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DEPARTMENT OF ENGINEERING SCIENCE AND MECHANICS

DESIGN AND IMPLEMENTATION OF AN ELECTRONIC FUEL INJECTION SYSTEM FOR A HYDROGEN INTERNAL COMBUSTION ENGINE IN A HYBRID VEHICLE

WADE MCCORKEL

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Reviewed and approved* by the following:

Joel Anstrom
Research Associate, Larson Transportation Institute
Thesis Supervisor

Christine Masters
Assistant Professor of Engineering Science and Mechanics
Honors Advisor

Judith A. Todd
P. B. Breneman Department Head Chair
Professor, Department of Engineering Science and Mechanics

*Signatures are on file in the Schreyer Honors College and the Engineering Science and Mechanics office.

ABSTRACT

With the current oil crisis looming, the search for an alternative fuel is one of the most pressing issues for modern day society. A realistic option is the use of hydrogen as a fuel in an internal combustion engine. According to Argonne mechanical engineer Steve Ciatti, "Hydrogen-powered internal combustion engines (H_2ICEs) are a low-cost, near-term technology. They can be the catalyst to building a hydrogen infrastructure for fuel cells." Using hydrogen as a combustion fuel can be implemented relatively quickly and successfully. Although the conversion from gasoline to hydrogen is rather simple, optimizing the engine for efficiency is quite challenging. One necessary addition is an electronic fuel injection system in order to control the air/fuel ratio, which directly affects engine efficiency and performance.

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Chapter 1

Introduction

The present oil situation does not have a bright outlook. Oil prices have been at all time highs in recent years with no end in sight. Whether oil supplies run out or environmental policies make oil production too expensive, there needs to be alternative fuel research in order to find a solution.

A realistic short-term option is the use of hydrogen as a fuel in an internal combustion engine (ICE). Switching an engine from gasoline to hydrogen is rather straightforward and simple. Almost all of the internal combustion engines in cars can be converted. When operating under the proper conditions, an H_2ICE produces almost no pollutants. The only thing necessary would be a hydrogen fuel infrastructure, which could be constructed now with the expectation of hydrogen fuel cells being a long-term option for alternative energy vehicles.

The focus of this research study is the design and assembly of an electronic fuel injection (EFI) system for an H_2ICE. In conjunction with this research, another study is exploring the implementation of a turbocharger.

Chapter 2

Literature Review

2.1 Properties of Hydrogen When Used as an ICE Fuel

This chapter summarizes the literature related to this research study and aims to accomplish three goals: 1) Highlight key challenges related to converting ICE's from gasoline to hydrogen, 2) Identify several fuel delivery techniques indicating why the Throttle Body Fuel Injection system was selected, and 3) Describe the key components of a Throttle Body Fuel Injection system.

The unique combustion properties of hydrogen make it a suitable alternative fuel worth researching and developing. Certain properties help performance, while others hinder it. Although clearly different from gasoline, hydrogen can be used as a fuel source in existing internal combustion engines with few modifications needed. The following table of properties will be discussed and analyzed as to why hydrogen may be a suitable alternative to gasoline.

Table 2.1: Relevant properties of Hydrogen and gasoline (1)

Property	Hydrogen	Gasoline
Density (kg/m^3)	0.0824	730[a]
Flammability limits (Φ)	0.1-7.1	0.7-4
Minimum ignition energy (mJ)[b]	0.02	0.24
Autoignition temperature (K)	858	550
Flame velocity (m/s)[b]	1.85	0.37-0.43
Quenching distance (mm)[b]	0.64	2
Stoichiometric air/fuel ratio by mass	34:1	14.7:1

[a] liquid at 0C, [b] at stoichiometry

Hydrogen has the best energy-to-weight ratio of any fuel. However, hydrogen's density is considerably lower than that of gasoline, so the amount of hydrogen in the combustion chamber is significantly lower than the amount of gasoline. Consequently, the energy density of a hydrogen-air mixture, and thus the power output, is reduced. Also, a very large volume is necessary to store enough hydrogen to give a vehicle an adequate driving range. The volumetric efficiency of a hydrogen-fueled engine is below 60%, which is almost 30% below that of gasoline (2). The decreased power output can possibly be overcome by advanced strategies such as turbocharging and fuel injection, which is the objective of this research.

In comparison with other fuels, specifically gasoline, hydrogen has a much wider flammability range. As a result, hydrogen can be combusted over a wide range of air/fuel mixtures. This makes hydrogen capable of running at an extremely lean mixture. A lean mixture is one in which the amount of fuel is less than the stoichiometric or chemically ideal amount needed for combustion with a given amount of air. When a stoichiometric mixture combusts, all the fuel and air will combust with nothing leftover. The stoichiometric air/fuel ratio for hydrogen is 34:1 (3). This research hopes to achieve a lean air/fuel ratio of 113:1 through certain fuel injection techniques. A convention with hydrogen is to use the equivalence ratio instead of the air/fuel ratio. The equivalence ratio is defined as the stoichiometric air/fuel ratio divided by the actual air/fuel ratio. The goal of this project is to achieve an equivalence ratio of $\varphi=0.3$, which corresponds to 34:1/113:1.

Hydrogen-air mixtures have notably lower ignition energy than gasoline-air mixtures. Ignition energy is the minimum amount of energy necessary to ignite an air/fuel mixture. Hydrogen's ignition energy is one order of magnitude lower than that of gasoline (4). This enables hydrogen engines to ignite very lean mixtures, however this makes the fuel more susceptible to preignition. Preignition describes the event wherein the air/fuel mixture in the cylinder ignites before the spark plug fires. Preignition may be initiated by some external heat source such as superheated carbon deposits or residual exhaust gases. Preventing this phenomenon is one of the foremost challenges associated with running an engine on hydrogen (5). Preignition will be discussed further in section 2.2.1.

Although hydrogen is easily ignited by some external heat source, the fuel is relatively difficult to autoignite. Autoignition occurs when high temperatures or pressures cause a air/fuel mixture to spontaneously ignite without an external source of ignition, such as a flame or spark. This can occur from high compression or hot spark plugs. According to Sierens et al (6), cold rated spark plugs are recommended with hydrogen so the spark plug does not approach the autoignition temperature. The autoignition temperature plays a key role when determining the proper compression ratio to use for an engine, since the temperature rise during compression is related to the compression ratio. The temperature rise is shown by the equation:

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

where:

$\frac{V_1}{V_2}$ = the compression ratio

T_1 = absolute initial temperature

T_2 = absolute final temperature

γ = ratio of specific heats

If the temperature exceeds hydrogen's autoignition temperature, then preignition will occur. Thus, the absolute final temperature limits the compression ratio. Diesel engines, a type of compression ignition (CI) engine, operate based on autoignition. The large engine compression ratios create temperatures high enough to ignite the fuel-air mixture without the need for spark plugs. However, the temperature needed to autoignite hydrogen is substantially higher than that for gasoline or diesel. So hydrogen is best suited for a spark ignition (SI) engine (7).

Hydrogen's small molecular size allows the fuel to break down quickly and burn rapidly. This property is advantageous for two main reasons. Firstly, it facilitates the formation of a uniform mixture of air and fuel. Secondly, hydrogen has a relatively high flame velocity compared to other fuels. These characteristics coupled with a high autoignition temperature make hydrogen a smooth burning fuel and very resistant to engine knock (8).

