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Conversion of a Gasoline Internal Combustion Engine to a Hydrogen Engine

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ABSTRACT

An inexpensive hydrogen injection system was designed, constructed and tested in the Mechanical Engineering (ME) laboratory. It was used to supply hydrogen to a gasoline engine to run the engine in varying proportions of hydrogen and gasoline. A factory-built injection and control system, based on the injection technology from the racing industry, was used to inject gaseous hydrogen into a gasoline engine to boost the efficiency and reduce the amount of pollutants in the exhaust. A fully programmable NOS Launcher Progressive Nitrous Controller was used with the ability to control injection of a fuel based on engine performance parameters such as RPM and manifold air pressure. The system was first tried out successfully on a 2-cylinder Briggs & Stratton gasoline engine. It was then modified to fit on a 6-cylinder TOYOTA gasoline engine mounted on a computer-linked test stand. The test stand is equipped with sensors and measurement systems that can be programmed to measure and record the parameters in the performance analysis of an IC engine such as: rpm, torque, power, air-fuel ratio, temperatures, rate of fuel consumption, thermal efficiency, brake mean effective pressure etc. The test stand can be used to compare the performance of the engine with gasoline and hydrogen in any pre-selected proportions of the two fuels (0% to 100%). Both these engines are operational and are planned to be used for student experiments in the M E department at WVU Tech. The project demonstrates an economical (approximate cost: $1000) hydrogen injection system that could be built from readily available, off-the-shelf components for a gasoline engine equipped with an on-board (ECU) computer designed to control combustion. The primary learning objective of the project was to be able to convert a gasoline engine to operate by burning hydrogen with gasoline or by itself as an alternate fuel. Upon successful installation of the system on a computer-linked engine test stand, the plan is to enable students to conduct performance tests on a 'dual-fuel' engine.

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1. Problem Statement

The goal of the project (originally a senior design project) was to design, install, and test a hydrogen injection system that can be used on a commercial gasoline internal combustion engine (ICE). The factory-installed gasoline injection system would still operate to control gasoline injection while a separate hydrogen injection system would be added to control injection of hydrogen. A sensor would be used as feedback in the closed loop system to cut back on gasoline as hydrogen is injected.

The original plan was not to build a complete hydrogen conversion system, but to devise a method of assisting gasoline engines by injecting gaseous hydrogen into the engine. The objective was to devise and build a relatively inexpensive conversion kit that could be used to boost the efficiency of any commercial gasoline engine, such as an automobile engine. Problems encountered in the current project include safety, location and method of injection, injection timing and control, fuel storage, control of hydrogen to gasoline ratio, and volumetric efficiency.

The initial plan included the selection and installation of a dynamometer to determine the engine efficiencies while running on gasoline alone, on hydrogen alone and then with mixtures of gasoline and hydrogen in varying proportions. Tests would be run with or without a supercharger to find the optimum running conditions, efficiency and running conditions. However, it was decided later to use a currently available computer-linked TOYOTA engine testing stand that has programmable measuring sensors and virtual gages that can display and record engine test results (operated by the software: DYNOmite™ by LAND & Sea Inc.) These tests are planned for the future as either senior design projects or part of the lab course for seniors.

2. Availability of Hydrogen as a fuel

In 2010, the first of the three hydrogen supply stations was set up at Yeager Airport, Charleston, WV, under the supervision of the Air National Guard and funded by the US Department of Energy. The facility is designed to produce up to five kilograms per day of hydrogen by electrolysis. It is an on-site hydrogen production and refueling station at the beginning of what was optimistically named, the “I-79 hydrogen corridor” from Charleston, WV, to Pittsburgh, PA. The original plan was to have two similar “hydrogen filling stations”: one at Morgantown, WV and the other at Pittsburgh, PA, so that a ‘hydrogen automobile’ could travel a distance of about 220 miles from Charleston to Pittsburgh on hydrogen only.

The National Guard outfit at Yeager Airport now has a Chevrolet Silverado 2500 pickup truck that runs on hydrogen fuel. The truck was converted by Quantum Technologies to run completely on gaseous hydrogen. Three storage tanks placed in the bed of the truck can hold between five and six kilograms of hydrogen at a pressure of about 6000 psi. The truck could drive to Beckley, WV and back, a distance of nearly seventy (70) miles, before having to re-fuel.

The Quantum Technologies' conversion kit used on the Silverado replaces the original factory installed gasoline fuel injectors and fuel rails with larger injectors and much larger fuel rails. The factory air intake had been removed and replaced with a custom-made air intake and a supercharger. The engine is still computer controlled and utilizes the factory installed computer and engine management system.

