to ensure a good seal.

Figure 8. Insertion End of the In-Cylinder Pressure Sensor

The decision on the location of the pressure sensor was limited as there was very little space due to the diesel fuel injection lines. The sensor needed to be as close as possible to the center of the cylinder. Cylinder number one, the cylinder closest to the flywheel, was chosen because it had the most open space and ease of access to the engine. Only a fuel return line needed to be relocated to make room for it. Figure 9 shows the location of the in cylinder pressure sensor in the cylinder head. The blue line leading away from the engine to the right is the fiber optic cable which links the sensor to the signal conditioner.

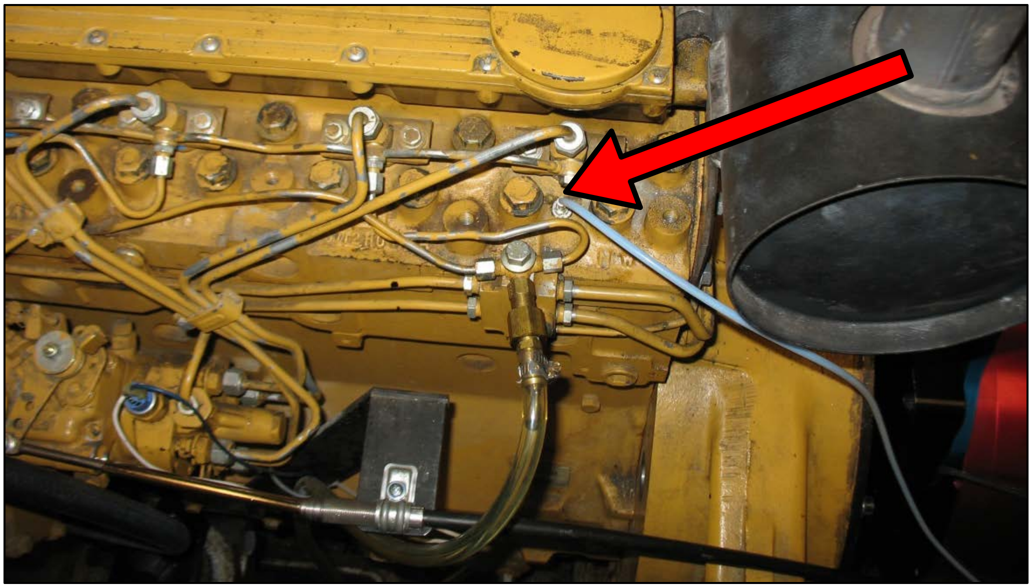

Figure 9. In Cylinder Pressure Sensor Location in the Engine Block Head

The sensor passes through the water jacket so cooling is done by the engine cooling system. This increases the longevity of the sensor but adds complexity to the removal process. This is a relatively inexpensive sensor and very durable.

This sensor is not connected to the dynamometer because the data recording rate needs to be much higher. For these experiments it was sampling at 7200 Hz in order to get a clear definition of the pressure curve over the power stroke of the engine, in contrast the dynamometer was set to record data at only 2 hz. A simple data recorder from DataQ was used to record the voltage output from the sensor at the desired rate. The time of each sample was recorded in a notebook so the cylinder pressure data could be matched up with the data taken by the dynamometer.

4.5. Exhaust Gas Analyzer

The exhaust gas analyzer is a vacuum system that sucks in exhaust gasses from the exhaust stream and then, through a series of tests, outputs the various quantities. It measures the percent of O_2 in the exhaust as well as the percent of CO and CO_2. It also measures the parts per million (PPM) of hydrocarbons (HC), and NO_x emissions (NO and NO_2). The setup was just serviced in the last year and most of the internal sensors were replaced and recalibrated. The analyzer is turned on and allowed to zero before being inserted into the exhaust stream. Figure 10 shows the display for the exhaust gas analyzer. The displayed reading is a baseline to show the content of the air inside the engine lab.

Figure 10. Exhaust Gas Analyzer

The hose for sampling gas is inserted three feet after the turbo in the exhaust. This placement was simply chosen because of the break between the exhaust for the engine and the vent for the lab. A pipe was inserted with a hole for the analyzer to slide into.

4.6. Procedure

Before data was taken the engine would first be turned on and warmed up to make sure everything was at steady states. First, the diesel fuel supply to the engine was turned on. Next, the water must be turned on, both to the engine coolant system, as well as, to the dynamometer load control. The load control valve is left closed until the engine is ready to turn on. The dynamometer computer is then turned on and setup to show the gauges for the experiment. The computer screen displays all of the relevant data during an experiment such as torque, power, coolant temp, air flow rate, diesel fuel flow rate, intake manifold pressure, etc. After the computer is ready, the dynamometer is plugged in and the engine is ready to be turned on. There are two switches to the right of the computer display used to control electrical power to the engine. There is a master switch and a starter switch. The master switch is used to cut power to the engine in an emergency. If this switch is turned off the voltage signal to the fuel supply solenoid on the engine will shut off, cutting the fuel supply to the engine. The starter switch is used to send power to the electric starter mounted on the engine. Figure 11 shows the control panel. Once the engine is warmed up, meaning the engine coolant is above 50°C, the background of the coolant temp gauge in the bottom right corner of the control screen turns from a blue to green and then the engine is ready to start an experiment.

Figure 11. Dynamometer and Engine Control Panel

All experiments were conducted using the same procedure. First, an engine speed and load was chosen. Three speeds were chosen for this report. All three loading conditions were partial load tests due to the limitations of the test equipment. The three speeds for this experiment were 1350, 1800, and 2100 rpms. The load on the engine was supposed to be the same for all tests but with limitations on load control it was attempted to be held somewhere between 650-700 kPa mean effective cylinder pressure.

Second, the engine speed and load were set and remained constant. The engine throttle was configured to be controlled by a lever on the dynamometer computer control panel to the left of the keyboard. The dynamometer load was controlled by a knob on the panel to the right of the keyboard. The load was dependent on the flow rate of water into the dynamometer; the more water flowing into the dynamometer the more load was applied. Once the engine was set at a speed and load it was allowed to reach steady state.

Third, hydrogen input was increased in increments of 0.5 standard cubic feet per minute (SCFM). Data was recorded at every incremental set point. The engine's governor system was relied on to decrease diesel fuel input. The governor uses diesel fuel to regulate engine speed. When hydrogen is added to the incoming air more energy enters the engine and the engine speed increases. In order to maintain a constant engine speed, when hydrogen is added, the governor will reduce the amount of diesel fuel injected into the cylinders. This change adds less diesel energy and brings the engine speed back down to the point it was running at without any hydrogen.

Two areas where testing could not be done were at full throttle and at engine idle. Full throttle could not be done because the engine's governor had no room to reduce diesel fuel. Idle could not be done because the diesel flow meter was not reading at such a low flow rate. The diesel flow meter does not output a reading until the diesel flow rate is over a certain amount, this amount being more than engine idle.

5. RESULTS AND DISCUSSION

There are four main parameters of interest in this study. The first is energy input; a comparison of the sources of energy input and the ratios between them. Second is engine efficiency; how the efficiency changes with the addition of hydrogen. Third is engine emissions; does the addition of hydrogen have an effect on engine emissions and what effect does it have. Fourth is cylinder pressure changes; what happens to the pressure trace inside the cylinder during combustion as the concentration of hydrogen increases. These are the main parameters but others will be discussed as well.

5.1. Mean Effective Pressure and Loading Conditions

In order to be able to compare these results with those from other engines, a common loading needs to be used such as mean effective pressure (MEP). MEP can be used to compare different engines because it focuses on piston loading instead of engine power output. MEP represents a pressure that would produce the same power if it were constantly applied to the piston over the entire stroke. The following equation was used to determine MEP for the engine used in this report.

$$MEP = 2\pi * \frac{\tau * n_c}{V_d} \tag{3}$$

MEP is the mean effective pressure (kPa), τ is engine torque (Nm), n_c is the number of strokes per power cycle (n_c=2 for this experiment), and V_d is engine displacement (m^3). Three loading conditions were used in this experiment; 1350 rpms, 1800 rpms, and 2100 rpms. Table 1 shows the loading conditions for the experiments.

Table 1. CAT Loading Conditions

Speed	Torque	Power	MEP
RPM	Nm	kW	kPa
1350	199	28	625
1820	216	41	679
1825	223	43	701
1816	220	42	691
1818	214	41	672
2100	229	50	719

The 1800 rpm test was repeated multiple times so a statistical analysis was possible. The 2100 rpm and 1300 rpm loading conditions did follow the same general trend as the 1800 rpm test. They were not repeated because of time and budgetary concerns. As a result most of the data analysis will focus on the 1800 loading condition.

The water brake dyno made it difficult to recreate the exact loading condition from a previous test. The water flow rate of the building is unreliable. Slight adjustments with the load control knob would sometimes result in a 3 kW change in power output so the engine was set as close as possible at the beginning of the test and then not adjusted thereafter.

Testing was not done at idle or at full load. Below the 1300 rpm test the diesel fuel meter would not output readings so no testing was done below this. Redline for this engine is 2300 rpm. Above the 2100 rpm test the governor was unable to control the amount of diesel fuel input so no testing was done in this region either as it would just be adding extra power which is not the objective of the research.

5.2. Power Output

One of the objectives of the research was to have an unchanged power output for the engine as the source of energy changes from a diesel only to a diesel/hydrogen hybrid. As was stated earlier the loading conditions were set at the beginning of each test and were not adjusted, and the engine's governor was relied on to maintain engine speed and power output. Figure 12 below shows how the power output of the engine changes as the percent energy from hydrogen increases for all three loading conditions.

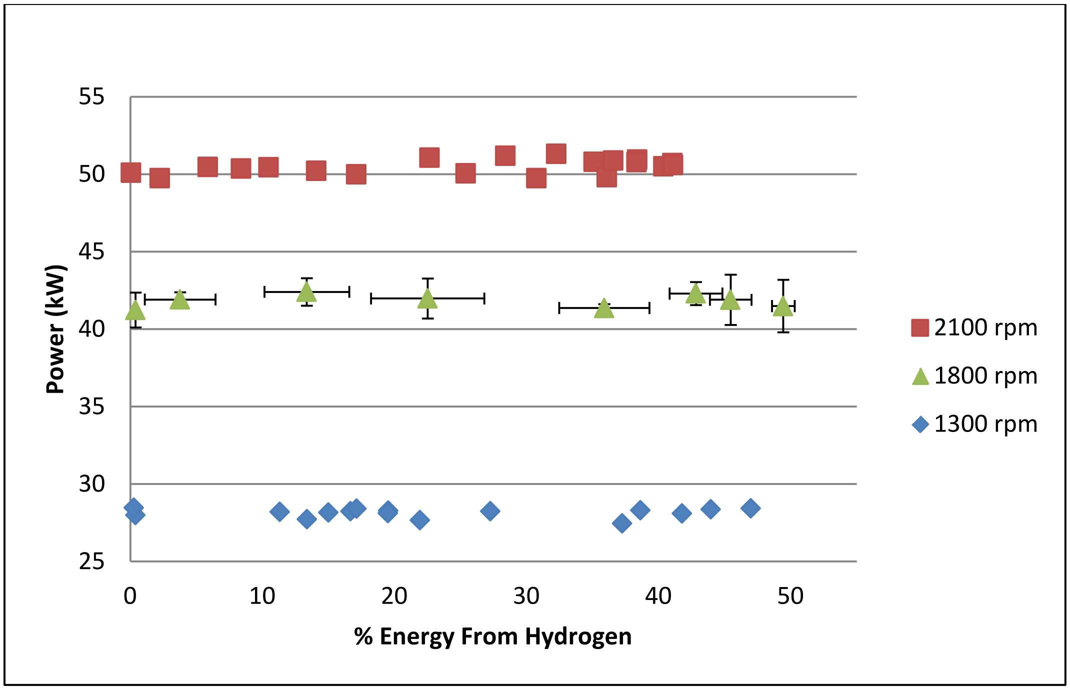

Figure 12. Engine Power Output as Hydrogen Energy Input Increases, All Loading Conditions

As the percent energy from hydrogen increases the engine's power output remains unchanged. For the 1800 rpm tests the error bars are shown with an average power output of 41.8 ± 1.0 kW. The governor provided the tests with a constant power output for all loading conditions meeting the unchanged power output objective.