Engine knock, also referred to as pinging, occurs when combustion of the air/fuel mixture starts off correctly in response to ignition by the spark plug, but one or more pockets of the air/fuel mixture spontaneously combusts outside the normal combustion front. To explain further, combustion inside the cylinder initiates at the spark and a propagating flame front travels down the cylinder igniting the remaining mixture. However, this flame front further compresses the unburned mixture adding more heat and causing combustion if the autoignition temperature is exceeded.

It should be noted that knock is a specific type of autoignition and different from preignition since it occurs after the spark has fired. To the human ear, the two are impossible to differentiate. Both are highly undesirable as they can lead to poor engine performance or damage (9). However, hydrogen's high flame velocity ensures the flame front quickly travels down the entire cylinder igniting all of the mixture and its high autoignition temperature allows the unburned mixture to be compressed to very high temperatures before igniting. Thus, engine knock is less likely to occur in a hydrogen-fueled engine than in a gasoline-fueled engine.

The quenching distance for hydrogen is considerably smaller than that of gasoline. Quenching distance is the distance between a flame and external surface at which quenching, or extinguishing, begins. Hydrogen's small quenching distance allows the flame to burn closer to cylinder walls than gasoline. This increases the tendency for backfire since the flame from a hydrogen-air mixture passes a nearly closed intake valve more closely than a gas-air flame (10**)**. Backfire is an explosion that occurs outside of the combustion chamber either in the intake or exhaust system. This topic will be discussed in more detail in section 2.2.2. When running an ICE on hydrogen, the valve and ignition timing must be accurately set to ensure there will be no backfiring.

Table 2.2: The properties of Hydrogen and their significance as an ICE fuel (1)

Property	**Significance**
low density	lower volumetric power output
wide flammability limits	greater emission control
low ignition energy	increased susceptibility to preignition
high autoignition temperature	unsuitable for compression ignition engines
high flame velocity	lowered susceptibility to knock
short quenching distance	increased susceptibility to backfire

2.2 Difficulties of Hydrogen as an ICE Fuel

2.2.1 Preignition

Preignition is referred to as the combustion of the air/fuel mixture inside the cylinder prior to the spark discharge. The cause of preignition is believed to be a hot spot, such as a lubricant deposit or spark plug rather than the high temperature residual gas itself (2). This results in an inefficient, rough running engine and can cause serious damage. Preignition is much more common in hydrogen fueled engines compared to other ICEs because of hydrogen's wider flammability range, lower ignition energy and shorter quenching distance (11). A possible solution to preignition is redesigning the fuel injection system. One of the objectives of this research is to eliminate preignition so the engine operates smoothly and safely. Incorporating port injection or throttle body injection helps to reduce the chance of preignition compared to carburetion.

2.2.2 Backfiring

Backfiring is defined as combustion prior to spark discharge that occurs in the intake or exhaust system rather than inside the combustion chamber. A major hurdle to overcome with hydrogen is backfiring in the intake manifold. An engine is vulnerable to backfire whenever the intake valve is open. If preignition occurs while the intake valve is open then the flame can propagate quickly into the intake manifold due to hydrogen's high flame velocity and very short quenching distance. When this occurs there is a loud popping sound from the resulting explosion of the air/fuel mixture in the intake manifold. This can cause severe damage to engine components, cause performance to suffer, or simply cause unstable operation (12). Although backfire and preignition are both types of explosions before spark ignition and are indistinguishable to the human ear, the difference is the location of the explosion. Backfiring occurs outside the combustion chamber while the intake valve is open, while preignition occurs inside the combustion chamber while the intake valve is closed.

There are some strategies that have been used to avoid backfiring. Using an injection system, either port or throttle body injection, helps to decrease the occurrence of backfiring. Running the engine with a lean mixture (goal of φ=0.3 for this study) also helps (13). A combination of these two techniques will be explored through this research.

2.2.3 Decreased Power Output

Without any modifications to the engine, the power output of a H_2ICE is significantly lower than a gasoline equivalent, usually about half the output. A big cause of this is the low volumetric power density of hydrogen. Obviously, gasoline, a liquid, will have a higher volumetric power density than hydrogen, a gas. Additionally, running a lean mixture, in order to eliminate backfiring, severely cuts the power output (14). However, the combination of a fuel injection system and a supercharger can replace the lost power and even increase the power output to the same level as a stock gasoline engine.

2.3 Fuel Delivery Techniques

There are several methods for fuel delivery to the combustion cylinder in an ICE. Choosing the method of fuel delivery is especially important when using hydrogen as the fuel. Depending on the technique, problems such as preignition, backfiring and lowered power output can be improved, if not eliminated. The following section will briefly discuss four fuel delivery strategies: carburetion, port fuel injection, throttle body injection and direct fuel injection.

2.3.1 Carburetion

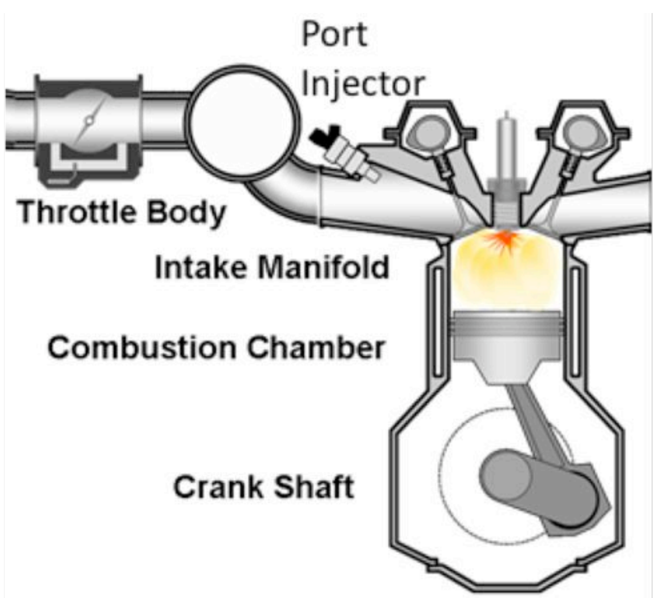
Carburetion is the simplest and cheapest method to introduce fuel into the combustion chamber (15**)**. Carburetors function by using the venturi effect to create a pressure drop, which draws fuel from a precisely machined orifice called a jet. High-pressure fuel lines, fuel injectors or an electronic controller are not needed. There is a throttle plate that controls the airflow but, aside from that, there is no other control over the amount of fuel injected, injection timing, or the air/fuel ratio. Since the operating boundaries of the H_2ICE are limited by certain air/fuel ratios that cause preignition and backfire, it is imperative to be able to control these factors for safe, efficient operation (16**)**.

Therefore, carburetion is not a desired choice when using hydrogen, although it can be used and is actually the current method of fuel delivery on the engine. Carburetors have idle and open throttle adjustment screws to give some tuning capabilities but this control is not nearly accurate enough for a hydrogen application. Using a fuel injection system would add control over injection timing and duration and could possibly eliminate preignition and backfire.

2.3.2 Port Fuel Injection (PFI)

Similar to carburetion, port fuel injection introduces the fuel into the airstream in the intake manifold. However, PFI uses fuel injectors, mounted on the intake manifold near the cylinders, as shown in Figure 2.1, that are actuated by solenoids to shoot a precise amount of fuel. The injectors are controlled by an Engine Control Unit (ECU), which sends signals for the injectors to open and close as well as when they should fire in relation to the spark timing. The

Figure 2.1 Port fuel injection setup



fuel is usually injected during the intake stroke while the intake valve is open. An oxygen sensor also communicates with the ECU to give closed loop feedback and make adjustments to regulate the air/fuel ratio (1).