3. Properties of Hydrogen

Hydrogen as a gas has an energy density of 270 Btu/ft^3 (10,050 kJ/m^3) at atmospheric pressure and 60 degrees Fahrenheit (15 degrees Celsius). When pressurized, hydrogen can have substantially higher energy density. For instance: at 3,000 psig, its energy density is close to 48,900 Btu/ft^3 (1,820,000 kJ/m^3), and at 10,000 psig the energy density is about 121,000 Btu/ft^3 (4,500,000 kJ/m^3). When hydrogen is in its liquid form, it has an energy density of 227,850 Btu/ft^3 (8,481,000 kJ/m^3). However, since liquid hydrogen requires a temperature of -420^{0}F (-250^{0}C), the use of liquid hydrogen was not a viable choice for the current and similar projects. Compared to other fuels, hydrogen has relatively low energy density. For example, methane has an energy density of 875 Btu/ft^3 (32,560 kJ/m^3) at atmospheric pressure, 184,100 Btu/ft^3 (6,860,300 kJ/m^3) at 3,000 psig, and 561,500 Btu/ft^3 (20,920,400 kJ/m^3) as a liquid. Propane has an energy density of 2,325 Btu/ft^3 (86,670 kJ/m^3) at atmospheric pressure and 630,400 Btu/ft^3 (23,488,800 kJ/m^3) as a liquid. Among the liquid fuels, gasoline has an energy density of 836,000 Btu/ft^3 (31,150,000 kJ/m^3), Diesel has an energy density of 843,000 Btu/ft^3 (31,435,800 kJ/m^3), and Methanol has an energy density of 424,100 Btu/ft3 (15,800,100 kJ/m3). Due to the low energy density of hydrogen compared to gasoline, a supercharger may have to be added to compensate for the low energy density, and in turn, it will help improve volumetric efficiency. Computations show that the energy content of one kilogram of hydrogen is equivalent to that of one gallon of gasoline. (At the time of this project, no reliable and accurate information was available on the cost of producing a kilogram of hydrogen for cost comparison with gasoline.)

Hydrogen has a high diffusivity property which allows hydrogen to disperse into surrounding air faster than gasoline. It also gives hydrogen two major advantages as a fuel: the diffusivity of hydrogen helps the formation of a more uniform mixture of the fuel and air and in case of a leak, it disperses quickly lowering the chances of unsafe fire hazard conditions.

Hydrogen also has a relatively high octane number which makes it easy to ignite at fairly low temperatures leading to better combustion. However, while its combustion characteristic makes hydrogen an excellent ICE fuel, it also causes problems such as pre-ignition, backfire or knock. Any hot spots or hot gases in the cylinder can ignite hydrogen before the compression stroke is complete causing knock, vibration and loss of power.

Hydrogen has a small 'quenching distance' (reportedly 1/3 of gasoline) and it sometimes allows the flame to travel back into the intake valve causing backfire. Finally, hydrogen has very low density: 0.005229 lb/ft^3 (0.08376 kg/m^3). However, it can be and has been, compressed in tanks up to 5,000 psi (35 MPa). Since the energy density is low, the storage tank space is an issue for hydrogen vehicles.

4. Hydrogen Injection Methods

There are three main types of hydrogen injection: central (or throttle-body) injection, direct injection and port injection. The simplest design is the central injection involving injection of the fuel during the intake stroke from the inlet of the air intake manifold. The advantage of this design is that the pressure for the hydrogen supply need not be as high as for other injection methods, and gasoline engines use this injection system making it easy to convert a gasoline engine to run on hydrogen. The problem with this injection is that it is likely to cause pre-ignition and backfire. Since the probability for irregular combustion is high for central injection, it was not used in the current project. Direct injection is the most technologically advanced method. It involves mixing the air and fuel in the **c**ombustion chamber after the air intake valve has closed during the compression stroke. This prevents pre-ignition in the intake manifold. Also, this method is said to produces about 40% more power than the central injection method. The disadvantages of this method include: production of higher nitrogen oxide (NOx) emissions due to short mixing time and the highest supply pressure of the three methods. Although direct injection is the best method to inject hydrogen, it was not used in the current project because the technology was not readily available at the time of this project. In the port injection method, air is supplied separately at the beginning of the intake stroke to cool down any hot spots in the cylinder. Hydrogen is then injected at the inlet port just after the beginning of the intake stroke because of which the probability of pre-ignition is reduced. The supply pressure needed for port injection is higher than for the central injection, but lower than direct injection. Port injection also uses a constant-volume flow rate injection system to 'time' and 'meter' the hydrogen into each cylinder. Port injection was chosen for this project because of low chances of knock and backfire, and the more readily available technology.

5. The NOS Progressive Controller

A new concept developed in the current project is the application of the NOS (nitrous oxide injection system) to inject the hydrogen into the individual air runners as additional fuel to the gasoline injectors. There are many merits to this option including sophisticated controller devices that can control injection by time based, rpm based, or MAP (manifold air pressure) based methods. This would be helpful when collecting quantitative data during dynamometer runs to analyze the most efficient mixture of hydrogen and gasoline at different rpm's of the engine. Also, the controller is designed to only operate at wide open throttle (WOT) condition. This feature needs to be overridden to make this system work for the current project.

6. Quantum Technologies Gaseous Fuel Injection Products

As far as could be determined, Quantum Technologies is the only company that designs and markets injection systems for gaseous fuels such as hydrogen. This company converted an 8-cylinder gasoline Chevy pickup truck for the demonstration of hydrogen combustion at Yeager Airport. Initially it was thought possible to adopt this already-developed technology to the six- cylinder TOYOTA engine to run on part hydrogen and part gasoline. The current project was focused on converting a port-injected gasoline engine to an all-hydrogen engine with a supercharger to regain the volumetric efficiency lost due to the low energy density of hydrogen. Quantum injection products are also designed for other gaseous fuels such as natural gas and propane besides hydrogen. They can also supply fuel injectors, pressure regulators, and electronic controllers etc. necessary for a full conversion. However, after inquiries, it was discovered that the cost of conversion with Quantum injectors was too high for this project.