5.3. Energy Input

Energy input is the main focus of this research. As stated earlier in the report, the goal of this project is to replace the fossil fuel energy, diesel fuel, with renewable energy, hydrogen. As the hydrogen mass input was manually increased the diesel fuel mass input was decreased by the governor. The following equations were used to calculate the energy input from the two different fuel sources.

$$E_d = \frac{Q_d}{7.48\frac{gal}{ft^3}} * \rho_d * H_d \tag{4}$$

$$E_{H_2} = \frac{Q_{H_2} * p_{H_2} * 144\frac{in^2}{ft^2}}{R_{H_2} * T_{H_2}} * H_{H_2} * 60\,\frac{min}{hr} \tag{5}$$

E_d is diesel fuel energy in BTU/hr, E_{H2} is hydrogen fuel energy in BTU/hr, Q_d is diesel fuel flow rate gal/hr, Q_{H2} is the hydrogen volumetric flow rate in ft^3/min, ρ is fuel density lbm/ft^3, H is heat of combustion in

BTU/lbm, p is gas pressure in psi, R is idea gas constant in lbf-ft/lbm R, and T is temperature in R. Diesel fuel is stored as a liquid and hydrogen is stored as a gas, this is why there are two different equations for calculated fuel energy. Since all the data was collect in BTU/hr the units were converted using the following equation.

$$\mathrm{E}\frac{KJ}{hr} = \mathrm{E}\frac{BTU}{hr} * 1.055056\frac{KJ}{BTU} \tag{6}$$

E is each of the fuel energies. Figure 13 shows the diesel fuel energy input as the percent energy from hydrogen increases for all three loading conditions.

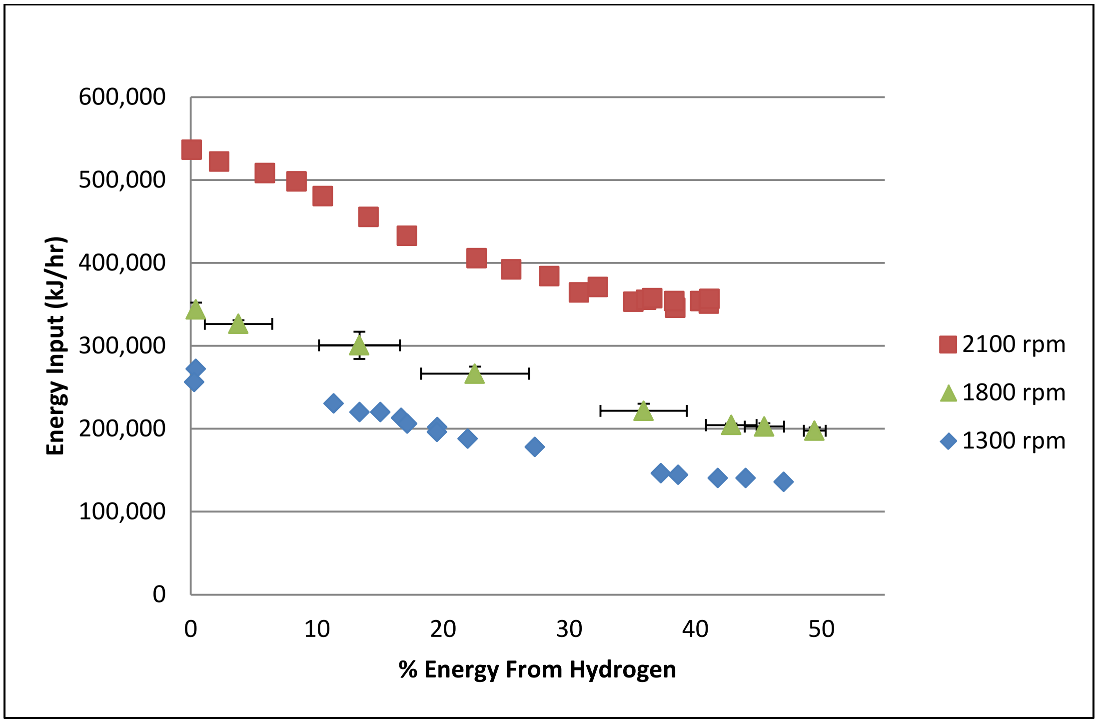

Figure 13. Diesel Energy Input as Hydrogen Energy Input Increases, All Loading Conditions

The general trend for all three data sets is for the diesel energy input to decreases linearly as the hydrogen is increased. At a point near 40% energy from hydrogen the governor stops decreasing the amount of diesel fuel in the combustion and the curves level off. It is estimated that this leveling off point is the lower limit of the governor to remove diesel fuel from the injectors. The leveling point is different for different engine speeds but is usually when hydrogen energy reaches 40% of the total fuel energy input. To see how this leveling point affects the total energy input Figure 14 shows both the diesel, hydrogen, and total energy input for the 1800 rpm tests.

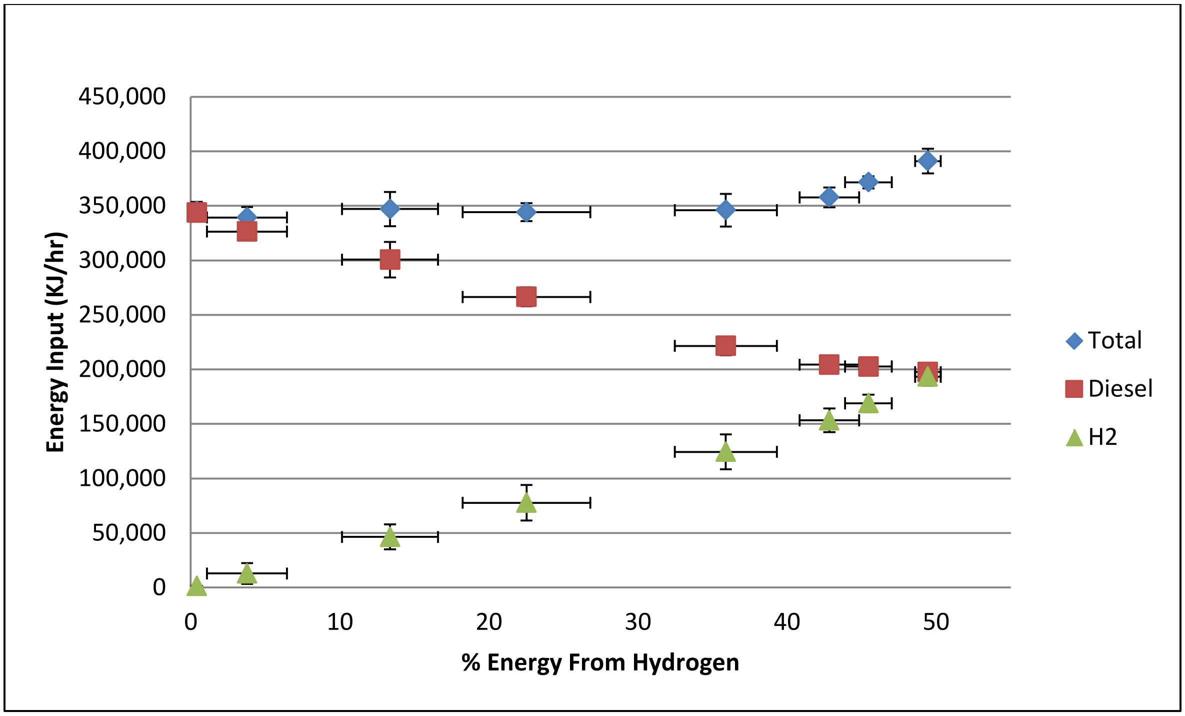

Figure 14. Comparing Diesel and Hydrogen Energy Input to Total Energy Input, 1800 rpm Test

The total energy input is just the sum of the diesel and hydrogen energy input. Near the 40% energy from hydrogen is the leveling point and this is where the total energy input starts to increase. The trend for the diesel fuel after the 40% energy from hydrogen is close to constant and the hydrogen trend is still increasing linearly. This is the reason why hydrogen was only added to this point. After the diesel fuel input stops decreasing the engine's efficiency starts to decrease.

5.4. Engine Efficiency

The objective of the project was to replace the energy of the diesel fuel with the energy of the hydrogen while maintaining normal operation. Having a decrease in engine efficiency constitutes an undesired change from normal operation. Energy Input in kJ/hr is used in the efficiency equations. To estimate the amount of hydrogen needed for a 50% diesel and 50% hydrogen input the diesel fuel input at the specific loading condition is converted into an energy flow rate. Then 50% of that flow rate is converted into a hydrogen mass flow rate. This assumes the burning characteristic remains unchanged. It was used as a starting point to see how much hydrogen was needed and how big of a hydrogen mass flow meter to purchase.

Engine Efficiency (η) is a way of determining the effectiveness of the fuel burn and how much of that energy is converted into usable power. In this report efficiency is calculated from the fuel energy input and the measured power output of the engine. The following equation shows how the engine efficiency was calculated.

$$\eta = \frac{P}{E_d + E_{H_2}} \tag{7}$$

P is engine power in kW, E_d is the energy input from diesel in kW, and E_{H2} is the energy input from hydrogen in kW. Figure 15 shows the engine's efficiency for all loading conditions as a function of percent energy from hydrogen.

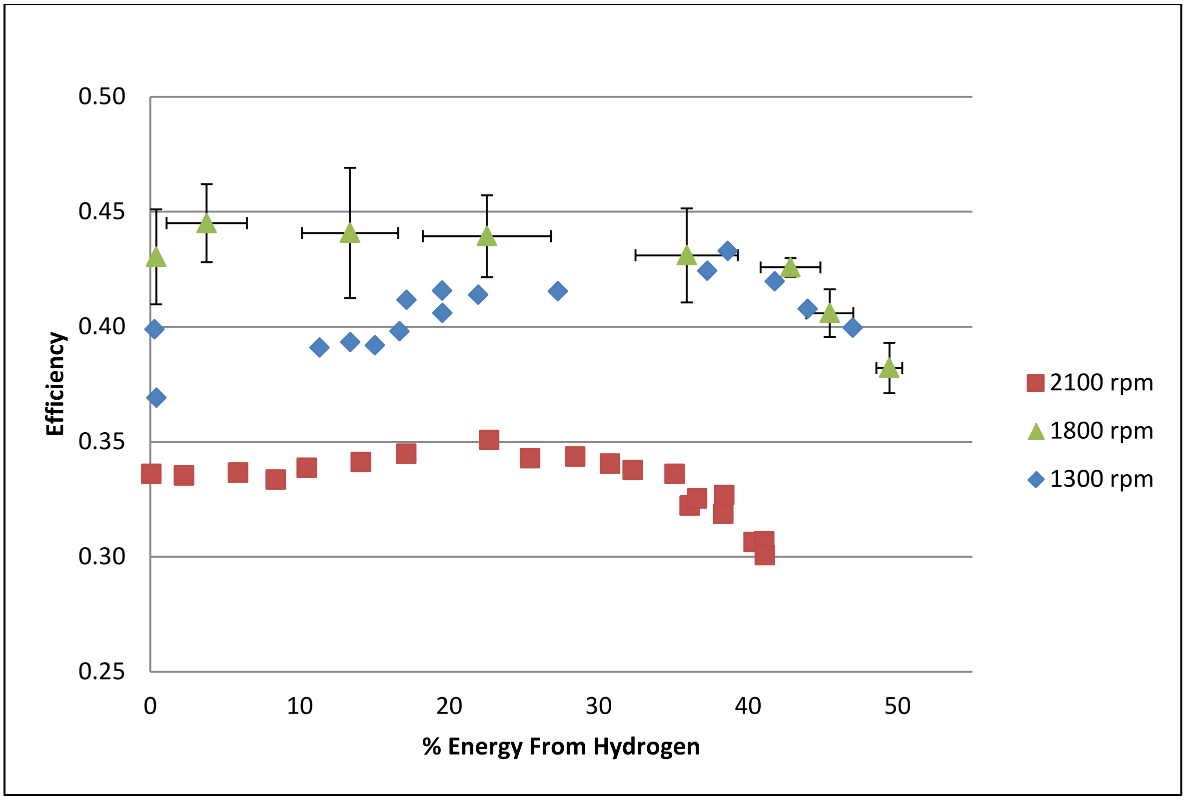

Figure 15. Engine Efficiency as Hydrogen Energy Input Increases, All Loading Conditions

Efficiency seems to trend depending on the loading condition. At 1300 rpm the efficiency seems to increase until 40% energy from hydrogen. Then it decreases back down to the initial value during normal operation near 50%. The other two loading conditions show a similar trend but at different levels of efficiency. At 1800 rpm and 2100 rpm the efficiency shows no real change until after the diesel leveling point, near 40% energy from hydrogen. This point discussed earlier in Figure 14 where the total energy input starts to increase. This energy increase combined with a constant power output, shown in Figure 12, explains the decrease in engine efficiency. With addition energy input but no power increase the efficiency must decrease.