PFI offers several advantages over carburetion. Most importantly, the ECU can control the injection timing and duration, which can reduce the risk of preignition and backfire (17). Also, the air/fuel ratio can be regulated during operation depending on specific throttle and engine speed settings. Another advantage of PFI over carburetion is an increase in power output, which, as mentioned earlier, is a significant problem for the H_2ICE. The power gains are most likely due to better filling of the cylinder. Figure 2.2 illustrates this advantage.

However, port fuel injection does have some drawbacks. The ECU, fuel injectors and an oxygen sensor with a controller add complexity and cost to the system. Also a custom fabricated intake manifold is usually required. Similar to carburetion, PFI is still susceptible to backfire because the air/fuel mixture is formed within the intake manifold during the intake stroke while

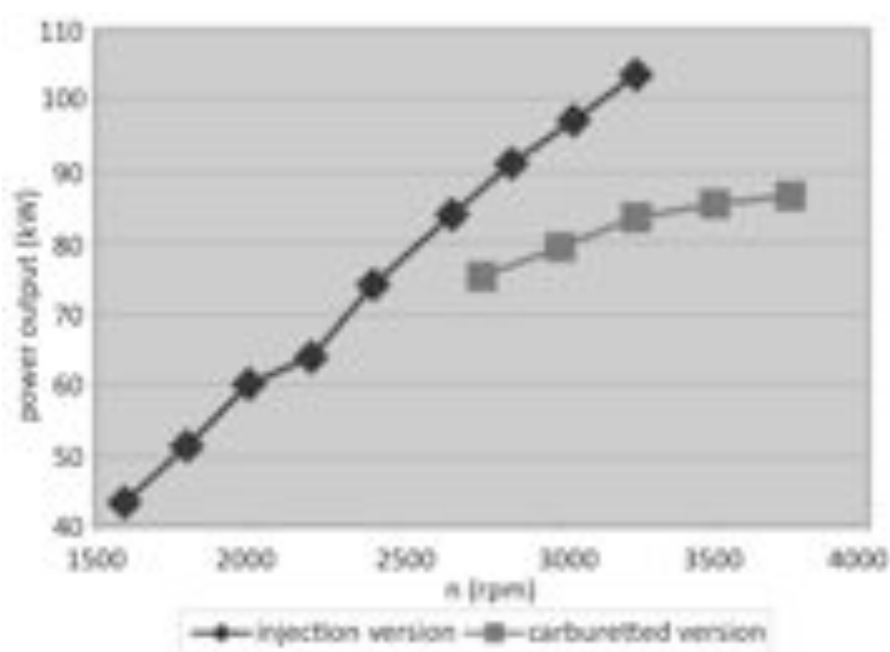


Figure 2.2 The power output of the same engine (12)

the intake valve is open. Depending on the application, the cost and complexity can be justified by the research goals.

2.3.3 Throttle Body Injection (TBI)

Throttle body injection is a combination of carburetion and PFI. A throttle body housing is almost indistinguishable from a carburetor. The only difference is that there is a fuel injector mounted on the throttle body. The fuel control is not as precise as PFI since the air/fuel mixture is formed at the same location as a carburetor and not near the cylinder but the air/fuel ratio can be controlled through closed loop feedback with an oxygen sensor. Although an ECU with sensors and wiring is required for the fuel injector, a TBI can simply be installed by unbolting the carburetor and replacing it with the throttle body. A TBI setup is straightforward and inexpensive.

2.3.3 Direct Fuel Injection (DFI)

Direct fuel injection is a type of electronic fuel injection where the fuel is injected directly into the cylinder, unlike PFI where the fuel is injected into the intake manifold. A key difference between direct and port fuel injection is that the fuel injection takes place after the intake stroke with DFI so essentially backfire is nearly impossible (18). This method requires higher pressure fuel lines than PFI so the injectors must be capable of handling higher flow rates and pressures.

In addition to backfire being essentially eliminated, DFI also has the advantage of the highest potential power output. The combustion chamber is already full of air when the hydrogen is injected after the intake valves are closed. So the air/fuel mixture is under a higher pressure and has greater mass than a mixture formed outside of the cylinder in the intake manifold, such as with carburetion and PFI. Due to the increased mass, the power output and volumetric efficiency are both increased (8).

However, direct fuel injection is not without its drawbacks. It is the most complex and costly fuel delivery technique. The entire system has to operate at higher pressures. Each cylinder requires an injector, unlike TBI where there is only one injector at the throttle body. Also, inhomogeneous mixtures are a likely possibility because the air and fuel have a short amount of time to mix. Consequences from inhomogeneous mixtures are higher NO_x emissions and decreased thermal efficiency.

2.4 Components of a Throttle Body Fuel Injection System

2.4.1 Engine Control Unit (ECU)

The engine control unit (ECU) is the brain of the electronic fuel injection system. It is responsible for receiving signals from all the sensors, calculating required actions based on these signals, and then sending command signals to the fuel injectors and/or spark plugs. It determines the amount of fuel to inject and injection timing from multidimensional performance maps. Input values for these maps, such as engine speed, is calculated from signals coming from sensor devices monitoring the engine. For applications that require the user to have a lot of control and flexibility over parameters, programmable ECUs are available that allow the user to customize almost every aspect of operation.

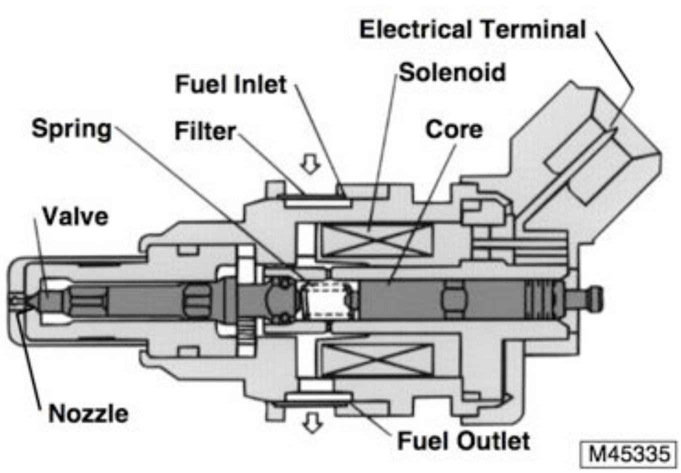
One such programmable ECU is a brand called Megasquirt. Megasquirt is a do-it-yourself programmable electronic fuel injection controller that is capable of controlling fuel injection, ignition timing and other parameters depending on which model is used. A 4” x 6” printed circuit board is assembled with the necessary components and then hooked up to a computer in order to communicate with the tuning software called Megatune. There is an additional board called the stimulator, which can give theoretical inputs such as engine speed, manifold air pressure and throttle position. Based on these inputs, it is possible to make estimates for injection duration and air/fuel ratio before actually installing the system in the vehicle. Megasquirt is very inexpensive due to its "build it yourself" aspect yet it delivers as good or better performance compared to other ECUs on the market.