7. The Self Designed Hydrogen Injection System

The final selection for hydrogen injection was a self-made system. Since a pulsing electronic signal is already being sent from the engine's computer to the individual fuel injectors, that signal could be spilt and sent to an electric solenoid valve to control the flow of hydrogen into the individual ports through a nozzle. The hydrogen pressure could be varied to change the hydrogen flow rate into the engine through a choked flow nozzle. Also the shared frequency of the signal from the engine's computer would keep the hydrogen flow rate in a consistent ratio with the flow rate of gasoline.

8. Racing Industry Fuel Injection Technology

It was decided to use the nitrous oxide injection technology (NOS) from the racing industry, and adapt it to fit the needs for hydrogen injection. Hydrogen flow would be controlled by choked flow through a nozzle. In other words, the fluid velocity is limited, (when traveling through the nozzle), to the local speed of sound. The maximum flow rate through the nozzle would be controlled by the pressure set on the pressure regulator. The nozzle diameter corresponds to the maximum hydrogen flow rate which is the flow rate needed to run the engine on 100% hydrogen. A controller could be used to give any desired percentage of the full flow through the solenoid valve. This enables full control of the fuel mixture into the engine. MathCAD calculation sheets were generated to calculate nozzle size and the pressure setting (on the PRV) to calibrate the injection system for an engine. The nozzle was sized such that maximum flow through the nozzle would be the flow rate of hydrogen needed to run the engine on 100% hydrogen at WOT at an average RPM for the engine. Also, Air-Fuel ratio versus percentage maximum flow rate of hydrogen injected was calculated using MathCAD.

EXPERIMENTAL DETAILS

A. Components of the Hydrogen Injection System

1. Hydrogen Tank

A hydrogen tank is needed to store the fuel for the system and its requirements include: adequate volume to store and supply enough hydrogen for the required running time, tank geometry to fit into the available space, a high enough pressure rating to optimize the storage volume against the construction cost of the tank, and the material compatibility with hydrogen to minimize the permeation through walls.

2. Hydrogen PRV

A PRV (pressure reducing valve) is required to reduce the tank pressure to a lower pressure needed for the solenoid valve and the nozzle (40-200 psi). Since the operational conditions at the nozzle correspond to a choked flow, the inlet pressure of the nozzle controls the maximum flow through the nozzle. Thus the choked-flow condition sets the maximum flow rate through the nozzle when the engine is operating with 100% hydrogen. A relationship can be derived between the thermochemistry of combustion of one mole of fuel and the 0%-100% control of the hydrogen flow rate through the solenoid valve. With this relationship, stoichiometric Air-Fuel (A/F) ratio tables can be prepared to program the on-board Electronic Combustion Unit (ECU) for efficient performance. Requirements for the hydrogen PRV include: working pressure that is equal to or above the maximum tank pressure rating, ability to accurately hold the outlet pressure between 50 and 200 psi as needed, a gage with a reasonable least count, an outlet size compatible with hydrogen injection tubing/hose and a compatible inlet size to fit the tank outlet.

3. Hydrogen Solenoid Valve

The Progressive Controller would be connected to the solenoid valve and a computer software will be used to control the percentage of maximum flow rate of hydrogen to the injection nozzles. Requirements for the hydrogen solenoid valve include: a pressure rating of 800 psi (with a Factor of Safety of 4), compatibility with the chosen progressive controller, inlet and outlet sizes compatible with hydrogen injection tubing/hose, fail-close design, a material compatible with hydrogen that limits permeation through walls and a frequency response that meets progressive controller requirements.

4. Progressive Controller

A progressive controller would be used to control the percentage of the maximum flow rate of hydrogen through the solenoid valve. Requirements for the progressive controller include: control of hydrogen injection based on RPM or time, ability to set operation boundary conditions for A/F ratio and percentage hydrogen injection, compatibility with the solenoid valve, and the ability to receive and process the feedback of operating conditions such as A/F ratio, MAP and RPM.

5. Hydrogen Injection Nozzles

Injection nozzles would be used to inject hydrogen into the air intake manifold right behind the intake valve. Requirement for the hydrogen injection nozzles include: a nozzle diameter adequate to handle the maximum flow rate to run the engine with 100% stoichiometric hydrogen at choked flow condition.

6. Hydrogen Tubing/Hoses

Tubing or hoses would be used to transport hydrogen from the PRV to the solenoid valve and then to the nozzles. Requirements for the tubing/hoses include: a diameter large enough to handle the maximum flow rate, a pressure rating of 800 psi (FS = 4), a material that is compatible with hydrogen with minimal permeation through walls, lengths of tubing/hose that allow flexibility and movement of experimental set up, and the connector sizes compatible with those of the PRV, solenoid valves, and nozzles.

B. Selection of Specific Components for the Injection System

In this section a brief description of the specific components needed to install a complete hydrogen injection system is presented. The arrangement is identical to the system used on the two engines (2-cylinder Briggs & Stratton and 6-cylinder TOYOTA engines.)

1. Hydrogen Tank and Pressure Reducing Valve

For the current project, a commercial steel tank available from a local gas supplier was used. If the injection system were to be used on a vehicle, a special tank would be needed with fittings that are compatible with the refilling stations such as the one at Yeager Airport or similar hydrogen suppliers. DyneTek® offers tanks (with PRVs) ranging in capacities from 0.94 to 4.26 kg of hydrogen specifically made for automobiles.