With the engine efficiency decreasing a question arises as to where the extra energy is going. There are many hypotheses to where that energy could be going. It could be going into the engine's water jacket, raising the temperature of the engine coolant. It could be increasing the temperature of the exhaust gases, effecting emissions. The test setup did not have any equipment to measure the hydrogen content of the exhaust emissions. It is possible some of the hydrogen or diesel fuel was not consumed in the combustion process. Unburned diesel fuel would result in an increase in hydrocarbon emissions. Effects related to emissions will be discussed in a later section. It could also be released as noise. When the engine was running on a percentage of hydrogen higher than 35% a noise started to resonate. This noise got steadily louder as the percentage of hydrogen was increased.

5.4.1. Engine Coolant Temperature

Losing energy to the engine coolant would not be ideal. If this were the case then an increase in coolant temperature would be measured. For this experiment the engine's thermostat was disabled so such a temperature change could be measured. Before hydrogen was introduced into the engine during an experiment the engine coolant was allowed to reach a steady state with manual adjustments the external flow of the engine coolant heat exchanger. Once this point was reached no adjustments were made for the rest of the run. As the percentage of hydrogen increased so did the coolant temperature. Figure 16 shows the rise of coolant temperature as a function of percent energy from hydrogen.

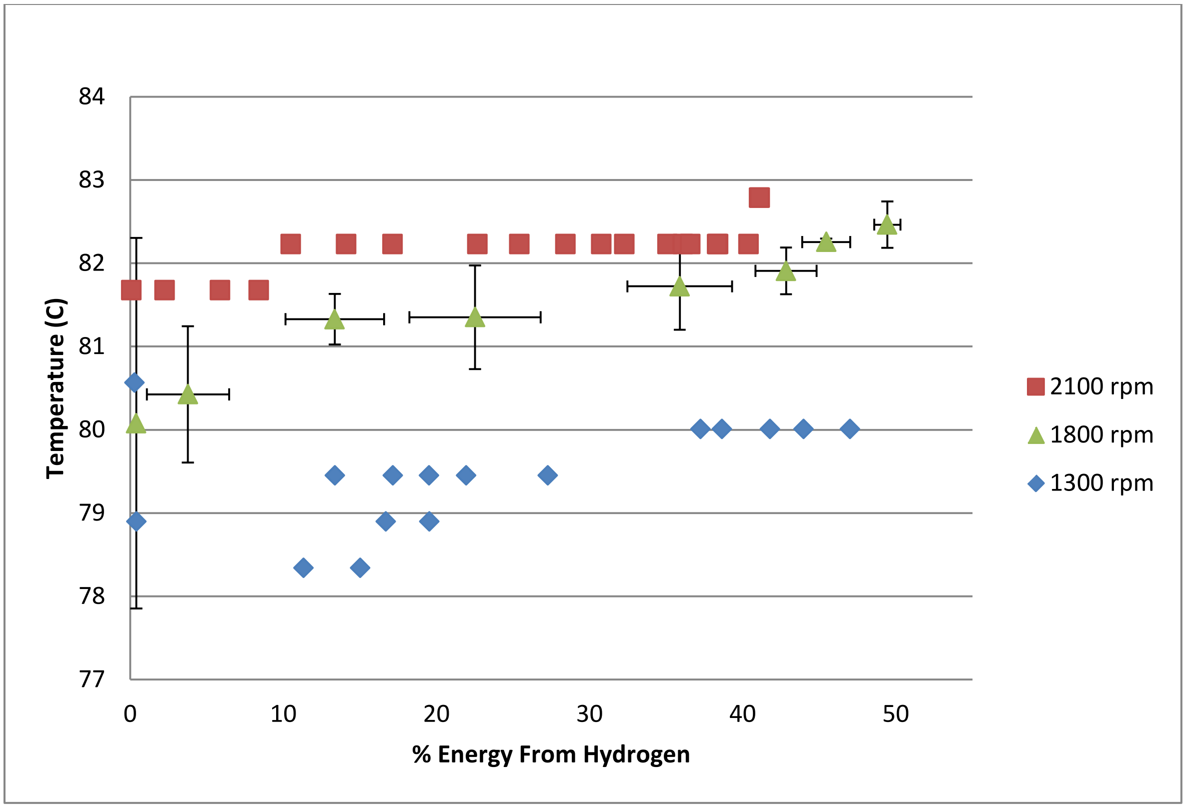

Figure 16. Engine Coolant Temp. as Hydrogen Energy Input Increases, All Loading Conditions

The trend for all three loading conditions was a temperature increase. The temperature increase for the 1800 rpm test shows the coolant temperature rise less than 2.4 ± 0.6 degrees C. The 2100 rpm test also shows an increase but it is smaller and the data for the 1300 rpm test is unreliable.

5.4.2. Exhaust Gas Temperature

The exhaust gas temperature rose about 100F from the beginning of the test where the engine is at steady state running on only diesel fuel to a 50/50 split. The higher temperature the exhaust is the less energy is being transferred to the pistons and into work therefore resulting in an efficiency decrease. Figure 17 shows how the exhaust gas temperature rises as a function of percent energy from hydrogen.

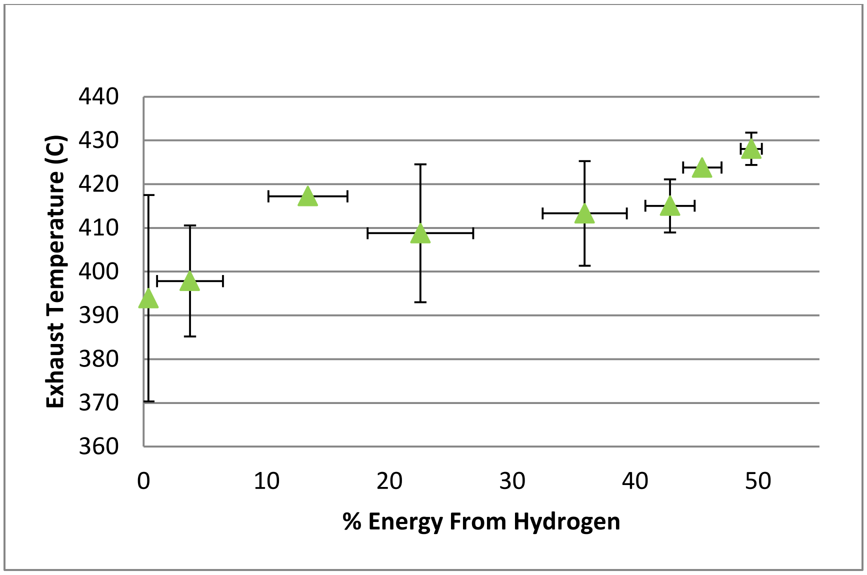

Figure 17. Exhaust Gas Temperature as Hydrogen Energy Input Increases, 1800 rpm Test

The temperature was taken from the exhaust stream immediately after the turbocharger turbine. The thermal couple was inoperative for one of the 1800 rpm experiments so the data for the exhaust gas has larger confidence intervals. The general trend shows the exhaust gas increasing in temperature from 393 ± 23 degrees C to 428 ± 4 degrees C accounting for a 9% increase in exhaust gas temperature.

5.4.3. Air Intake Volume

Intake air did slightly decrease as hydrogen was increased. Figure 18 shows the decrease of air as a function of hydrogen flow rate.

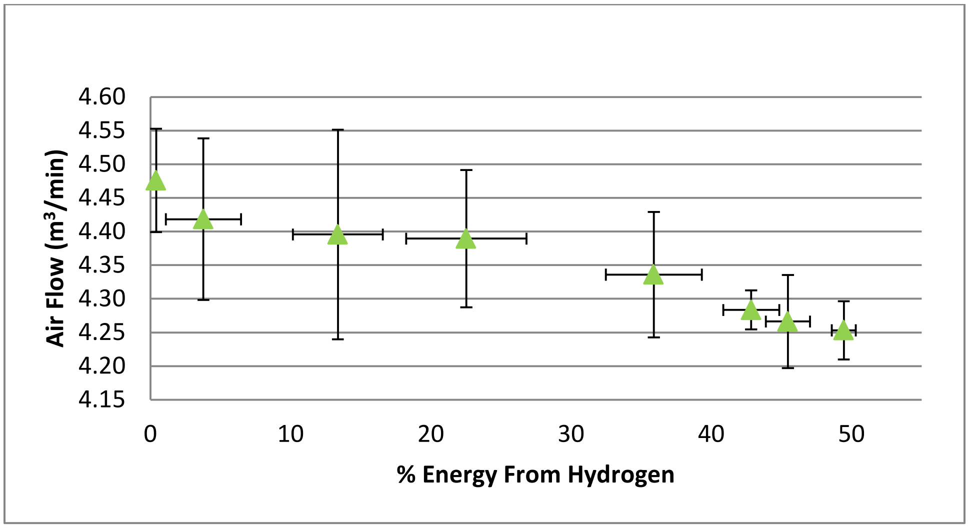

Figure 18. Air Intake Volume as Hydrogen Energy Input Increases, 1800 rpm Test

The air intake volume drops a total of 0.22 m^3/min from normal operation up to 50% energy from hydrogen. There are two possible explanations for this.

The first explanation could be as simple as lab room air density changes. The 0% energy from hydrogen was recorded at the beginning of the test, when the lab is cool. The 50% energy from hydrogen was recorded at the end of the test, when the lab was warmest.

The second explanation could be that the hydrogen was displacing the air as it was being injected into the intake manifold. This explanation seems less likely as the hydrogen is injected after the turbo compressor so the intake air does not get displaced by the input of hydrogen.

5.5. Engine Emissions

The emissions equipment in these experiments was not accurate enough to compare with the results with the government standards mentioned earlier in this paper but it is worth noting that the standards call for a reduction in emissions with each successive tier, tier 4 being the most stringent. The emissions data for these experiments will be comparing normal operation to hydrogen operation.

Emissions overall did not change very much. As was expected carbon emissions were decreased when running on a diesel hydrogen mixture. Less diesel fuel in the cylinder means fewer carbon emissions. Carbon dioxide (CO_2) emissions were decreased but carbon monoxide (CO) emissions remained constant throughout the test. Hydrocarbons (HC) increased slightly but the resolution on the emissions tester did not give a clear picture as to what was happening with either HC or CO emissions. Figure 19 shows all the emissions measured for the 1800 rpm tests.