2.4.2 Fuel Injector(s)

A fuel injector is nothing more than an electronically controlled valve, or a solenoid. It is supplied with fuel from pressurized fuel lines and capable of opening and closing very rapidly and precisely. The timing and duration of being open is controlled by the ECU. There are injectors for liquid fuels as well as gaseous fuels.

Injectors come in all different shapes and sizes. Some have the fuel input port on top while others have it on the side, which is referred to as side-feed (Figure 2.3). Some are designed

Figure 2.3 A side-feed gasoline injector (19)



to be installed directly into the cylinder while others are designed to be installed in the intake manifold or the throttle body. It is important to also consider the injectors fuel flow capacity. An engine can be starved of fuel if the injector is too small, thus causing a power output decrease.

2.4.3 Sensors

A plethora of sensors is essential to a fuel injection system in order to monitor certain engine parameters and provide feedback to the ECU so it can calculate how much fuel to inject. These sensors include:

-Manifold Air Pressure sensor (MAP)

-Throttle Position Sensor (TPS)

-Idle Air Temperature sensor (IAT)

-Coolant Air Temperature sensor (CLT)

-Crankshaft position sensor (CKP)

-Universal Exhaust Gas Oxygen sensor (UEGO)

The system utilizes closed loop feedback to regulate the fuel flow depending on engine loads. Each sensor serves a distinct purpose.

The manifold air pressure (MAP) sensor converts the instantaneous manifold pressure into a voltage signal and sends it to the ECU. This is one of the readings needed to calculate the air mass flow rate, which in turn leads to calculating the required fuel flow. Some ECU packages, such as Megasquirt, come with a MAP sensor specifically built for the unit.

An obvious sensor that is required is a throttle position sensor (TPS). It is mounted externally on the throttle body and connects to the throttle butterfly valve shaft. The TPS is basically a variable resistor that changes resistance as the throttle opens. The ECU uses this signal to enrich the fuel mixture when accelerating and, if equipped, advance and retard the ignition timing (20).

An idle air temperature (IAT) sensor is used to monitor how hot the air coming into the engine is. This sensor is mounted in the intake manifold and changes resistance based on temperature changes. The input signal is used to adjust the air/fuel mixture for changes in air density.

A very important sensor is the coolant temperature (CLT) sensor. The CLT measures the temperature of the coolant in the engine, which tells the ECU if the engine is cold, warming up, at normal operating conditions or overheating. There are different operating strategies for each situation. For example, when the engine is warming up the air/fuel mixture should be rich (more fuel) to improve idle quality and prevent the engine from hesitating. On the contrary, when the engine is approaching normal operating conditions the air/fuel mixture is leaned out (more air) to reduce emissions and fuel consumption. Another significant responsibility of the CLT is to determine when the system goes into closed loop feedback. The UEGO will not be activated until the engine is sufficiently warmed up so the CLT signals the ECU when this occurs.

A crankshaft position (CKP) sensor reports to the ECU about the position of the crankshaft, which is necessary for controlling the fuel injectors. A typical sensor setup consists of a rotating disc somehow connected to the crankshaft and a static part mounted next to the disc. Usually a Hall effect sensor is used as the static part that uses a magnetic signal from the disc to trigger (21). Other methods that use optical or inductive signals to trigger can be used as well. Based on the signal, the ECU can calculate engine RPM and control fuel injection and ignition timing, if equipped.

The sensor that creates the closed loop feedback is the universal exhaust gas oxygen (UEGO) sensor. This sensor produces a variable voltage based on the air/fuel mixture of the exhaust gas. Then a signal is relayed back to the ECU to either add more fuel or more air in order to maintain a desired air/fuel ratio. Unlike traditional narrowband oxygen sensors, a wideband sensor tells *how* rich or lean the mixture is instead of just telling if it is one or the other. This allows for far more accurate and efficient engine operation and makes a wideband UEGO the desired choice. With the UEGO installed, closed loop feedback is setup with the ECU, which also gives more control than open loop feedback (22).

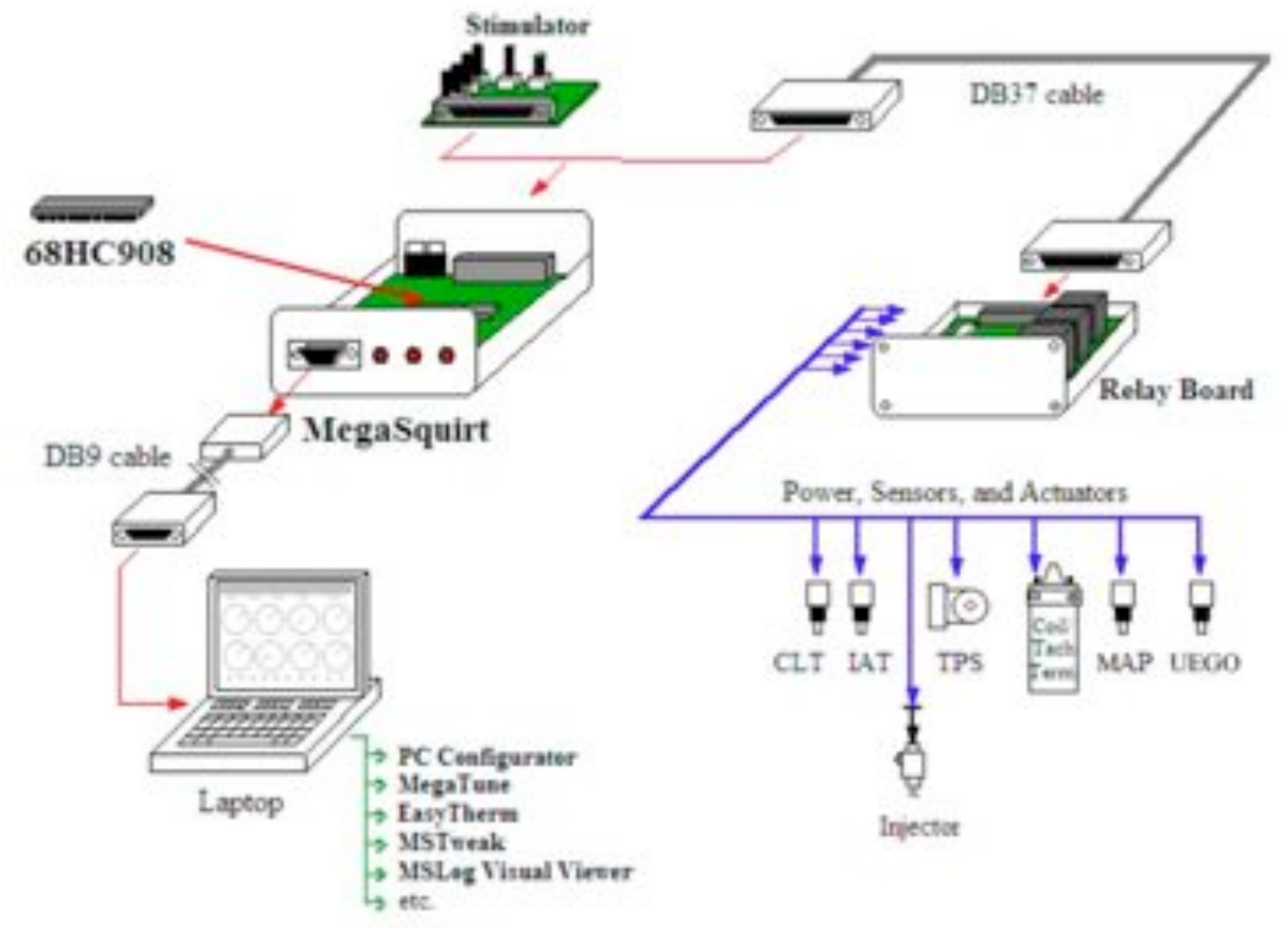
2.4.4 Throttle Body and Fuel Lines

A throttle body is a housing made from a metal casting that holds an injector, the fuel pressure regulator and the throttle butterfly valve. It serves the same purpose as a carburetor with the only difference being the fuel is introduced using an injector instead of an orifice. It can be installed by simply unbolting and removing the carburetor then bolting in the throttle body. No custom fabrication work is necessary.