2. Hydrogen Solenoid Valve

A "Super Big Shot Solenoid Valve (*#16010-NOS)"* rated at 1000 psi with an inlet and outlet of ¼" NPT was used. It has Kel-F sealing material and is compatible with hydrogen. The solenoid and the controller are made by the same company, and therefore they should be compatible.

3. Progressive Controller

The controller used was "15977 - NOS Launcher Progressive Nitrous Controller" the highlights of which are: fully programmable via laptop, desktop, or additional handheld device; compatible with Windows 2000, ME, XP, and Vista; innovative NOS bus 2-wire network interface for seamless integration with other Holley/NOS supported products; easy to use graphical software; free software and firmware updates updatable by the user; downloadable off the internet; full data-logging capability for easy reviewing of past runs through a laptop; ability to save configuration files for easy set-up at different tracks or for weather conditions; and fully programmable two stages of nitrous control.

Progressive Ramp Features include: *RPM Based:* programmable Trigger and End RPM points, programmable RPM trigger set point and adjustable from 0 to 20,000 RPM *Time Based*: programmable Delay time and Ramp time; adjustable from 0-10 seconds MAP (boost) based; programmable RPM trigger set point; programmable MAP trigger and MAP end points; adjustable from -14.7 to 85 psi Nitrous Percentage; programmable start and final percentages; and adjustable from 0 to 100%.

Safety Features Include: Rich/Lean cutoff based on A/F ratios, MAP (boost) pressure cutoff, RPM cutoff and nitrous pressure (when using a nitrous pressure sensor) and programmable as a linear curve or non-linear by individually adjusting 20 separate points - this applies to all four delivery methods.

4. Hydrogen Injection Nozzles

Aluminum nozzles (such as: 13500 Fogger Nozzle, 13760 NOS Precision SS Jets, and 15990 NOS 1/16 NPT Pipe Tap) use interchangeable stainless steel "jets" (orifices) to change the inside nozzle diameter. The nozzles and jets are rated for 1000 PSI. ¼" holes must be drilled into the intake manifold of the engine, and tapped with a 1/16" NPT tap. The nozzle must connect to a hose with a 3AN fitting.

5. Hydrogen Tubing/Hoses

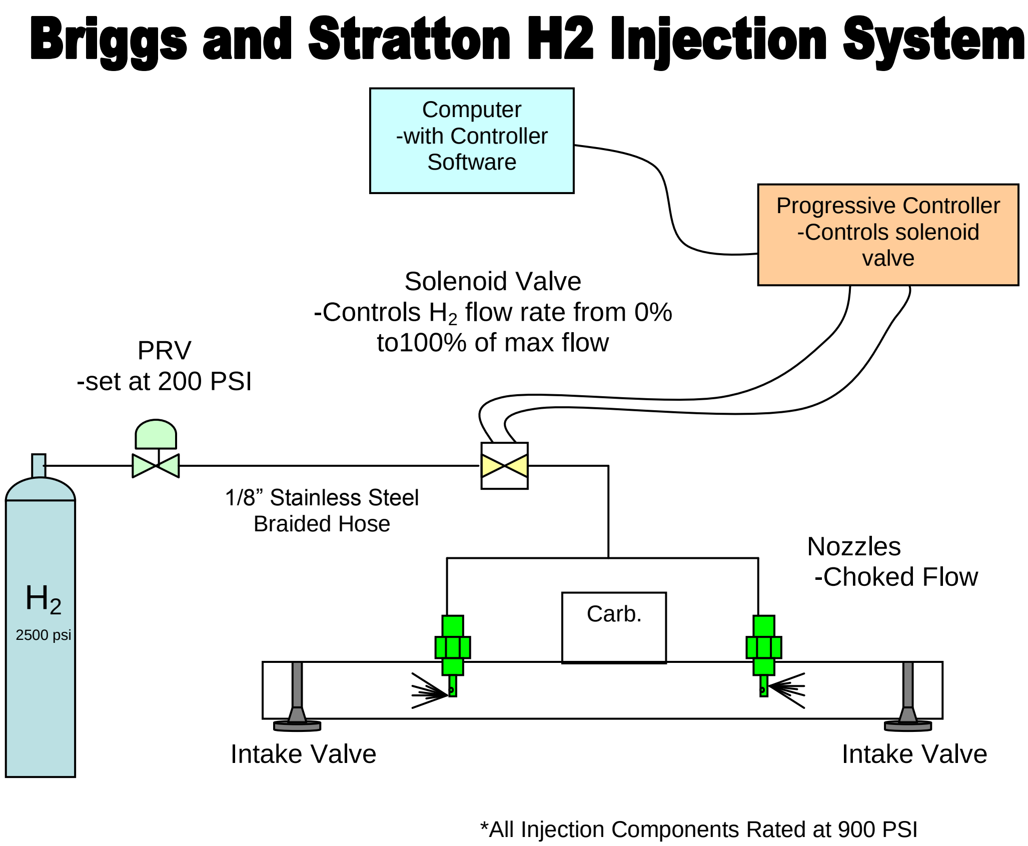
Hoses (such as: *15305 –NOS 4AN-4AN 20' Stainless Steel Braided Hose and 17970-NOS 4AN-1/4" NPT Adopter and 4AN fittings)* may be used to connect the tank to the solenoid valve and the solenoid to ports in the inlet manifold. The hose should be Teflon coated to make it compatible with hydrogen, and be rated for 1000 psi. An 4AN-1/4" adapter connected directly to the solenoid valve inlet permits connection of the 4AN-4AN 20' hose. A brass tee adapter (*16777-NOS 1/8" NPT*) is connected to the solenoid outlet using the ¼"NPT male end. The 1/8"NPT to ¼"NPT adapter is used to connect the brass tee adapter to the two distribution blocks (*16700-NOS 1/8"NPT).*

The distribution block connects to the 1/8"NPT-1/4"NPT adapter coming from the brass tee and three hoses connect the block to the nozzles. The 3AN-1/8" *(15030-NOS)* Teflon coated hose connects the block to each nozzle. The total estimated cost of the injection system was $1,108 plus the cost of the DyneTek® tank and the PRV.