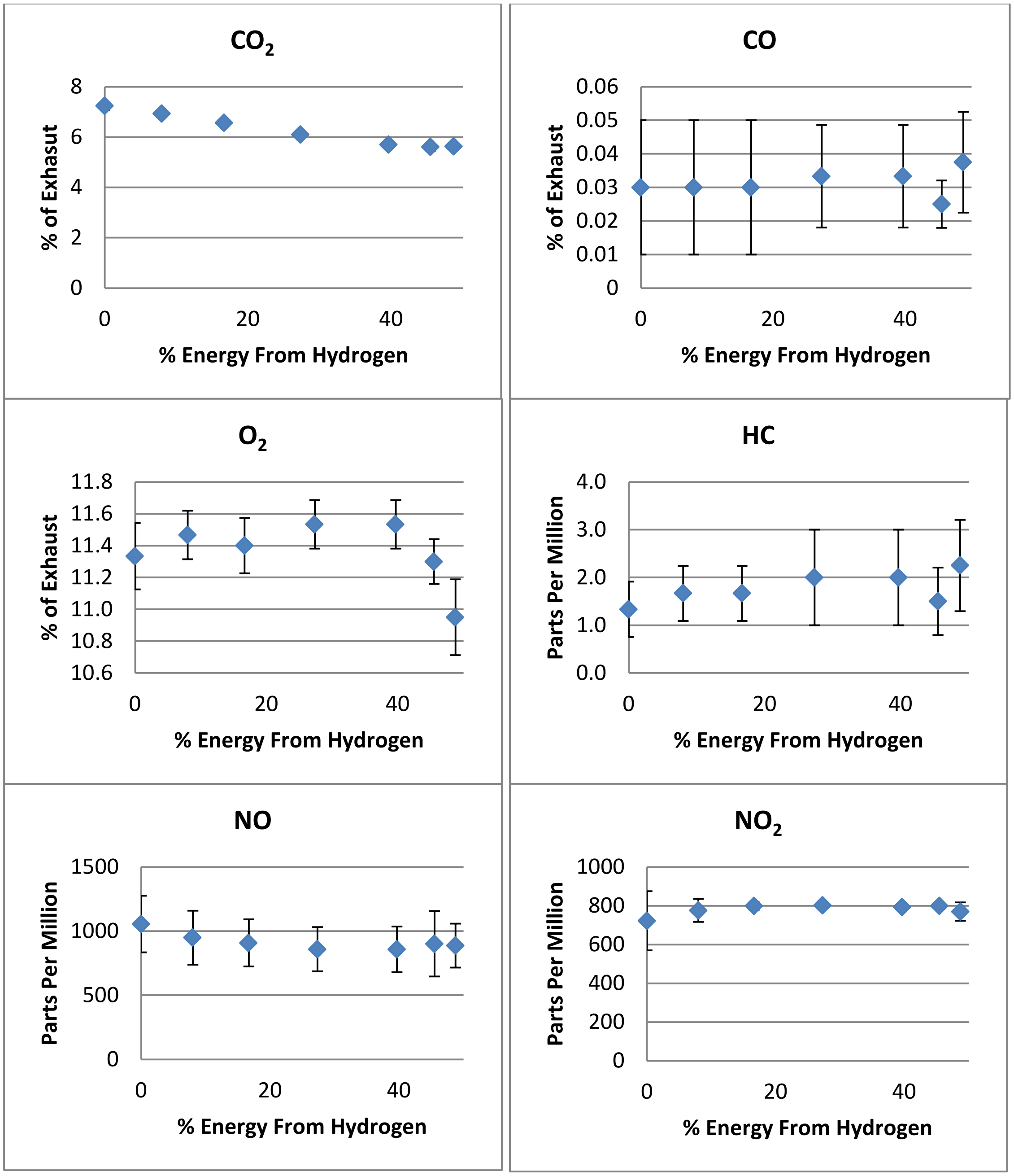

Figure 19. All Engine Emissions as Hydrogen Energy Increases, 1800 rpm Test

Oxygen (O_2) does start to decrease at the higher end of the hydrogen flow rate. At this point there is more combustible fuel in the cylinders than during standard operation which may account for the decrease. The 40% mark is the point referred to earlier where the engine's governor stops decreasing the amount of diesel fuel injected. With the increase in combustible fuel in the cylinder as well as elevated engine temperatures, a more complete combustion could be taking place thus resulting in less oxygen in the exhaust. In addition the amount of intake air decreases as time in the experiment goes on. As the lab heats up from the engine the air density decreases and there is less air entering the engine. The decrease in air intake was shown earlier in Figure 18.

CO_2 is the most predictable of the exhaust gasses. It deceases at a linear rate as hydrogen is increased. Under normal operation CO_2 makes up 7 percent of the engine's exhaust. When hydrogen accounted for 50% of the energy input the CO_2 emissions are decreased by 20% to 5.6 percent of the exhaust. Right before the engine efficiency starts to drop off at the 40% energy from hydrogen the CO_2 emissions make up 5.7 percent of the exhaust. This shows the amount of CO_2 in the exhaust is related to the amount of diesel fuel in the cylinder because once the 40% energy from hydrogen point is hit the diesel fuel does not decrease anymore and the CO_2 emissions do not change anymore. The CO_2 emissions were very repeatable and the largest error for the CO_2 measurements was ±0.15% of exhaust.

CO and HC emissions are much more uncertain. They both do not show any trend based on the amount of hydrogen injection. The error was large for both of these parameters. For CO the average error was ±0.016% of exhaust. This equates to a 50% error for most of the data. The same is true for HC, the average error was ±0.77 ppm in exhaust, this equates to a 44% error. CO and HC were not very repeatable. The resolution of the testing device made it unclear what was really happening. For example, the display for the CO emissions gave an output in hundredths (0.00). This means during the tests a change in the display of 0.01 was a 30% change in the data.

Nitrogen emissions seem unaffected by the percentage of hydrogen. Nitrogen monoxide (NO) never changes by more than 200 ppm over the length of the test. It initially starts high and is at its lowest when the hydrogen percentage is 40% after this it goes up again. Nitrogen Dioxide (NO_2) emissions do not show a notable change for the whole test. They change by no more than 50 ppm but with the largest error being at the lowest point no change can be determined. This is an unexpected outcome as usually NO_x emissions will increase with increased combustion temperatures.

5.6. In Cylinder Pressure Curves

Analysis of the pressure curves from inside the cylinder is a good way to answer some of the question from the previous section. There are two major changes to the pressure curves as the percentage of hydrogen increases. The most noticeable is a rise in peak pressure and the second being the location of that peak pressure. Figure 20 shows the pressure curve from normal operation running at 1800 rpm and 691 kPa MEP with 0% of the energy coming from hydrogen.

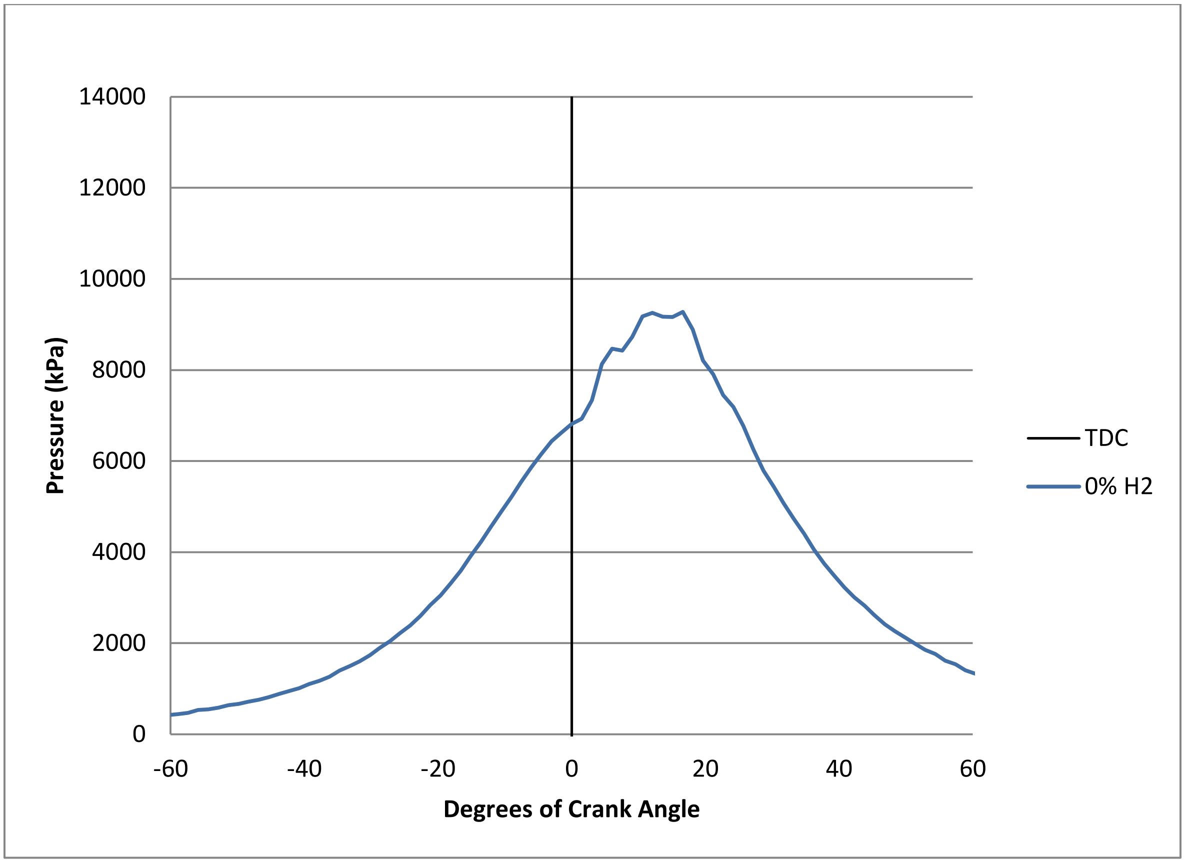

Figure 20. Cylinder Pressure Curve during Power Stroke, 0% Hydrogen

The curve shows a steady pressure increase before TDC. Then after TDC there is a sharp increase in pressure. This sharp increase is when the air fuel charge ignites. The peak cylinder pressure is spread out over a 10° crank angle there is no single sharp peak pressure point. There are not jagged changes in cylinder pressure and peak pressure is after TDC. The normal curve changes as hydrogen is added to the engine.

The normal pressure curve does not change significantly with a small amount of hydrogen added. Figure 21 shows the pressure curve for operating at 1800 rpm and 691 kPa MEP with 32% of the energy coming from hydrogen.

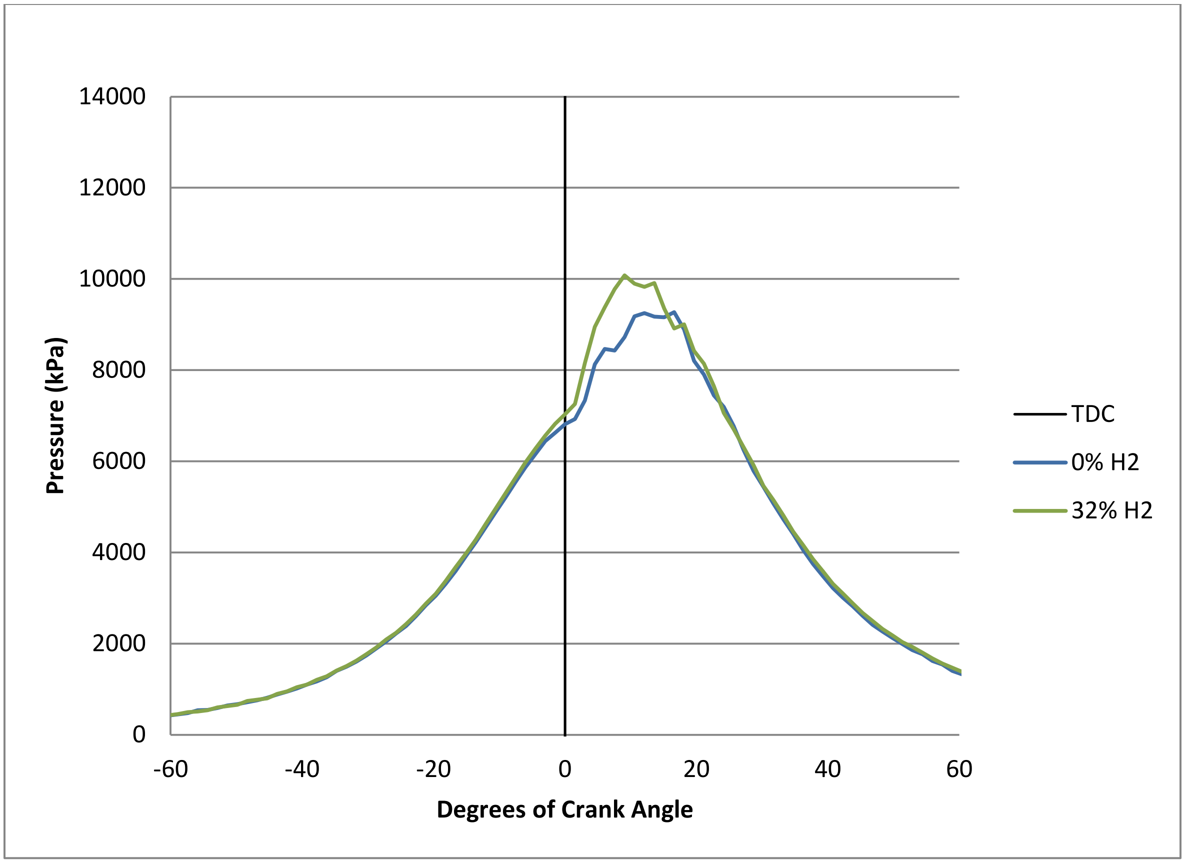

Figure 21. Comparing 0% and 32% Energy from Hydrogen Cylinder Pressures during Power Stroke

The peak pressure does increase and the location of the peak pressure does advance in the power stroke cycle. The peak pressure raises about 1000 kPa, about 11%, when hydrogen accounts for 32% of the total energy input. The location of the peak pressure also advances 3 degrees earlier in the power stroke bringing the peak pressure closer to TDC. This overall rise in cylinder pressure would increase the mean effective pressure in the cylinder. Peak pressure must occur after TDC for the engine to operate efficiently.

If the peak pressure is before TDC then two things happen. The first is that before TDC the piston is still moving up toward the cylinder head compressing the gas inside. If the air fuel mixture ignites before the compression stroke is complete the compression of expanding gasses will take in more work reducing the engines efficiency. Additionally the compression of expanding gasses produces a lot of noise and extra wear on engine parts greatly reducing the engine life. This event is sometimes referred to as engine “ping” or “knock”.

Operating the engine on a mixture of 32% energy from hydrogen does not change the basic operation of the engine. Once the percentage of hydrogen increases above this point negative affects begin to be observed inside the combustion chamber. Figure 22 shows the pressure curve for operating at 1800 rpm and 691 kPa with 40% of the energy coming from hydrogen.