In some cases, special fuel lines might need to be fabricated in order to reach the fuel injector if it has changed orientation. These fuel lines must be able to withstand the high pressures associated with gaseous hydrogen. A fuel pressure regulator will be needed to control the fuel pressure.

The total EFI system looks like Figure 2.4 when it is installed. This particular diagram is using Megasquirt and its respective circuit boards, which will be covered in detail in Chapter 4. Once all these components are assembled and integrated together, an iterative tuning process can take place in order to optimize engine operation.

Figure 2.4 A complete EFI system using Megasquirt circuit boards



Chapter 3

Engine Background

3.1 Engine Specifications

The engine was installed in a 1992 Ford Escort station wagon. The vehicle was in a series hybrid setup. A 144-volt battery pack supplied the power to the wheels and the hydrogen engine is an assist engine to extend the range. The battery pack only provides enough power for the vehicle to travel 40-60 miles. On the other hand, with the hydrogen engine charging the battery pack during operation, the vehicle can travel almost 300 miles.

The engine was a Kawasaki FD620D V-twin taken off of a John Deere lawnmower. It had a stock gasoline power rating of 20 HP. Table 3.1 summarizes the important engine specifications.

Table 3.1 Engine Specifications

Engine Model	Kawasaki FD 620D
Cylinder Configuration	90 V-twin
Cycle	4-stroke
Fuel Delivery	Carburetion (originally)
Valve System	OHV
Cylinder Bore	76 mm (2.99 in)
Stroke	68 mm (2.66 in)
Piston displacement	617 cc (37.7 cu in)
Max. Output	20 HP/ 3600 rpm (gasoline)
Dry Weight	41.5 kg (91.5 lbs)

Chapter 4

EFI System

4.1 Market Study

A thorough market study was conducted to find the optimal ECU as well as a capable injector. Both components needed to meet certain requirements while also abiding by a budget.

4.1.1 Engine Control Unit – Megasquirt

Today's automotive accessory market has a wide variety of fuel injection systems and engine control units available. Many control units are specifically built for a certain car and engine. However, the first criterion to meet for this system was that the unit had to be fully customizable. Since the engine setup used was a very unique one due to using hydrogen instead of gasoline, an ECU that gave the programmer maximum control was essential. This narrowed down the search to do-it-yourself kits designed for hobbyists and racers.

One such kit brand called Megasquirt was recommended by a researcher and further explored. After careful assessment, it was concluded that Megasquirt would be able to meet the engine fuel supply needs. Freely available software called Megatune provides an easy-to-use program to tune the unit. Another great benefit of using this system was the extensive user resources available online. Not only were step-by-step assembly guides available, but also detailed and very active user forums are available to troubleshoot any problems.

Megasquirt offered several different models varying with capabilities, pre-assembly, and cost. Those models include MS-I, MS-II, Microsquirt, and MS-II Sequencer. MS-I is the most basic, offering only fuel control but is the least expensive option. MS-II has more functionality and additional features such as ignition control, idle air control, 12 X 12 tuning tables (MS-I uses

8 X 8; thus MS-II will run smoother), and faster processor speeds. Its price tag is slightly higher than MS-I. The Microsquirt model is essentially the same as the MS-II model except it comes fully assembled. Some differences include dual spark capability, no internal MAP sensor and no idle air control. Also, Microsquirt is much more expensive than MS-II. The MS-II Sequencer was developed when customers using Microsquirt wanted a system that could handle sequential injection. So the capabilities of this model is comparable to MS-II except with a higher price tag.

Evaluating the different models and asking some key questions helped to determine which model was the correct choice. First off, there were three different circuit boards to choose from, V2.2, V3.0 and V3.57. One board, V3.57, was pre-assembled, which made it more costly and less customizable. The other two required the user to assemble them and had comparable prices. Although V2.2 was slightly cheaper, the V3.0 main board had more options, improved circuitry and more extensive documentation online. The V3.0 board was able to control both high and low impedance injectors. Also, the designers of Megasquirt recommended this board. The board used with the system was the V3.0 main board.

Next, the question of whether or not the system would need to control ignition timing was asked. Since the engine already had an ignition control unit, Megasquirt would not need to control ignition. Another critical question that had to be answered concerned how large the injectors used would be. Since the engine used was very small compared to the racing engines typically used with Megasquirt, it was concluded that the injectors would also be relatively small. So essentially the ECU only had to control fuel, no ignition timing or idle valves, for relatively small injectors. These answers ruled out MS-II, Microsquirt and MS-II Sequencer because they have unnecessary features, which would add pointless cost to the system.

After considerable thought and research, the decision to use MS-I with the V3.0 main board was made. This combination was able to meet the engine needs while also giving plenty of flexibility to the user and falling within budget constraints. A comparison table (Table 4.1) shows the different feature sets for each model.

Table 4.1 Megasquirt model comparison table

	MS-I	**MS-II**	**Microsquirt**	**MS-II Sequencer**
Fuel Control	✓	✓	✓	✓
Do-it-yourself	✓	✓		
Ignition Control		✓	✓	✓
Recommended with large injectors		✓	✓	✓
Cost	**$187**	**$247**	**$400**	**$550**

4.1.2 Injector

Selecting a proper fuel injector is a vital process to ensure the engine will run at maximum capacity. If the fuel injector is too small, then the engines fuel flow to the cylinder will be restricted thus lowering the power output. If the fuel injector is too large, then it may be difficult to set a small enough pulse width while idling. Injectors specifically designed for hydrogen use are hard to find. Nevertheless, after consulting some fellow researchers it was realized that CNG (compressed natural gas) injectors would work for a hydrogen application as well since CNG is also a gaseous fuel. Several injectors have been found, however, one has not been selected due to lack of information at the current time. Further research and analysis is required before a decision can be made. These injectors can be seen in Figure 4.1 below.