C. Testing of Injection System on the Briggs and Stratton Engine

Initial testing of the Hydrogen Injection System was carried out on a twin cylinder, 23 hp, carbureted gasoline engine that was donated by Briggs and Stratton Co. The nozzle diameter required for choked conditions was computed (d=0.0463 inch). Testing on a smaller 2-cylinder engine was thought to be important: to work out the wiring and operational features of the controller; to understand qualitatively what percentage of hydrogen would work with different RPM's; and to see if there are any issues with pre-ignition, knocking or backfire.

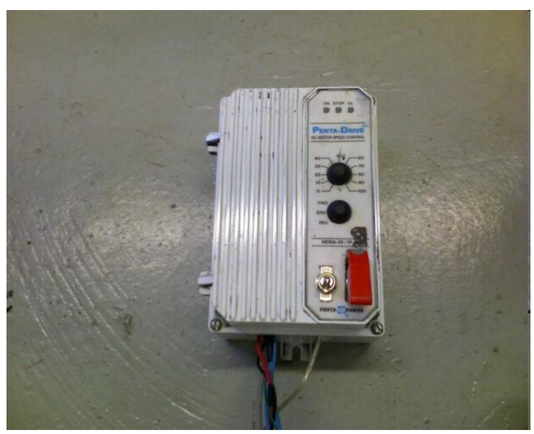
Figure 1. Line Diagram of Briggs and Stratton Hydrogen Experiment



During this test, the engine was run with only hydrogen and no gasoline. The RPM's were varied by controlling the hydrogen flow rates (as a percentage of full-flow) to determine the quantity of hydrogen needed for the smooth operation of the engine at different engine speeds (RPM’s). Knock-free operating ranges were recorded to get a better understanding of how the injection system performs.

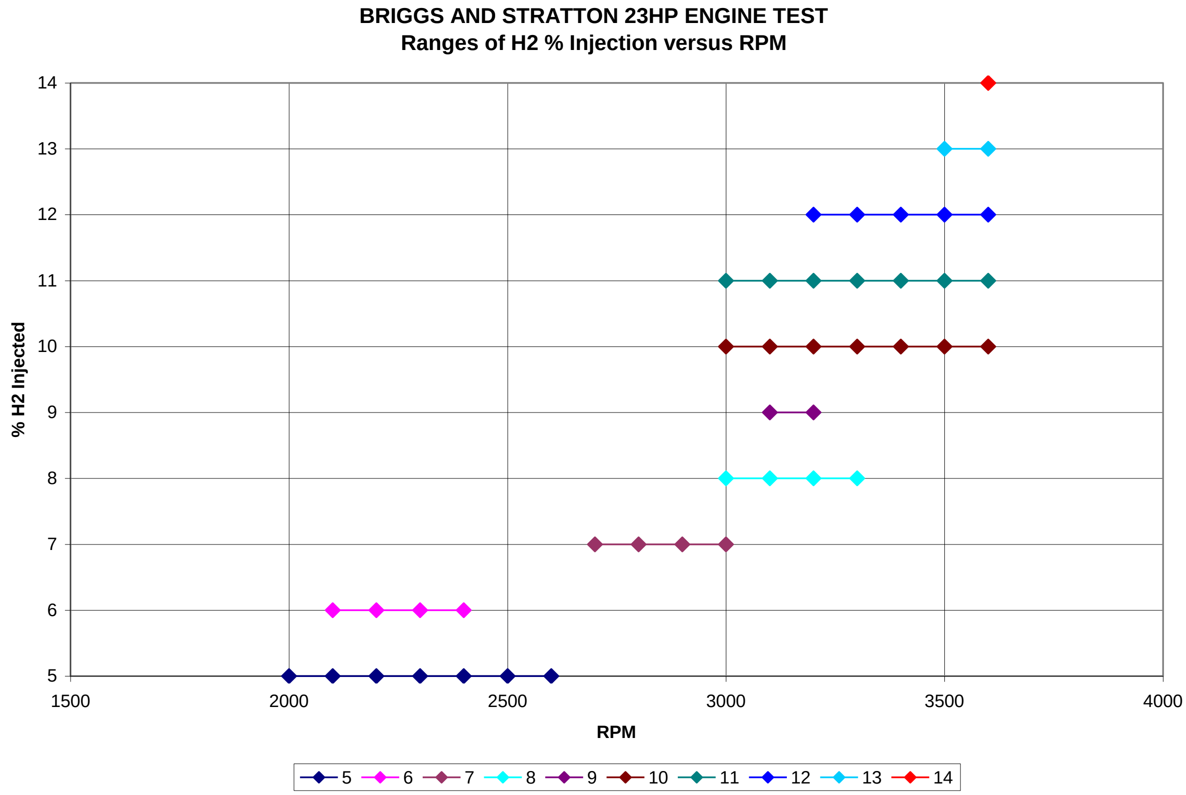
Figure 2. Photographs of the Briggs and Stratton Experiment Installation