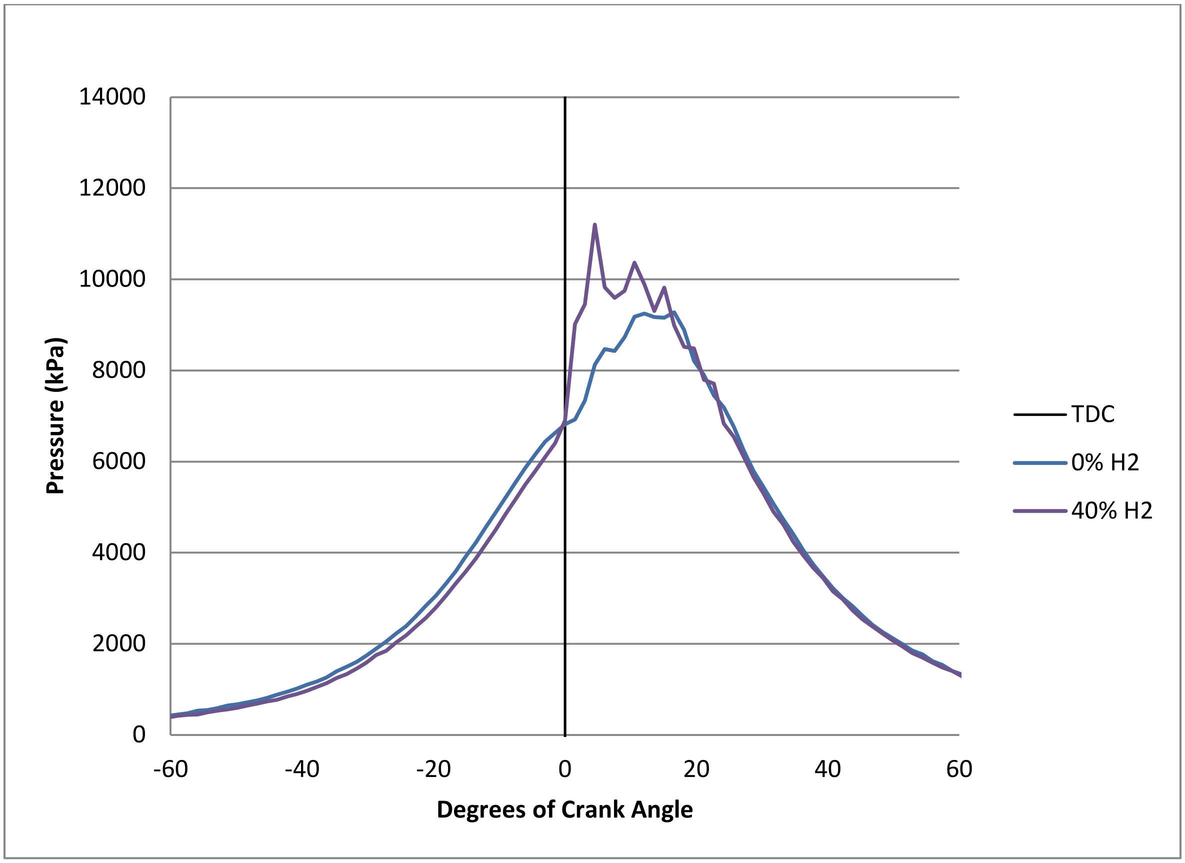

Figure 22. Comparing 0% and 40% Energy from Hydrogen Cylinder Pressures during Power Stroke

This is where the pressure curves start to change in a negative way. The peak pressure is still climbing as hydrogen is being added in greater quantities. The peak pressure is now 2000 kPa, or 22%, higher than during normal operation. This is only a partial throttle test so this engine was built to withstand much higher cylinder pressure but these same characteristics would take place if the engine was running at full throttle. At full throttle a 22% rise in peak pressure could result in mechanical failure.

The location of the peak pressure is also continuing to advance earlier in the power stroke. It is now only 4 degrees after TDC. At this point a third characteristic begins to be observed. A pressure fluctuation in the power stroke shows the pressure rise and fall multiple times. This is not preferable and this is engine knock. The pressure front is sweeping back and forth inside the cylinder across the sensor causing sudden pressure changes.

As the percentage of hydrogen increases, so does the peak cylinder pressure. The reason for this is more combustible fuel inside the cylinder at the moment of ignition. Hydrogen burns faster than diesel fuel.

The hydrogen and air are premixed and are near a homogeneous mixture. The diesel fuel needs to be injected, vaporized, and mixed with the air before it can burn. When the first particles of diesel fuel start to burn this ignites all the hydrogen. With the hydrogen and diesel fuel burning at the same time the peak cylinder pressure increases quicker than before. Once the engine's governor stops removing diesel fuel, the amount of combustible material inside the cylinders is more than normal operation. Figure 23 shows the pressure curve for operating at 1800 rpm and 691 kPa with 50% of the energy coming from hydrogen.

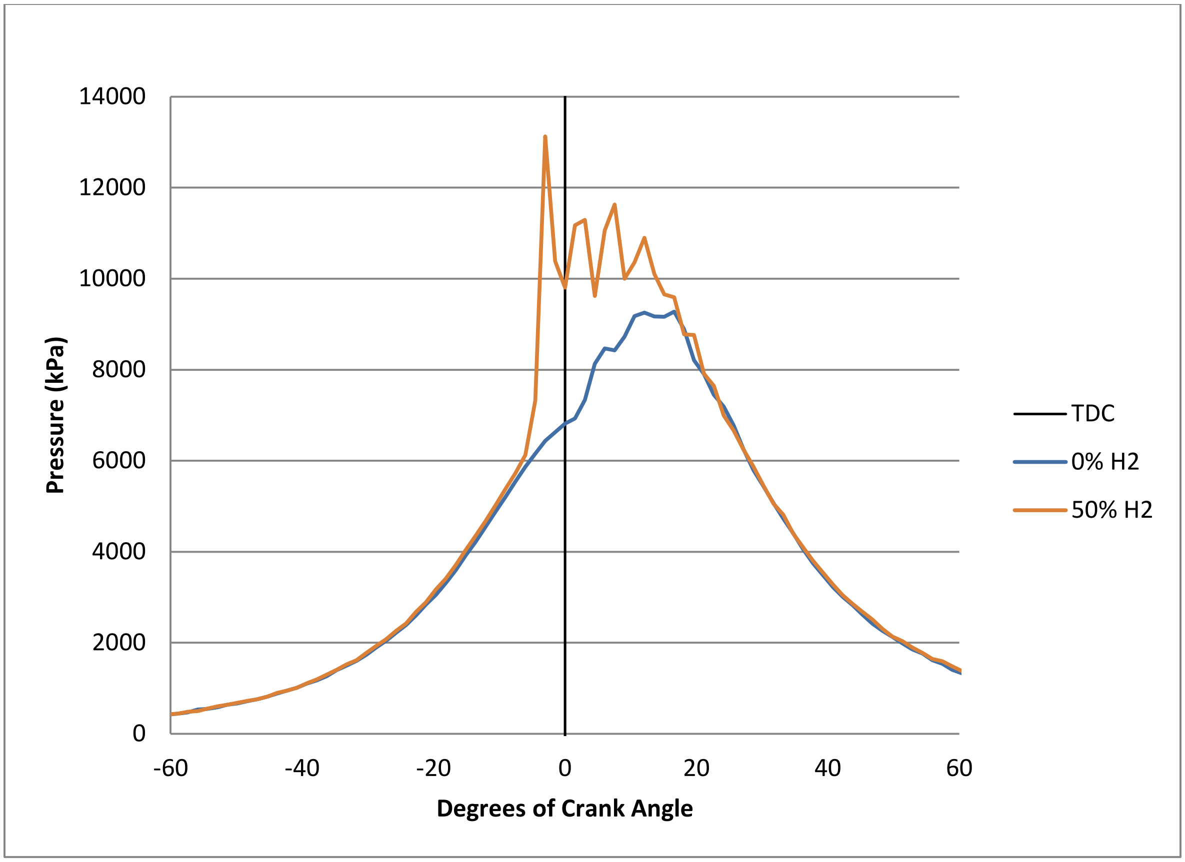

Figure 23. Comparing 0% and 50% Energy from Hydrogen Cylinder Pressures during Power Stroke

At this point the pressure characteristics inside the cylinder are completely different from normal operation. There are a series of issues. The peak pressure is now 3 degrees before TDC. It is also greater than 13000 kPa, about 44% higher than normal operation. Engine knock is very evident with pressure fluctuations of up to 1700 kPa after the initial peak. If the engine were to run in this state for an extended amount of time mechanical failure is probable.

The injection timing of the diesel fuel needs to be changed. When the engine is running normally the diesel fuel must be injected early so it has time to mix with the air before igniting. When running on a combination of diesel fuel and hydrogen the hydrogen is already mixed with the air upon entering the cylinder. Not all the diesel needs to be mixed with the air in order for the engine to produce power. Once the first molecule of diesel ignites, it sets off the hydrogen. This could in turn accelerate the vaporization and mixing of the remaining diesel fuel.

With the fuel burning faster, the pressure rises to a higher peak, and also reaches that pressure earlier in the power stroke. In Figure 23 the peak pressure is at a different location when running normally than when running with 50% hydrogen. The more hydrogen in the cylinder means the earlier the peak pressure is reached because hydrogen burns faster than diesel fuel. The diesel injection timing determines ignition, and subsequent burning of all fuel inside the combustion chamber. When running on large amounts of hydrogen the diesel injection timing needs to be retarded. In the case of 50% energy from hydrogen the diesel injection timing needs to be retarded by about 16 degrees based on these experiments for this engine.

The engine experienced very little changes from 0-35% hydrogen operation. The efficiency did not change and the total energy input did not change. The 35% mark is where the hydrogen starts to noticeably influence the combustion process. The peak pressure and peak pressure location begin to noticeable change from normal operation. Above 35% hydrogen engine knock starts to occur. As the amount of hydrogen is increased the sound increases. It is a steady rhythmic sound that is predictable.

As more of the combustion energy comes from hydrogen and the combustion speed increases the combustion process begins to change from the Diesel cycle to be more like the Otto cycle. In the Diesel cycle the model is a constant pressure volume expansion and with the Otto cycle the model is a constant volume pressure rise. With all the hydrogen burning very quickly this represents more of a constant volume pressure rise. This is not necessarily a bad thing but it is something to take into account when designing an engine. With the rapid rise in cylinder pressure the curve becomes more unstable as well showing signs of engine knock.

5.6.1. Pressure Curve Overlay

To see the overall effect of progressively adding hydrogen, all of the pressure traces were overlaid. As was discussed above, the three things that change are the peak cylinder pressure, the timing of the peak cylinder pressure, and the stability of the cylinder pressure over the power stroke. Figure 24 shows all the pressure curves overlaid to see how the addition of hydrogen changes the combustion.