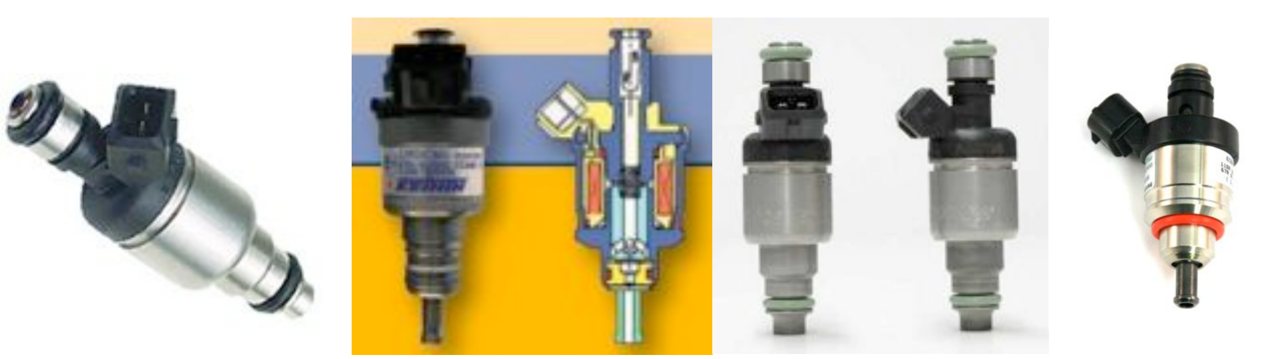
Quantum Technologies located in Irvine, California was the only company found that manufactures hydrogen-specific injectors. The injectors are high quality and built to handle hydrogen under immense pressures up to 552 kPa (80 psi). One questionable feature is the very large fuel flow capacity. The flow rate is listed as 0.8 g/s at 552 kPa, which is converted to 534 L/min using the density of hydrogen (0.08988 g/L). The calculated flow rate required by the engine is only 117 L/min (see Appendix A). This significant difference may affect engine performance and tuning thus discarding Quantum injectors as an option. Also, the price for these injectors is unknown but estimated to be high.

Keihin Fuel Systems manufactures several different CNG injector models that appear to meet the engines flow rate requirements. There are four different models of the injector KN3-CNG with flow rates ranging from 80-156 L/min at 255 kPa (37 psi). The price for one injector is $122, which seems to be a reasonable price for a gaseous injector.

Another injector that might have a flow rate that is too high is made by RC Engineering Inc. Their model PQ2-3200 has a flow rating of 0.8 g/s at 75 psi, much like the Quantum injectors. The price for this injector is quite expensive with a price tag of $225. The questionable flow rate issue and the cost make this injector an unlikely final pick.

The least expensive injector that may still meet the system constraints was found on a website called The CNG Store. The manufacturer was unknown but some specifications were available. It was listed as model number INJ-1-H2000 with a flow rate of 175 L/min at 300 kPa (43.5 psi). The price was only $89.95 but the unlisted manufacturer raises some skepticism.

Figure 4.1 Gaseous fuel injectors (From left to right: Quantum, Keihin, RC Eng, The CNG Store)



Additional research needs to be done before a decision is reached. The scarce information available online makes it necessary to directly contact companies through email or on the phone. Although, this technique has yielded few results so far.

4.2 Injection Method Decision

The two injection methods being evaluated were throttle body injection (TBI) and port fuel injection (PFI). Due to cost and complexity, direct cylinder injection was not considered. Looking at performance capabilities, a PFI system has the potential to tune more precisely due to having an injector for each cylinder. However, a TBI setup has the edge when considering cost and simplicity. For the engine used, this method requires only one injector whereas PFI requires two. PFI also requires a custom fabricated manifold in order to house the injector while TBI is a simple plug-and-play unit with an injector housing built into the throttle body.

A major factor that greatly influenced the decision was the fact that two gasoline throttle bodies for the engine were already on-hand. There would be no additional cost or added complexity yet the desired outcomes for the engine could be met. After weighing all the factors the decision was made to utilize the throttle bodies and go with a TBI setup.

4.3 Assembly

The V3.0 board, referred to as MS-I henceforth, was delivered as a blank board with all the components separated in plastic bags. Assembly took place in the battery room of Research B with a workbench and required tools available. The tools needed included a soldering iron, solder, anti-static strap, needle nose pliers, wire cutters and a computer. Megasquirt has extensive assembly guides online with step-by-step instructions. These guides proved to be priceless throughout the process.

Along with MS-I, two other boards were ordered, which aided in assembly and will aid with installation of the system. The first board was called the relay board. As shown in Figure 4.2, this was a simple board with minimal components. It serves as a central wiring location for sensor wires and also helps to prevent the main board from getting burned. It simplifies the installation and helps to organize the system.

The second board was called the stimulator. This board sends the same input signals to MS-I as an engine would so the user can hook the system up to a computer and get an idea of outputs to expect through Megatune. The stimulator also is used throughout the assembly of MS-I to ensure the components are properly installed and functioning. This simple checking tool can save someone hours of troubleshooting if something did not function after assembly. As seen in Figure 4.3, there are five black knobs that control the inputs to MS-I. These inputs are engine RPM, throttle position, exhaust oxygen, manifold air temperature and coolant temperature. A user can run Megatune and see how the different inputs affect the outputs such as injector pulse

Figure 4.2 Relay board assembled

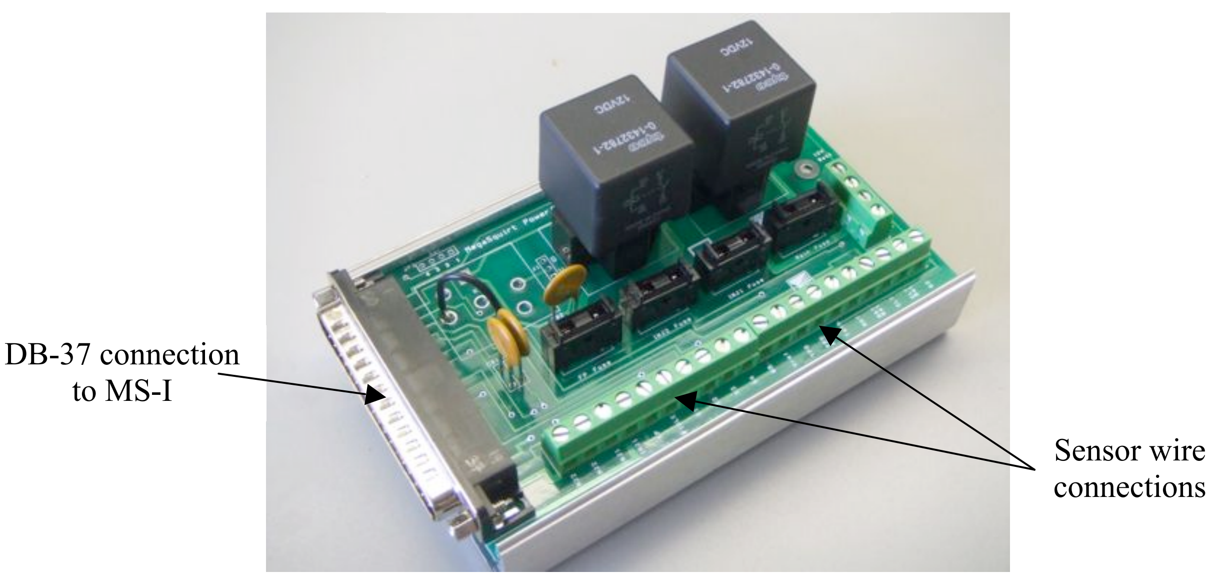
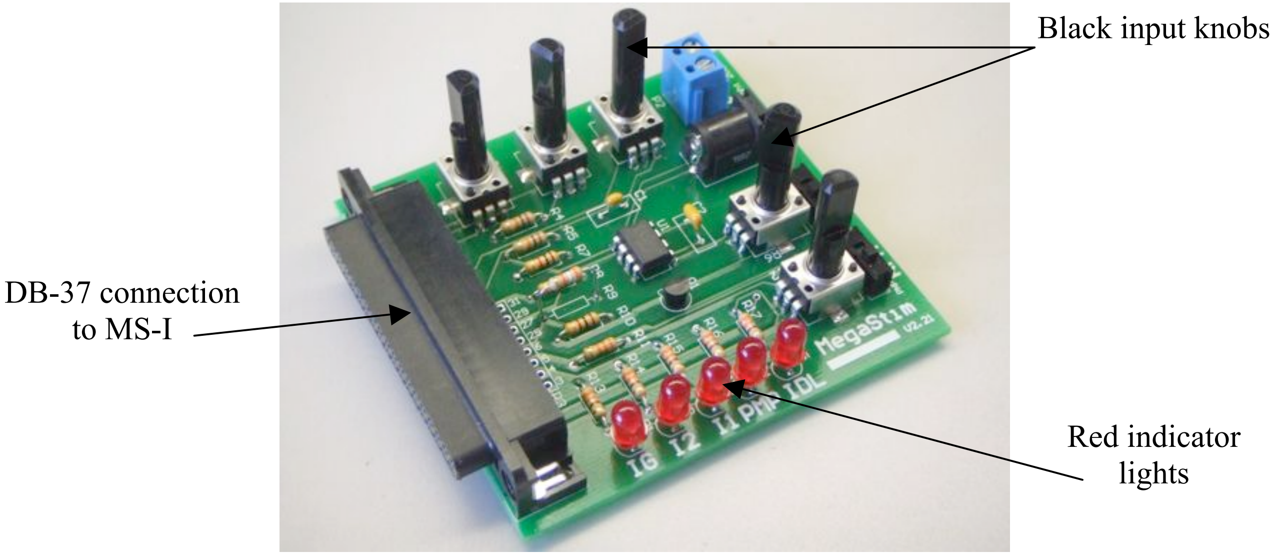