(a) Engine Showing Tank in background (b) Engine Showing Solenoid Valve



(c) Controller Showing Wiring (d) Simplified Controller Box

Figure 3. %Hydrogen and RPM for Briggs and Stratton; Without Knock



Results

Figures 2a and 2b show the Briggs and Stratton Engine used in the experiment. Figures 2c and 2d show the controller safe box that was used to protect and simplify all of the wiring for the injection system. Figure 3 shows a slight increase in hydrogen required by the engine with increasing RPM’s. This was expected, but the low percentages were not. However, the engine was not under any load, and was no where near wide open throttle (WOT) condition. This means that the volumetric efficiency was far from 100%, so the engine needed only 5-15% of the calculated flow rate for 2000 RPM at WOT or 100% volumetric efficiency. The results were consistent with expectations. Therefore, the same method of calculations for sizing the nozzle diameter could be used for the 6- cylinder TOYOTA engine.

D. TOYOTA 6-Cylinder Hydrogen Injection System Testing

A computer-linked TOYOTA 6-Cylinder, 3-liter, Sienna Van engine connected to a hydraulic DYNOmite™ Dynamometer was used for this part of the project. During testing, the engine performance was to be compared using two 12- minute runs. The first run was to be all gasoline, and the second run was all hydrogen. The all-hydrogen run lasted for only 9½ minutes due to the solenoid valve "freezing up" due to the large pressure drop (hence a large temperature drop) across the valve. A program was written to calculate the Air Fuel (A/F) ratio. Another program was written to calculate actual A/F ratios with varying equivalence ratios. The testing objectives were: to design the hydrogen injection curve for use with the Progressive Controller, comparison of heat loss when using hydrogen and gasoline as fuels and comparison of energy used by the engine when the fuels are hydrogen and gasoline.

Figure 4. Diagram of Toyota 6-cylinder Engine Test

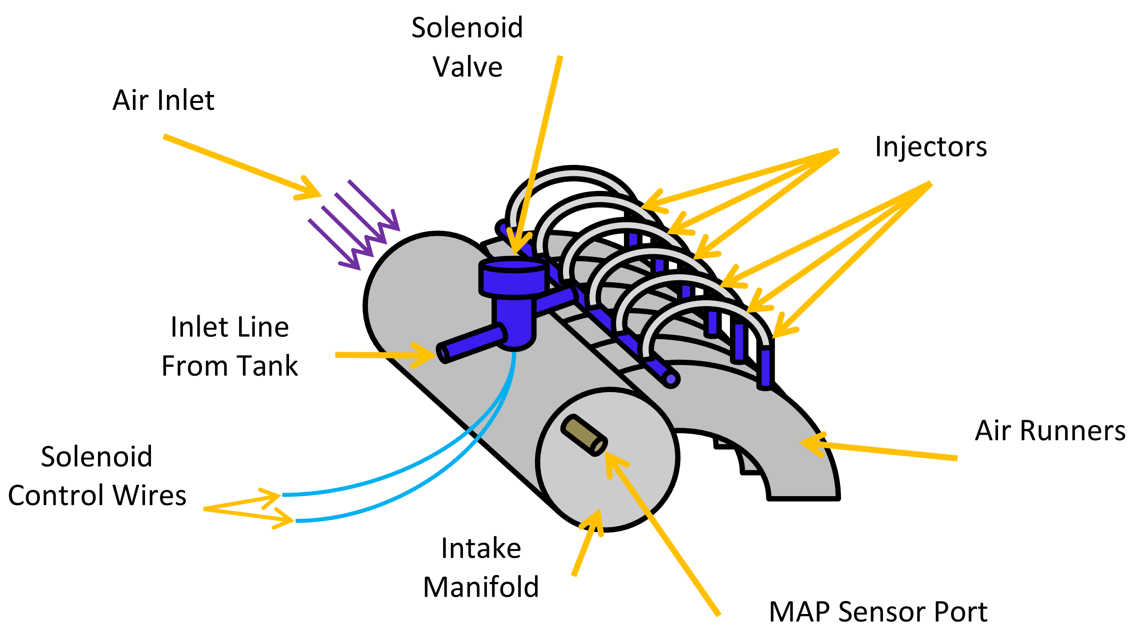


Diagram of Injection System on Toyota V6

Test Results

In order to design the injection curve for the Progressive Controller, an energy balance was used as follows. The engine was run from 500 to 3500 RPM on gasoline and the fuel flow rate was recorded in lb/hr. The amount of energy used for each cylinder was computed using the recorded gasoline fuel flow rate. Then the percent hydrogen needed to produce equal amount of energy was calculated. It should be recalled here that the term "percentage" refers to the percent of full flow through the nozzles needed to run the engine when it is operated using only hydrogen.