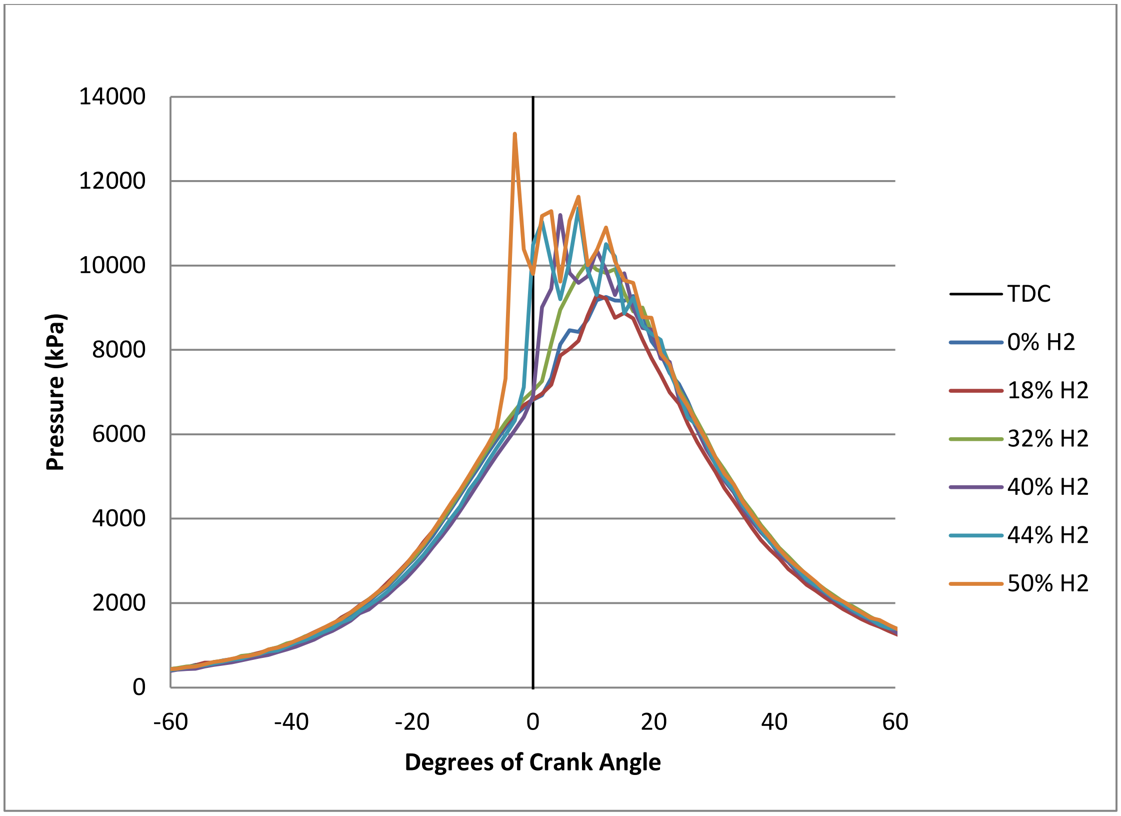

Figure 24.   Comparing all Cylinder Pressures during Power Stroke

The baseline engine with no hydrogen is represented by the lowest line in the graph above. It can be seen from this graph that the pressure changes happen incrementally as more hydrogen is added. The peak pressure increases and advances in the piston cycle each time an additional amount of hydrogen is added. The engine knock also increases greatly with large amounts of hydrogen. There is a difference of around 16 degrees of crank angle between the normal operation peak pressure and the 50% energy from hydrogen peak pressure.

5.6.2. Cylinder Peak Pressure Variation

Also of note when the engine was running at high quantities of energy from hydrogen the peak cylinder pressure varied by a much larger percentage than when the engine was running under normal conditions. Figure 25 shows the peak pressure for seven different power stokes while the engine is operating normally and with 0% energy from hydrogen.

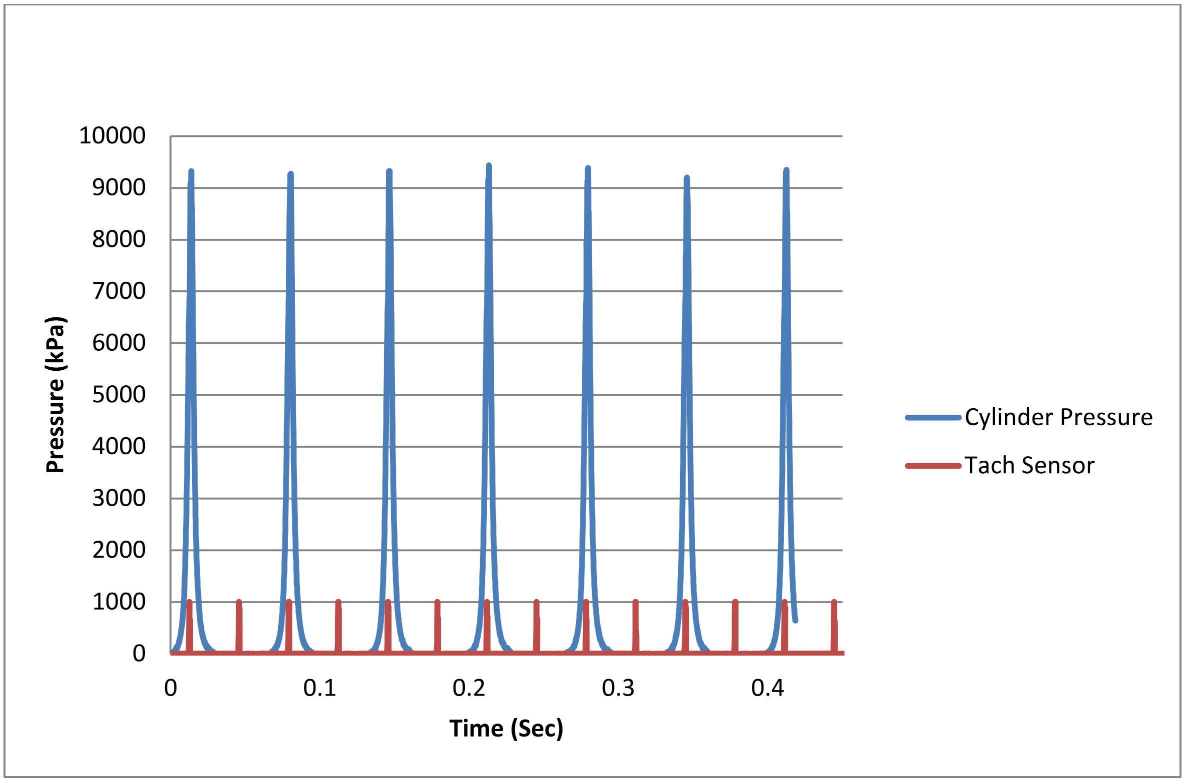

Figure 25. Comparing Cylinder Peak Pressure Over 7 Power Strokes, 0% Hydrogen

The peak pressure from cycle to cycle is stable and repeatable. The peak pressure fluctuates by about 1-2% from power stroke to power stroke. The consistent pressure is representative of how the engine was designed to operate. As the percentage of hydrogen was increased and engine knock became more evident the peak pressure began to fluctuate greatly. Figure 26 shows the peak pressure from eight different power strokes.

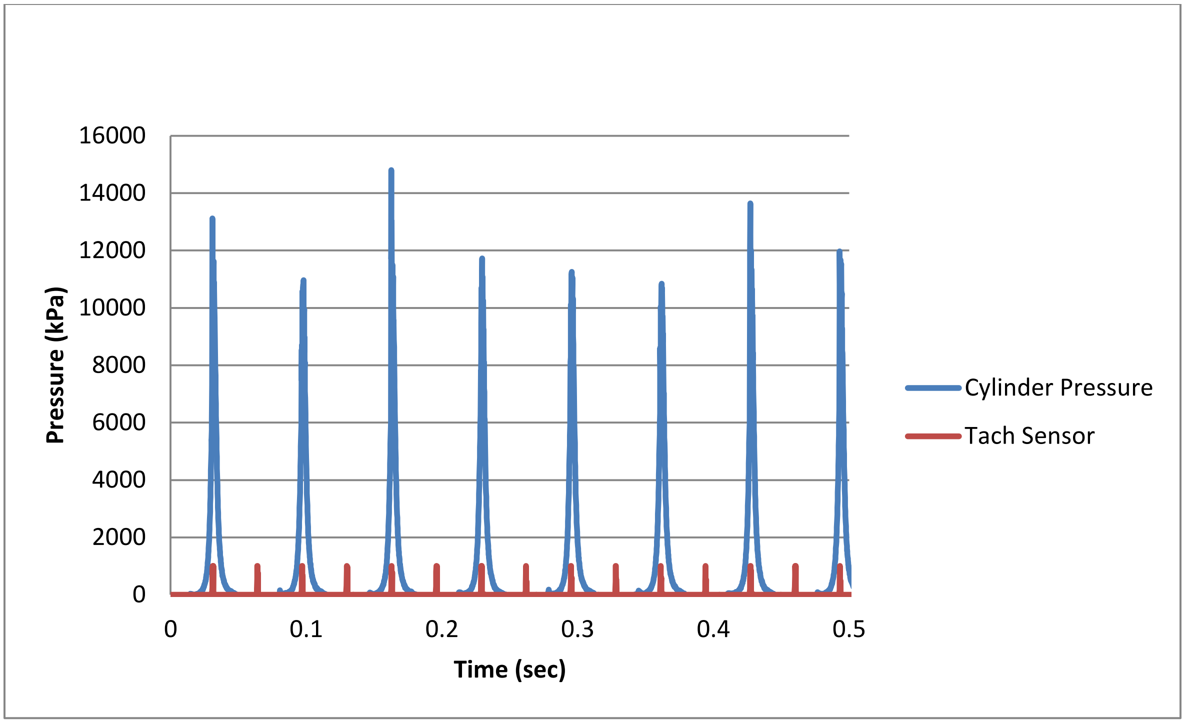

Figure 26. Comparing Cylinder Peak Pressure Over 8 Power Strokes, 50% Energy from Hydrogen

The peak pressure from cycle to cycle is unstable and not repeatable. The peak pressure fluctuates by about 10-25% from power stroke to power stroke. This engine operation shows the increased engine knock during engine operation. There are a few things which could be happening in this situation.

It is possible that because of the pre mixed hydrogen air fuel mixture and the fact that hydrogen burns faster than diesel fuel, not all the diesel fuel is burning. If there were amounts of unburned diesel in the cylinder this would show up as increased particulates in the exhaust gases. During the test it was observed that the amount of hydrocarbons in the exhaust did increase.

The other possibility is that the in cylinder pressure sensor was not recording data fast enough to catch the exact peak pressure for every power stroke. Even though the data acquisition system was recording at 1920 samples per revolution the difference between the peak pressure recording and the next data point was up to 21% lower. If the data acquisition system did not take a reading at the peak pressure this would then give a false peak pressure up to 20% lower than the true peak pressure.

5.7. Kubota Engine Testing Results

Although not the main focus of this report additional experimentation was done with a 2,000 cubic centimeter diesel Kubota engine. The engine design was similar to the CAT engine although the Kubota did not have an intercooler after the turbocharger. Both engines had a mechanical governor system to control the engine speed. Table 2 shows the loading conditions of the Kubota engine.

Table 2. Kubota Loading Conditions

Speed	Torque	Power	MEP
RPM	Nm	kW	kPa
1400	104	15	653
1670	122	21	767
2000	129	27	811

The test runs with this engine also did not have all the same sensor equipment as the CAT engine tests. These tests only had the data acquisition equipment which accompanied the dynamometer. This means only power and fuel consumption was recorded. A cylinder pressure sensor was not installed and no emissions data was recorded. These tests were done just to see if the diesel energy replacement with hydrogen would be the same on both engines. These results would give a quick comparison between two different engine designs.

5.7.1. Kubota Power Output

Three different loading conditions were run and each condition was only run once. The test conditions and procedures were the same as the CAT engine. The engine power output was held constant as hydrogen was added to the intake manifold through the same hydrogen injection system as the CAT engine. Figure 27 shows the power output of the Kubota engine for three different loading conditions.

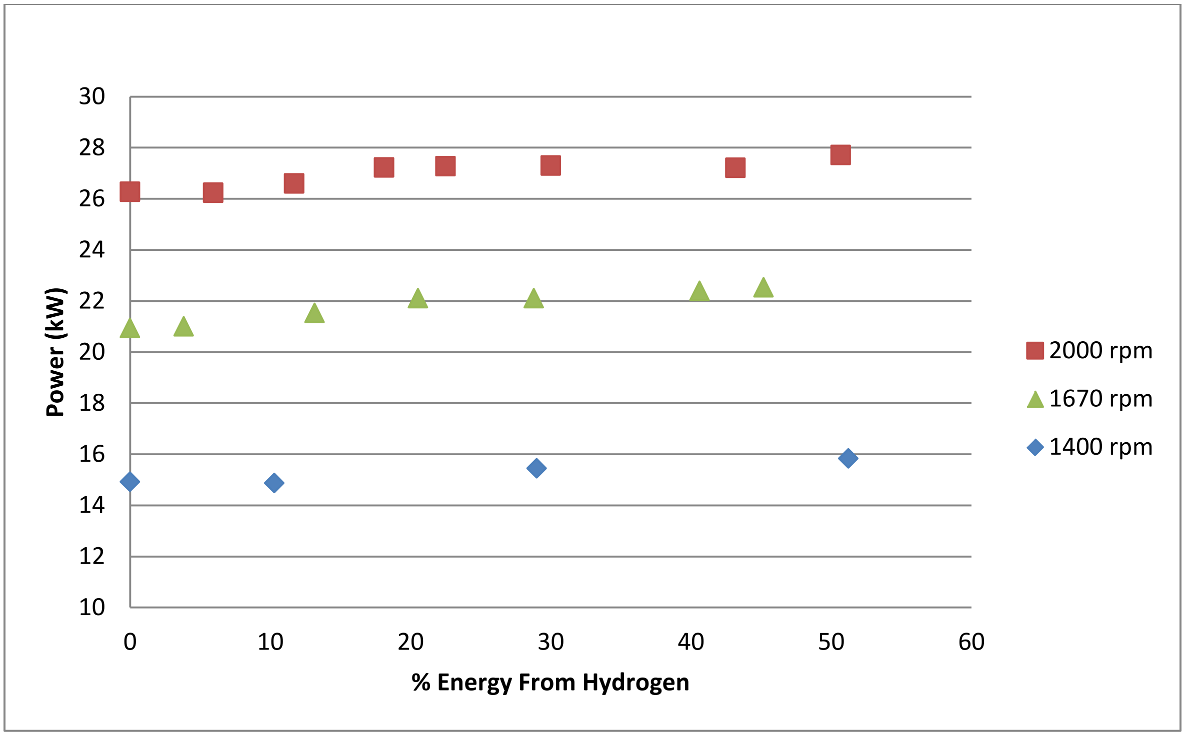

Figure 27. Kubota Engine Power Output as Hydrogen Energy Input Increases, All Loading Conditions

As the percentage of hydrogen was increased the power output remained relatively constant. As a trend the power output did slightly increase from 0 to 50% energy from hydrogen more than the CAT engine did.