Figure 4.3 The stimulator board assembled



width, air/fuel ratio and duty cycle. There are five indicator LEDs on the bottom side. From left to right, they signal ignition, injector 2, injector 1, fuel pump and idle valve. When any of those are "on" then the respective LED will light up to signal the user.

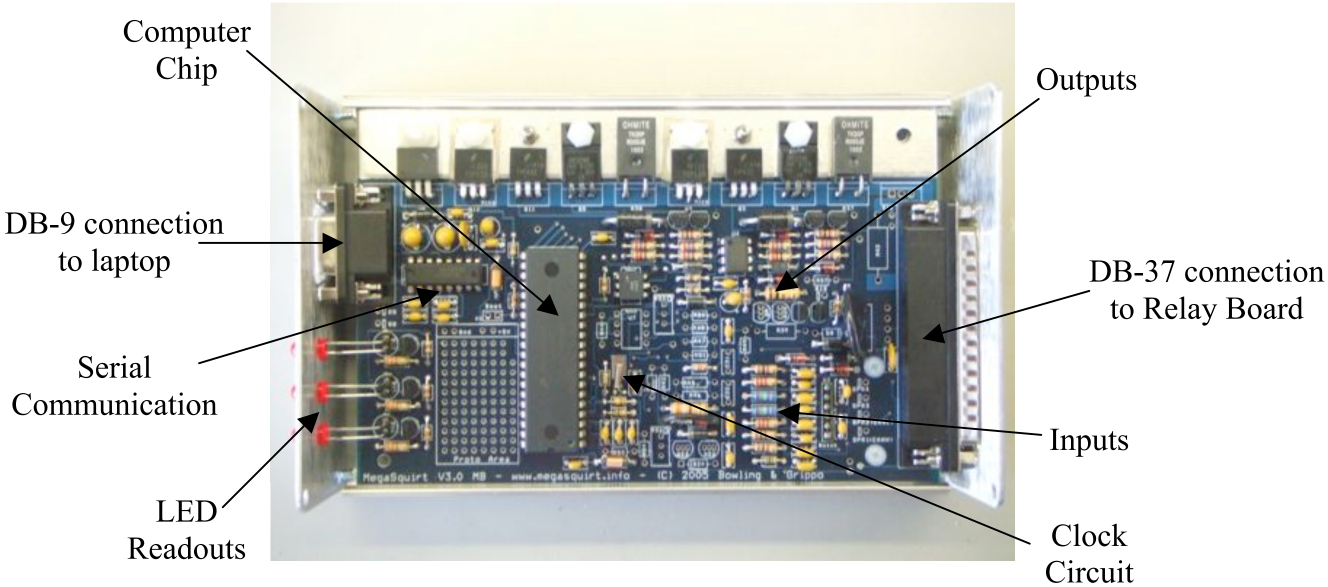
The assembly of MS-I was considerably more involved than either of the first two boards. The board is made up of resistors, capacitors, diodes, transistors and a computer chip. Not only were there a lot more components, but also there was periodic testing throughout the assembly to ensure different aspects of the board were functioning properly (Figure 4.4).

Figure 4.4 Testing the CPU socket connections on MS-I with the stimulator

Functions that were tested were power supply, serial communications with the computer, clock circuit to ensure the CPU was operating correctly, input signals and output signals. The different sections of MS-I are labeled in Figure 4.5 below. There was a brief problem with the serial communication to the computer but the problem turned out to be an issue with the computer reading the wrong COM port. Currently, the desktop computer in the battery room is setup to read MS-I but a PC laptop will be able to easily be configured to tune MS-I. Using a laptop is the optimal arrangement so the system can be tuned in the car during operation.

The MS-I board is the brain for the fuel injection system. From all the sensor input signals, it is able to instantaneously calculate the proper injector pulse width in order to maintain a desired air/fuel ratio. The preferred injector behavior is flash programmed onto the computer chip after tuning with the software Megatune.

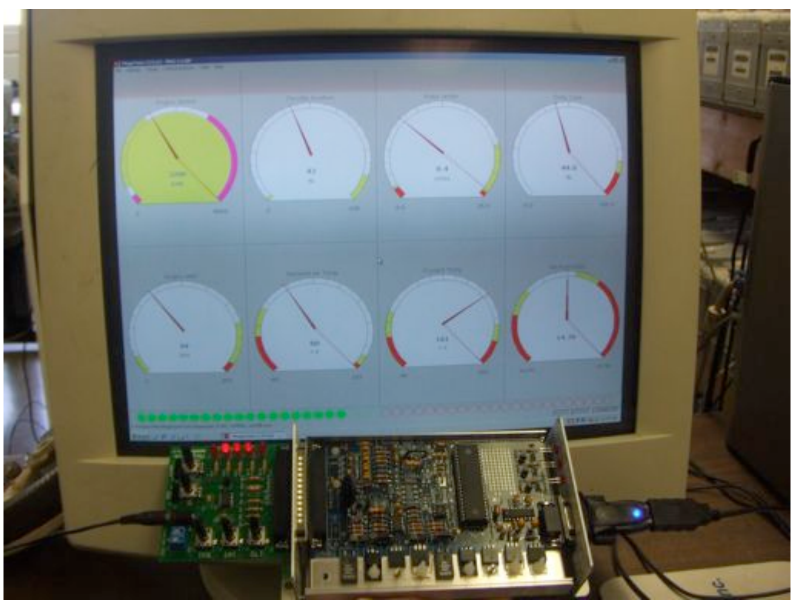
Figure 4.5 MS-I assembled on the V3.0 main board



4.4 Software – Megatune

Megatune is tuning software specifically designed for Megasquirt. It shows a dashboard display of important inputs and outputs so the user can see their behavior in real time. Theoretically, a user can hookup the stimulator to MS-I then hookup to a computer and "tune" the system based on the expected outputs. Figure 4.6 shows MS-I and the stimulator hooked up to a computer with Megatune running. One area of concern is the fact that Megasquirt is designed for use in a gasoline engine. So the readings and numbers are based on values for gasoline not hydrogen. This should not pose a major problem since there have been success stories of people using Megasquirt with CNG, which is a gaseous fuel and has a different air/fuel ratio than gasoline, just like hydrogen.