Figure 5. Hydrogen Injection Curve for Toyota 6-cylinder Engine

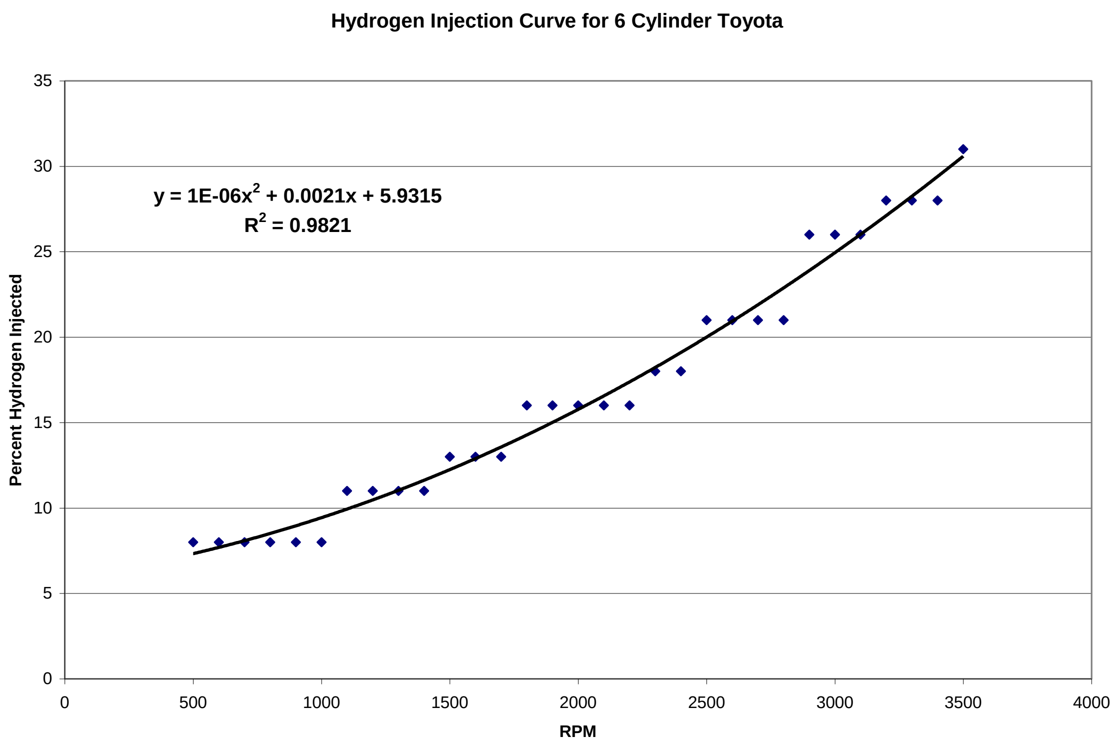
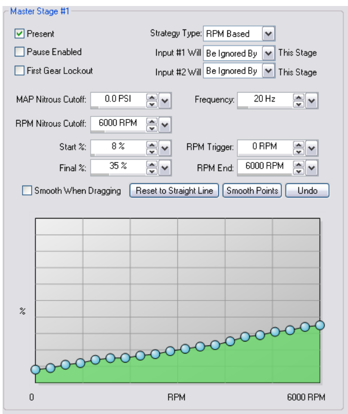


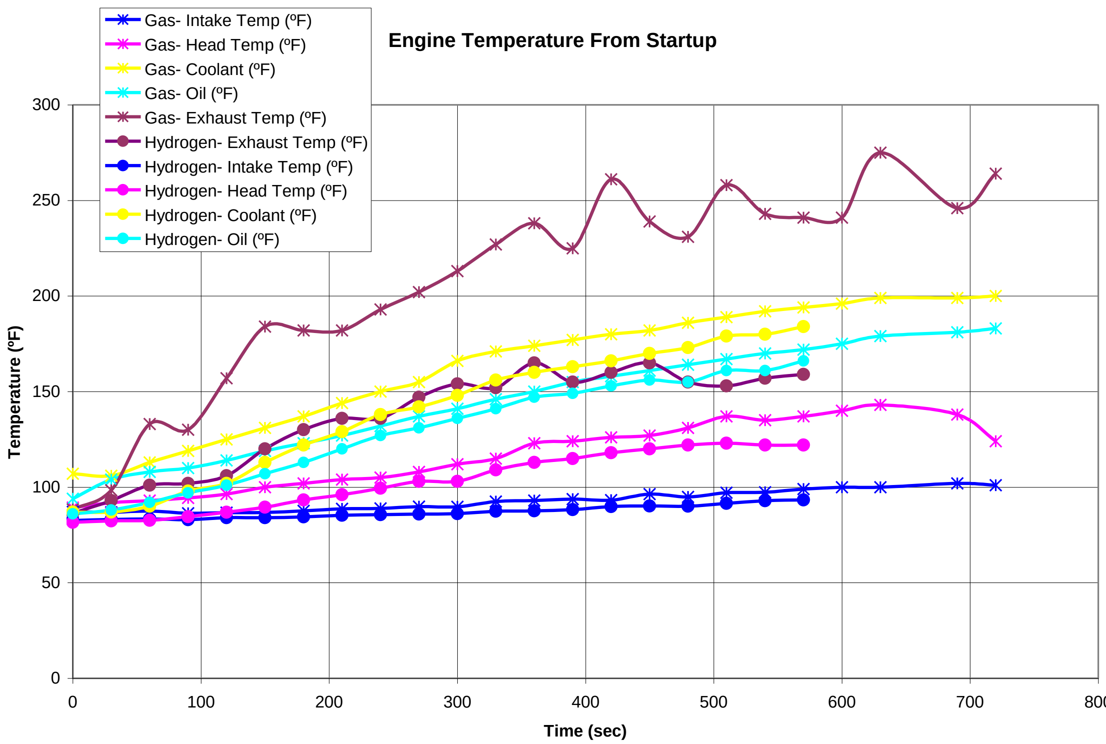
Figure 6. Designed Injection Curve for the Progressive Controller Software