5.7.2. Kubota Energy Input

As expected, although to less effect than the CAT engine, the engine’s governor reduced the diesel fuel input to hold the power output of the engine constant. This follows with the CAT engine test. Figure 28 shows the diesel energy input for all loading conditions as the percentage of hydrogen added increased.

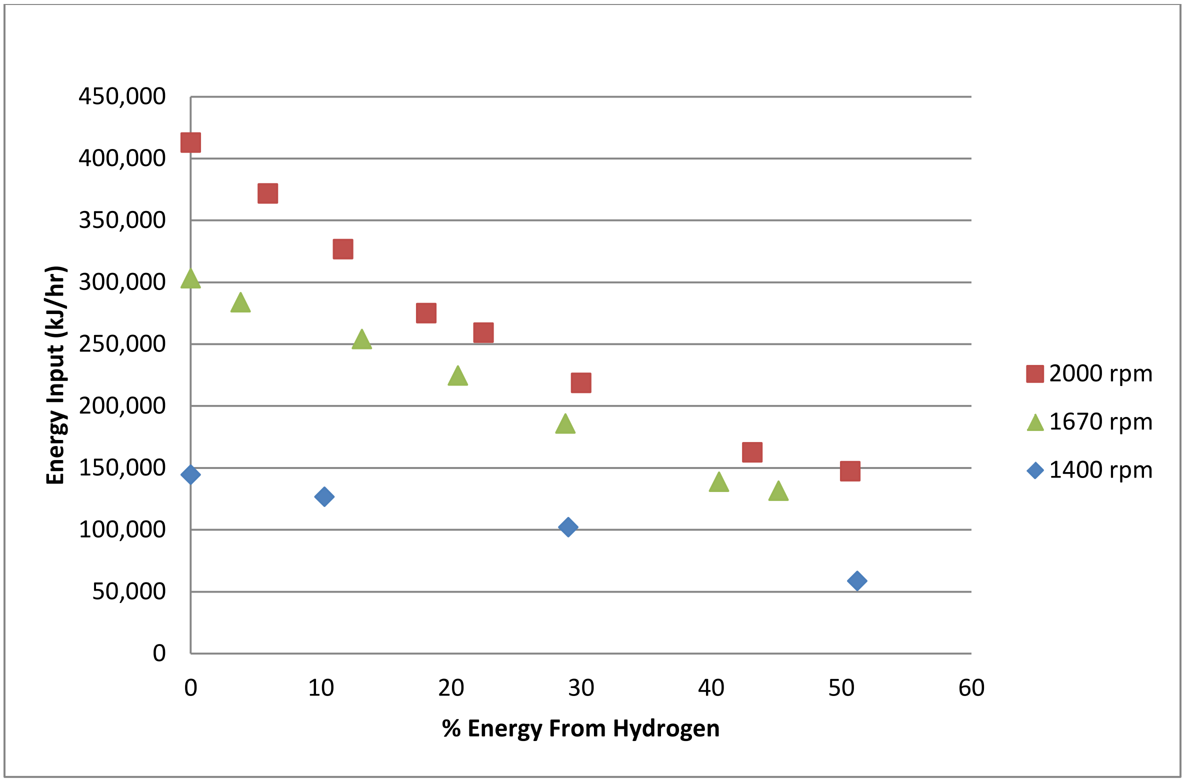

Figure 28. Kubota Diesel Energy Input as Hydrogen Energy Input Increases, All Loading Conditions

As the percentage of hydrogen added to the intake charge increased the amount of diesel injected decreased. Again these trends are the same as observed with the CAT engine. A difference of note though is the overall energy input for this engine does not differ that much from the CAT engine. This engine was producing about half the power the CAT engine was but the energy input is not half.

For example, the 1670 rpm test, running on diesel only the Kubota engine was receiving 300,000 kJ/hr of energy from diesel fuel. For the 1800 rpm tests running on diesel only the CAT engine was receiving about 340,000 kJ/hr. The power output of the Kubota was 22 kW and the power output of the CAT was 42 kW. This means the Kubota and CAT engine's had respective efficiencies of 0.43 and 0.25.

5.7.3. Kubota Engine Efficiency

The Kubota was producing half as much power but requiring almost 90% of the fuel the CAT required. Based on these observations one can assume that either the Kubota is a less efficient engine or the sensors were out of calibration for the tests. Figure 29 shows the Kubota engine efficiency as the percentage of hydrogen is increased.

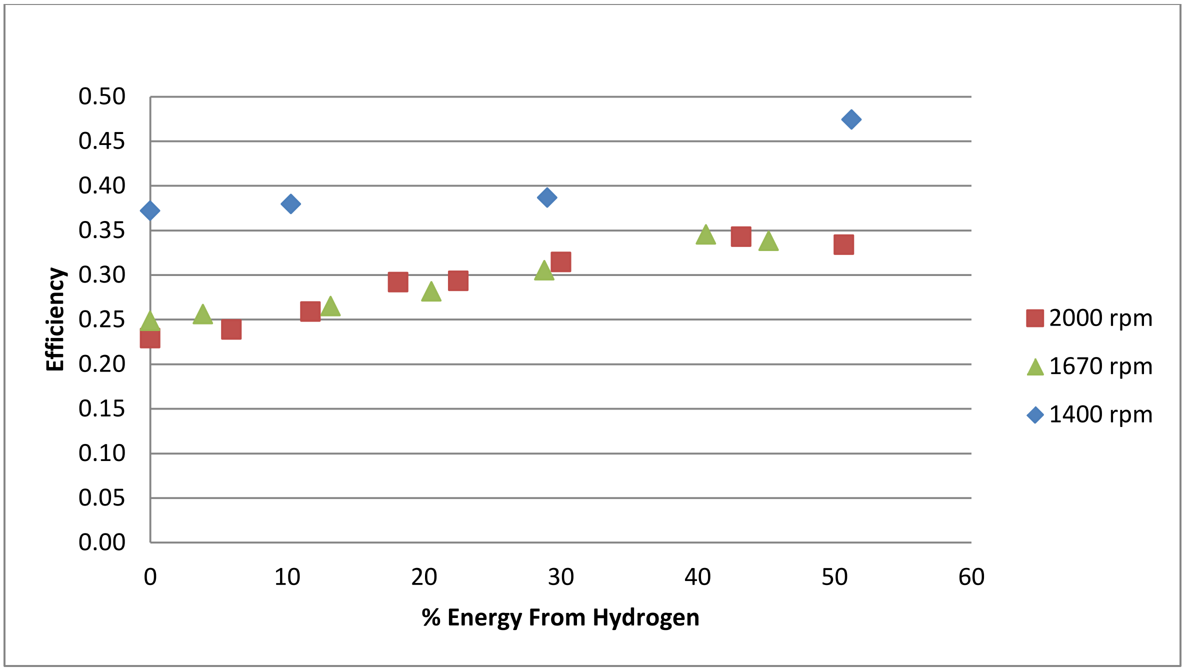

Figure 29. Kubota Engine Efficiency as Hydrogen Energy Increases, All Loading Conditions

From the figure it can be observed that the engine efficiency increased as the percentage of hydrogen increased. This is not the trend that was observed with the CAT engine. This data also tends to contradict itself. At 1400 rpms the engine efficiency stayed constant until the hydrogen input increased above 40%. At the other two engine speeds the engine efficiency increased until the hydrogen input increased above 40%. These are opposite trends which are not expected and would lead to the hypothesis that one or more of the sensors were out of calibration for this testing.

The diesel fuel flow sensor was oversized for this testing. The entire test was performed using less than 10% of the span of the flow sensor. The sensor would either give a reading or give zero reading. The sensor is rated for a minimum flow rate and this test was performed below that minimum flow rate. If the diesel flow sensor was overestimating the diesel flow rate that would explain the lower than expected engine efficiencies under normal operation.

Under normal operation the diesel fuel is the only fuel energy contributing to the engine efficiency calculations. As hydrogen is added though diesel fuel energy contributes less to the efficiency equation and hydrogen fuel energy contributes more. As the overestimated fuel gets reduced and is replace by an accurately measured fuel the overall result would be an apparent increase in overall engine efficiency as the total energy input would decrease.

6. CONCLUSION

6.1. Summary

The objectives of these experiments were to see the effects of hydrogen on the performance of a diesel engine. The purpose for choosing hydrogen was to reduce carbon fuel input thus reducing carbon emissions and to switch a fossil fuel source with a sustainable fuel source.

Total fuel mass decreased but total energy input increased at the 50% hydrogen mark. As the engine got to the point where the governor could no longer remove diesel fuel the total energy input started to exceed the amount used in normal operation. Hydrogen has more energy per unit mass so near the 50% hydrogen point the total fuel mass input decreased.

Engine efficiency was unchanged until the 50% hydrogen mark was reach where the efficiency began to decrease, thus necessitating additional engine modifications. An engine which is running on only a 35% hydrogen mixture would only require the addition of the hydrogen plumbing and there would be no change from standard engine operation. The efficiency would be unchanged, there would be no extra engine noise, and carbon emissions would be decreased.

Emissions showed a decrease in carbon emissions but no change in nitrogen emissions. Oxygen emissions greatly decreased near the 50% hydrogen mark and this could be due to a more complete combustion due to addition fuel in the cylinder or less air charge in the combustion chamber. Overall the emissions equipment was not good enough to produce credible results to use for discussion.

Cylinder pressure curves showed that with an increase in the percentage of hydrogen the peak cylinder pressure rose, from 9000 kPa to 13000 kPa, and the location of the peak pressure in the power stroke advanced, from 10° after TDC to 3° before TDC, in the piston cycle. These changes produced a significant amount of engine knock. This knock is due to the fuel in the combustion chamber burning up almost completely at the beginning of the power stroke. In a compression ignition engine combustion of the fuel is supposed to occur over the majority of the power stroke. This changes the overall way the energy is released in a negative way.

To overcome these issues it is recommended that for future work the diesel injection timing be retarded to see if this results in decreased engine knock and therefore the ability to add a larger percentage of hydrogen. Retarding the diesel fuel injection should delay the peak cylinder pressure and move the overall energy release into a more usable portion of the power stroke.

Adding large amounts of hydrogen changes the engine model from a Diesel cycle to and Otto cycle. The premixed hydrogen/air mixture burns almost instantly rising the pressure rapidly. This may require multiple, smaller, hydrogen injections at very high hydrogen percentages if the energy distribution needs to be spread out over the power stroke to mimic the Diesel cycle.

6.2. Future Work

This research is an early component of the alternative fuel research program at NDSU. There are many more items to research in terms of fully understanding the opportunities and constraints related to diesel hydrogen duel fuel operation. The first thing is diesel injection timing changes necessary to inject more hydrogen. The diesel injection needs to be computer controlled so when the engine is running on diesel only it operates with one set of injection points and when it is running with hydrogen it runs a different set of injection points. It is hypostasized that if the diesel injection timing was delayed the percent energy of hydrogen could go up to or past 90%. In addition of delaying the timing; the amount of diesel fuel injected needs to be controlled. Near the 90% hydrogen region the amount of diesel injected will need to be greatly reduced.

Mixing may also be an issue. Near the 50% hydrogen range the peak pressure changed by as much as 3,900 kPa from power stroke to power stroke. This may be because of mixing. If the hydrogen is not mixing evenly with the intake air charge through the manifold and more hydrogen is entering one cylinder as opposed to another the engine efficiency would be affected. Additional fins inside the intake or perhaps multiple injection point would help fix this problem.

Other parameters that need more research are emissions. The emissions data collected in this experiment shows a decrease in carbon emissions but all other emissions returned inconclusive results. If the nitrogen emissions did show to be a problem at higher concentrations of hydrogen then some kind of emissions control would need to be implemented such as exhaust gas recirculation. This process could be done with variable valve control to trap some of the exhaust gasses. A better exhaust gas analyzer needs to be used for future experiments to better understand exhaust gas emissions.