Figure 4.6 MS-I connected to a computer with Megatune running



Chapter 5

Future Recommended Work

5.1 Source an Injector

As far as the fuel injection system is concerned, the final component that needs to be added is the gaseous fuel injector. This is quite a critical component though. As mentioned earlier in section 4.1.2, the flow rate of the intended injector is imperative to get maximum power output from the engine. A decent selection of injectors has already been found, however, more information about them needs to be researched. Information such as the vast difference in flow rates (80 L/min up to 534 L/min) and will the injector be durable enough to withstand the high pressures associated with hydrogen. When these questions are answered, sourcing an injector should not be too difficult.

5.2 Installation and Tuning with Turbocharger

Another research project correlated with this one has found a turbocharger that will suit the engine. Once the turbocharger is finalized and the EFI system is complete, both systems can be installed in the car. Both need to occur simultaneously because tuning the EFI system without the turbocharger is wasted effort. However, it may be advisable to install the EFI system first, make sure the engine can run, then install the turbocharger and tune everything. This will ensure that the EFI system is functioning properly and also get the timing and pulse width close to the final values.

5.3 Emissions Control

The ultimate goal of using fuel injection is to control the air/fuel ratio so the engine emissions virtually go to zero. According to White et al, significant emissions control have been attained by simply running at an equivalence ratio of less than 0.5 (8). This suggests that once the EFI system is tuned with the turbocharger and the engine is running at an equivalence ratio of 0.3 then the emissions may already be reduced to near zero. However, once the system is installed and running there may be drastically different results. Techniques such as exhaust gas recirculation or three way catalytic conversion could be explored to reduce emissions.

5.4 Test Power Output

The main goal of the two current research projects is to restore the power output of the engine back to its stock gasoline value of 20 HP. The turbocharger will gain back the power coupled with the EFI system to regulate the air/fuel ratio for optimal performance and efficiency. Testing the engine to find out the power output with this new system installed will be essential to see if the goal was met.

Chapter 6

Conclusion

Despite sourcing an ECU and assembling the circuit boards, the EFI system was not installed in the car. A joint research project installing a supercharger concluded the supercharger on-hand was too large but found a turbocharger that will work. These two systems shall be installed simultaneously then tuned for efficiency. However, before installation can take place a gaseous fuel injector must be sourced that meets the engines fuel flow requirements. It is the hope of the researchers that once the total system is installed there will be a power output observed of 20 HP, close to the stock gasoline value.

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APPENDIX

A 1. Calculation of Engine Fuel Flow Rate

The first step to calculating the required fuel flow rate for an engine is to calculate the volume flow rate for air. This is dependent on engine displacement, RPM, volumetric efficiency and piston revolutions per engine cycle.

$$VolumeFlowRate_{air} = \frac{(EngineDisplacement)(RPM)(VE)}{(Piston\,\mathrm{Re}vs)}$$

Engine displacement = 0.617 L
RPM = 3600
VE = 0.90
Piston revolutions per engine cycle = 2 (for a 4-stroke engine)

$$VolumeFlowRate_{air} = \frac{(0.617L)(3600rev/\min)(0.90)}{(2rev)} = 1000L/\min$$

Next, the Ideal Gas Law using this volume flow rate for air can calculate the mass flow rate for air. Instead of using volume and mass, the respective flow rates are used.

$$MassFlowRate_{air} = \frac{(\Pr essure)(VolumeFlow_{air})(MolarMass_{air})}{(R)(Temp)}$$

Pressure = 1 atm
Volume Flow Rate = 1000 L/min
$MolarMass_{air}$ = 29 g/mol
R = 0.08206 Latm/molK
Temperature = 298 K

$$MassFlowRate_{air} = \frac{(1atm)(1000L/\min)(29g/mol)}{(0.08206Latm/molK)(298)} = 1185.91g/\min$$

Next, by using the desired air/fuel ratio, the mass flow rate for hydrogen can be calculated. For this research, an air/fuel ratio of 113:1 was used.

$$MassFlowRate_{H_2} = MassFlowRate_{air}\left(\frac{1}{AFR}\right)$$

Mass Flow Rate$_{air}$ = 1185.91 g/min
AFR = 113:1

$$MassFlowRate_{H_2} = (1185.91 g/\min)\left(\frac{1}{113}\right) = 10.495 g/\min$$

Finally, considering the density of hydrogen is 0.08988 g/L, the fuel flow rate of hydrogen can be calculated.

$$FuelFlowRate_{H_2} = \left(\frac{MassFlowRate_{H_2}}{Density_{H_2}}\right)$$

$$FuelFlowRate_{H_2} = \left(\frac{10.495 g/\min}{0.08988 g/L}\right) = 116.756 L/\min$$

Therefore, the required flow rate of a fuel injector for this engine would be at least 117 L/min.

Academic Vita

EDUCATION

B.S. in Engineering Science, May 2010
Schreyer's Honors College – Honors in Engineering Science
Minor in Engineering Entrepreneurship
The Pennsylvania State University, University Park, PA

Study abroad in Florence, Italy – Palazzo Rucellai
Summer 2009 – Studied Italian architecture and food

Teaching Assistant for ENGR 407: Technology-Based Entrepreneurship

Teaching Assistant for EDSGN 100: Introduction to Engineering Design

Woodshop Assistant for an on-campus engineering lab

PROFESSIONAL EXPERIENCE

<u>The Hershey Company – Hershey, Pennsylvania</u> Summer 2009
Packaging Systems Engineering Intern
- Designed, built, and implemented packaging solutions for the Reese's line
- Worked in Monterrey, Mexico and trained Spanish-speaking mechanics
- Learned and troubleshot automated robotic systems at Twizzler plant in Lancaster, PA

<u>Nucor Steel – Hickman, Arkansas</u> Summer 2008
Mechanical Intern
- Became skilled in hands-on engineering such as welding, torch cutting and plasma cutting
- Completed projects individually from assessment to installation

<u>PSU KnowHow – State College, Pennsylvania</u> Fall 2007 - present
Student Tutor
- Tutor engineering subjects such as math, physics, and engineering mechanics
- Responsible for scheduling and teaching students on a semester-long, one-on-one program

<u>KW Lawnrangers – Hershey, Pennsylvania</u> Fall 2001 – August 2007
Co-Owner and Operator
- Established a landscaping business grossing over $115,000
- Hired, trained and managed a full-time employee
- Conducted marketing campaigns to grow client base annually by 40-60%

HONORS AND AWARDS

- President's Freshman Award
- President Sparks Award
- Best Engineered Design ED&G 100 – Fall Showcase 2006
- Penn State Mr. Engineer 2008
- Andrew Pytel Scholarship
- Arthur Wilcox Scholarship
- Louis A. Harding Scholarship