The designed hydrogen injection curve is shown in Figure 5. The data points are the calculated percent hydrogen needed for every 100 RPM from 500 to 3500 RPM. The trend line is a 2nd order polynomial with a goodness of fit of 0.98. The reason for the step like data points is the poor resolution of the data recorded from the dynamometer. The least count of the fuel flow in lb/hr was 0.5; meaning only single digits were shown in the dynamometer software. This is accurate enough, however, for the purpose of our calculations. Figure 6 shows the 'Designed Injection Curve' generated for the Progressive Controller Software and how it was used.

For the heat loss comparison between all-gasoline and all-hydrogen operations, two 12-minute runs were to be performed. The first run was all-gasoline and lasted 12 minutes; the second run was for all-hydrogen and lasted only 9½ minutes due to the solenoid valve "freezing up" caused by the pressure drop across the valve. The engine was allowed to cool back to ambient temperature between runs.

Figure 7. Temperature Results for Heat Loss Comparison Test



The results shown in Figure 7 suggest that when the engine was run on hydrogen, the temperature of the engine was cooler at the air intake manifold, engine head, coolant, and oil with an average difference of only about 10 ºF compared to gasoline operation. However, the exhaust temperature was significantly cooler when running on hydrogen than gasoline. Toward the end of the run, when the temperatures began to stabilize, the difference in temperatures was about 90 ºF. This temperature difference is most likely due to the fact that the exhaust of the engine running on all-hydrogen is mostly water (H_2O) vapor.

Energy consumed by the TOYOTA engine was computed when tested separately with hydrogen and gasoline for 9.5 minutes of running time each. (Heat consumptions were calculated assuming a thermal efficiency of 20% and the lower heating values of hydrogen and gasoline as 120,000 kJ/kg and 43,000 kJ/kg respectively.) During the two test runs, the engine consumed 4551 kJ of energy when running on gasoline and 4522 kJ when running on hydrogen. These numbers are nearly identical as expected. Furthermore, with the ratio of fuel masses used, it can be shown that the energy content of one kg of hydrogen is approximately equal to that of one gallon of gasoline.

A mixture of propane and gasoline was used for a test run of about 5 minutes. No data was recorded; the test was carried out mainly to check the compatibility of the injection system with a different fuel. Propane gas was injected based on the MAP. The engine was run on all-propane at very low loads (low MAP) such as idle, and was run on gasoline at high loads. This was fairly successful, but the engine required more than 5 seconds to converge on the correct A/F ratio for the given fuel mixture. When injecting propane based on RPM, no problem was encountered; the engine ran very smoothly, and the throttle was very responsive.

Based on these observations, it can be claimed that the general layout of the injection system discussed here for hydrogen can be used with any other gaseous fuel that is compatible with Kel-F seals and Teflon lined hose, provided a separate injection curve, similar to the one shown in Fig.6 (for gaseous hydrogen,) is designed for the given fuel. Secondly, a cautionary note concerning an all-hydrogen engine: the hydrogen injection system discussed here operated satisfactorily for about 9½ minutes only, for the reason mentioned earlier, when used with 100% of the maximum flow in an all-hydrogen mode. That is: the engine would run satisfactorily for about 9½ minutes under full-flow conditions and the solenoid would become too cold to work (due to pressure drop in the valve) and freeze up. There were no problems with the injection system when the engine was operated with a mix of hydrogen and gasoline, which in fact is the intended use of the system.

Acknowledgement

Our sincere thanks to Paul O. Steranka, Jr., Professor of Mechanical Engineering, WVU Tech, for his participation and assistance in the completion of this project and Briggs-Stratton Company for donating a 23 HP twin-cylinder engine for the project.

CONCLUSIONS

Experience with this project shows that it is possible to design and build a reliable and economical add-on hydrogen injection system to work with gasoline in a spark ignition engine. All components used in the system are readily available and off-the-shelf items that are fairly inexpensive and reliable. The ease with which the current system can be programmed to work with on-board ECU's that are almost universally available in modern automobiles, should make it highly attractive to anyone looking for a simple add-on hydrogen conversion kit to improve the fuel economy at the same time lower pollutants in the exhaust of a gasoline engine. As an added bonus to WVU Tech's Mechanical Engineering Department, we now have a functional hydrogen injection system which can be used to demonstrate the basic principles of a hydrogen-burning internal combustion engine. Plans are underway to install it in a traditional automobile to shuttle visitors and guests around the campus. Whatever the end use, the hydrogen injection system designed and built under this project successfully demonstrates the operation of a dual-fuel (hydrogen-gasoline) engine.

Our next action-plan is get ready the existing computer-linked test stand (with a 6-cylinder, 3-liter TOYOTA gasoline engine) for senior design projects and senior lab experiments to investigate the performance of a dual-fuel (hydrogen-gasoline) engine. The computerized test stand has software features that can be adopted to program the system to automatically measure, compute, record and display engine parameters and results such as: torque, RPM, temperature, power, air-fuel ratio, brake mean effective pressure, thermal efficiency etc. The experience should be highly useful in understanding the merits and potential problems associated with hydrogen as an alternate fuel in automobiles.

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