Fatigue tests need to be done to see if any hydrogen embrittlement happening in the intake manifold, cylinder walls, or engine head. No fatigue tests were done with this report only a proof of concept but if this were to go into the field it would need some durability and fatigue testing to see how the hydrogen affects the integrity of the engine.

Biodiesel could also be used to substitute in for the carbon diesel fuel. This would make the engine a biodiesel hydrogen hybrid engine in which case there would be now fossil fuel input. With this setup diesel injection timing may need to be changed again and the fuel lines need to be changed for one that can handle the biodiesel.

The final issue is hydrogen storage. If this is to ever be used on commercial vehicles the storage of the hydrogen needs to be addressed. With the current tank that holds around 3.5 kg the engine can only run for half an hour at a 50% hydrogen split. That time would be greatly decreased if the ratio of hydrogen was increased to 90% or higher.

6.3. Future Work Research Done by NDSU after This Work

All the work done in this paper at NDSU refers to mechanically controlled engines. Another grad student from NDSU, Kirk Bottelberghe, continued after this research with an engine that is controlled with an electronic control module (ECM) [31]. Most modern engines use ECM's to control the fuel injected into the engine with better control. An ECM can vary the fuel input better and more accurately than a mechanical injection setup. The work presented in this report was a baseline so that he would have a starting point.

The results from Kirk's work focused on how the computer was affected by the addition of hydrogen into the system. The diesel fuel was injected at two different times. The first was a pre injection with a small amount of diesel fuel and the second was the main injection with the majored of fuel. The first injection promotes mixing and starts combustion and the second injection is responsible for delivering the bulk of the fuel for the power stroke.

In these experiments the engine was also able to run hydrogen in amounts up to 60% of total energy input, with an increase in cylinder pressure. These results are consistent with previous work and are expected. What was not expected was the advancing of the injection timing by the engine's ECM.

The proprietary software for the engine advanced the timing as more hydrogen was added, during one test almost 4 times earlier in the cycle.

After Kirk's research another graduate student, Lee Kersting, conducted research focusing on the in cylinder pressure curves when operating under a combination of hydrogen and diesel fuel [32]. Lee's work used the same engine as Kirk's research. Lee analyzed the combustion process based on the size and shape of the in cylinder pressure curves.

Lee was able to achieve the highest diesel replacement of any research at NDSU at 74%. To get his results he took pressure curve samples at a variety of different speed and loading conditions. His results showed that the maximum rate of pressure rise increased as either load increased under normal operating conditions or as hydrogen fuel was added. Lee was able to observe results over a much larger engine operating range than was conducted in this research.

Lee was also able to look at how the ECM changed the injection timing when operating in the dual fuel mode. His research was able to observe the changes to injection time with similar results to Kirk's work.

Both of these projects start to explore the future work suggested in the previous section. They show that there is some work that needs to be done with diesel fuel injection timing to push the boundaries of hydrogen replacement. This is a step further down the path.

Based on these results more work needs to be placed into getting an unlocked ECM to be able to change diesel injection timings and amounts on the fly at the demand of the experiments. It would also be nice to integrate the hydrogen injection control to work in conjunction with the diesel fuel controller. For example, it would be nice to ratiometrically increase the hydrogen fuel as the diesel fuel is decreased. Once this is achieved more possibilities are open for research on this topic.

Part of integrated controls would also include more in cylinder pressure sensors if the budget permitted. In this report and both Kirk's and Lee's work, so much was learned from that single cylinder alone. If more cylinders could be equipped with pressure sensors more could be learned. If more cylinder pressure sensors are out of the question then an accelerometer or knock sensor would be nice to quantify the vibration observed in the testing with large amounts of hydrogen injection.

After fully integrated controls are developed and a more competent emissions sampling device needs to be procured. As described in this report the device used was old and inaccurate, and unreliable with the current setup. With more automated controls and robust exhaust emissions equipment the future of this research could really produce some interesting results.

7. REFERENCES

[1] Barnes, P. R., J. W. Van Dyke, F. M. Tesche, and H. W. Zaininger. *The Integration of Renewable Energy Sources Into Electric Power Distribution Systems*. National Assessment ed. Vol. 1. Oak Ridge: Oak Ridge National Laboratory, 1994. Print.

[2] Cho, Young-Sam. "GM Leads U.S. Carmaker Gains in China as Honda Sales Fall." *Bloomberg Business*. Bloomberg News, 9 Jan. 2012. Web. 15 July 2012. <http://www.bloomberg.com/news/articles/2012-01-09/gm-china-sales-rise-8-3-percent-in-2011-on-buick-chevrolet-cars>.

[3] Cain, Jim. "GM's U.S. Sales Increase 5 Percent in December." *Edgar Online* 4 Jan. 2012. Web. <http://www.barchart.com/plmodules/?module=secFilings&filingid=8335564&type=CONVPDF&popup=1&override=1&symbol=GM>.

[4] Madslien, Jorn. "India Prepares for Automotive Boom." *BBC News* 3 Apr. 2007. BBC News. Web. 25 Jan. 2011. <http://news.bbc.co.uk/2/hi/business/6521909.stm>.

[5] Hayward, Tony. "BP Statistical Review of World Energy June 2010." *BP.com*. BP, 1 June 2010. Web. 5 Mar. 2011.

[6] "Title 40 Chapter 1 Subchapter C Part 86 Control of Emissions from New and In-Use Highway Vehicles and Engines." *Electronic Code of Federal Regulations*. U.S. Government Publishing Office, 20 Aug. 2014. Web. 20 Aug. 2014.

[7] "Title 40 Chapter 1 Subchapter C Part 89 Control of Emissions from New and In-Use Nonroad Compression-Ignition Engines." *Electronic Code of Federal Regulations*. U.S. Government Publishing Office, 20 Aug. 2014. Web. 20 Aug. 2014.

[8] "Title 40 Chapter 1 Subchapter U Part 1039 Control of Emissions from New and In-Use Nonroad Compression-Ignition Engines." *Electronic Code of Federal Regulations*. U.S. Government Publishing Office, 20 Aug. 2014. Web. 20 Aug. 2014.

[9] Pillay, Dr. Pragasen. "Hydrogen Economy and Alternative Fuels." *IEEE.org*. Institute of Electrical and Electronics Engineers, 1 Jan. 2012. Web. 1 June 2012. <http://www.ieee.org/about/technologies/emerging/hydrogen_econ.pdf>.

[10] Rebenitsch, Ron, Randall Bush, Allen Boushee, and Jeremy Woeste. "Wind-To-Hydrogen Energy Pilot Project: Basin Electric Power Cooperative." *Osti.gov*. U.S. Department of Energy, 1 June 2009. Web. 1 May 2011. <http://www.osti.gov/scitech/servlets/purl/951588>.

[11] Harrison, Kevin. "Wind-to-Hydrogen Project." *Hydrogen and Fuel Cell Research*. National Renewable Energy Laboratory, 2 Dec. 2014. Web. 10 Jan. 2015. <http://www.nrel.gov/hydrogen/proj_wind_hydrogen.html>.

[12] "Hydrogen Fueling Station Locations." *Alternative Fuels Data Center*. U.S. Department of Energy, 13 Aug. 2012. Web. 1 Dec. 2012. <http://www.afdc.energy.gov/fuels/hydrogen_locations.html>.

[13] "FCX Clarity." American Honda Motor Company Inc., 1 Jan. 2012. Web. 1 Dec. 2012. <http://automobiles.honda.com/fcx-clarity/>.

[14] Siler, Steve. "GM Continues Project Driveway Fuel-Cell Development Program, Phases in Second-Gen Technology." *Car and Driver*. Hearst Communications, Inc., 23 Mar. 2010. Web. 8 Jan. 2012. <http://blog.caranddriver.com/gm-continues-project-driveway-fuel-cell-development-program-phases-in-second-gen-technology/>.

[15] Melendez, M., and A. Milbrandt. "Analysis of the Hydrogen Infrastructure Needed to Enable Commercial Introduction of Hydrogen- Fueled Vehicles Conference Paper NREL/CP-540-37903." *National Hydrogen Association Annual Hydrogen Conference 2005*. National Renewable Energy Laboratory, 29 Mar. 2005. Web. 5 Aug. 2011.

[16] Hsu, Bertrand D. *Practical Diesel Engine Combustion Analysis*. Warrendale: SAE International, 2002. Print.

[17] Jensen, Scott. *Energy Conversions Inc.* Web. 10 Jan. 2013. <http://www.energyconversions.com/index.html>.

[18] Shirk, M., T. Mcguire, G. Neal, and D. Haworth. "Investigation of a Hydrogen-assisted Combustion System for a Light-duty Diesel Vehicle." *International Journal of Hydrogen Energy* 33 (2008): 7237-244. Web. 16 Mar. 2015. <www.sciencedirect.com>.

[19] Bose, Probir Kumar, and Dines Maji. "An Experimental Investigation on Engine Performance and Emissions of a Single Cylinder Diesel Engine Using Hydrogen as Inducted Fuel and Diesel as Injected Fuel with Exhaust Gas Recirculation." *International Journal of Hydrogen Energy* 34 (2009): 4847-854. Web. 16 Mar. 2013. <www.sciencedirect.com>.

[20] Saravanan, N., G. Nagarajan, C. Dhanasekaran, and K. Kalaiselvan. "Experimental Investigation of Hydrogen Port Fuel Injection in DI Diesel Engine." *International Journal of Hydrogen Energy* 32 (2007): 4071-080. Web. 16 Jan. 2012. <www.sciencedirect.com>.

[21] Saravanan, N., and G. Nagarajan. "An Experimental Investigation on Optimized Manifold Injection in a Direct-injection Diesel Engine with Various Hydrogen Flowrates." *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 221 (2007): 1575-584. Print.

[22] Liew, C., H. Li, J. Nuszkowski, S. Liu, T. Gatts, R. Atkinson, and N. Clark. "An Experimental Investigation of the Combustion Process of a Heavy-duty Diesel Engine Enriched with H2." *International Journal of Hydrogen Energy* 35.20 (2010): 11357-1365. Print.

[23] Liu, S., H. Li, C. Liew, T. Gatts, S. Wayne, B. Shade, and N. Clark. "An Experimental Investigation of NO2 Emission Characteristics of a Heavy-duty H2-diesel Dual Fuel Engine." *International Journal of Hydrogen Energy* 36 (2011): 12015-2024. Print.

[24] Lilik, Gregory K., Hedan Zhang, José Martin Herreros, Daniel C. Haworth, and André L. Boehman. "Hydrogen Assisted Diesel Combustion." *International Journal of Hydrogen Energy* 35 (2010): 4382-398. Print.

[25] Szwaja, Stanislaw, and Karol Grab-Rogalinski. "Hydrogen Combustion in a Compression Ignition Diesel Engine." *International Journal of Hydrogen Energy* 34 (2009): 4413-421. Print.

[26] Miyamoto, Toru, Hirokazu Hasegawa, Masato Mikami, Naoya Kojima, Hajime Kabashima, and Yasuhiro Urata. "Effect of Hydrogen Addition to Intake Gas on Combustion and Exhaust Emission Characteristics of a Diesel Engine." *International Journal of Hydrogen Energy* 36.20 (2011): 13138-3149. Print.

[27] Shebeko, Yu.n., S.g. Tsarichenko, A.ya. Korolchenko, A.v. Trunev, V.yu. Navzenya, S.n. Papkov, and A.a. Zaitzev. "Burning Velocities and Flammability Limits of Gaseous Mixtures at Elevated Temperatures and Pressures." *Combustion and Flame* 102.4 (1995): 427-37. Print.

[28] Schihl, Peter, John Tasdemir, and Walter Bryzik. "Determination Of Laminar Flame Speed Of Diesel Fuel For Use In A Turbulent Flame Spread Premixed Combustion Model." *Proceedings for the Army Science Conference (24th), ADM001736* (2005). Print.

[29] Robbins, Scott, and George Glass. *Hydrogen Gas Safety Self-Study*. Los Alamos National Laboratory, 1 Aug. 2000. Print.

[30] Decker, Austin. *Data Summary*. Fargo, ND, 2008. Print.

[31] Bottelberghe, Kirk. *Emissions Reduction Technology Engine During Diesel-Hydrogen Dual Fuel Operation.* North Dakota State University. Fargo, North Dakota, 2001. Print.

[32] Kersting, Lee. *Charaterizing the Operation of a Dual-Fuel Diesel-Hydrogen Engine Near the Knock Limit.* North Dakota State University. Fargo, North Dakota, 2014. Print.