Gasoline Direct Injection Engine Cold Start Improvement by Injection of Hydrogen

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Abstract

A hybrid vehicle can be configured to have a hydrogen fuel cell and an internal combustion engine. The fuel cell requires hydrogen to produce electrical power and also emits a small amount of hydrogen. This hydrogen exhaust could be supplied into the intake air of the engine. The rapid combustion and low emissions of hydrogen could improve the engine's cold start performance. To better understand the effects of hydrogen, an experiment was conducted utilizing a gasoline direct injection (GDI) engine. The engine's performance was characterized by hydrocarbon emission and in-cylinder pressure measurements.

Introduction

Presently, hybrid vehicles are being developed to increase fuel efficiency and to meet certain state emission regulations. Hybrid vehicles are distinct from conventional vehicles since they consist of two different energy sources that provide propulsion. In one case, a hybrid vehicle can be configured to have a hydrogen fuel cell and an internal combustion (IC) engine. The fuel cell generates electricity through an electrochemical reaction that combines hydrogen with ambient air. For the most part, the only emission of the fuel cell is water vapor; however, a certain amount of hydrogen exhaust also exists [1, 2].

In some hydrogen fuel cells, the residual hydrogen is circulated back to the supply line of hydrogen or discharged to the environment. In the case of hydrogen circulation, additional systems may be required and the crossover of nitrogen from the air into circulation system is a concern. The direct discharge of the hydrogen into the environment is dangerous since it can occur in places with poor ventilation. Another alternative is blocking the hydrogen exhaust, which is termed as a dead-end system. Although this system proves that the fuel cell operates for a longer period of time, there is a gradual decrease of cell output voltage [2]. A feasible alternative is to supply a percentage of the hydrogen exhaust from the fuel cell to the intake air of the IC engine. The combustion of hydrogen in IC engines is favorable since the emissions are primarily nontoxic [3].

Another concern is the pollutant emissions of the hybrid's IC engine during cold start. Based on results from previous tests, port-fuel injected IC engines emit more hydrocarbons (HC) during cold start than in any other phase of the engine's operation. During cold start, enrichment of the fuel air mixture is required because fuel vaporization is insufficient for proper combustion. The excessive unburned fuel leads to high HC levels and thus increases exhaust emissions [7]. An alternative engine concept is the gasoline direct injection (GDI) engine, which injects gasoline directly into the engine cylinder. The direct injection of the fuel allows for the control of cycle-to-cycle fuel air ratio and permits rapid initial firing of the gasoline [4]. Overall, this engine has the potential to attain reduced HC emissions during cold start.

An experiment was conducted utilizing an existing GDI engine operated during the cold start phase. The objective of this experiment is to gain an understanding of how supplying the intake air with hydrogen will affect the GDI engine cold start performance. The performance of the engine is evaluated from hydrocarbon emissions and in-cylinder pressure measurements.

Description of Experiment

The experiment was conducted utilizing a single-cylinder GDI engine. The engine is based on a four-cylinder four-valve dual overhead cam (DOHC) Ford Zetec head. This head is mounted on a research engine block with an electric motor that starts the engine and maintains a constant engine speed. The head of the engine was modified for direct gasoline injection. The fuel injector is a Siemens high-pressure direct injector that was placed where the spark plug was located. Two spark plugs were then placed at the front and rear ends of the combustion chamber. The engine specifications can be viewed in Table 1 [4].

The performance of the GDI engine was characterized by hydrocarbon and in-cylinder pressure measurements. The hydrocarbon emissions were measured utilizing a Flame Ionization Detector (FID) total hydrocarbon analyzer. A piezoelectric in-cylinder pressure transducer acquired the cylinder pressure measurements [4].

Table 1: Engine Specifications

Engine Type	4-Stroke, 4-Valve DOHC, Single Cylinder
Combustion Chamber Shape	Pent Roof
Displacement	.54 L
Bore	84.8 mm
Stroke	95.3 mm
Compression Ratio	10.0 : 1
Spark Plug	Motorcraft IZFS2C
Direct Injector	Siemens Proto-type DI Injector @ 10 MPa

<u>Calculation of the Hydrogen Mass Flow rate</u>

The calculation of the hydrogen mass flow rate was required for the development of the supply system. The hydrogen amount was determined by estimating a percentage by volume of the total intake air. In this calculation, the percentage by volume of air was assumed to be 8%. This percentage was acquired from previous hydrogen-related experiments during the cold start phase [5]. From this assumption, the relationship between the volumetric flow rate, Q, of air and hydrogen is the following.

$$Q_{hydrogen} = .08 * Q_{air} \quad (1)$$

This indicates that the volumetric flow rate of air into the engine must be calculated first. Taking into consideration that the air flow rate into the engine increases as the engine speed increases during cold start, it was assumed that the hydrogen flow rate should be based on the air flow rate of the first combustion cycle. The engine speed and manifold pressure of the first combustion cycle were obtained from Figure 1. The volumetric flow rate of air can be calculated by multiplying the volume of the engine cylinder times the engine speed as shown in equation 3.

$$\rho = P / (R * T) \quad (2)$$

$$Q_{actual} = (RPM / 2) * V_{cylinder} \quad (3)$$

$$Q_{actual} \cong .001173 \text{ m}^3/\text{s}$$

where

$$V_{cylinder} = V_{displacement} + V_{clearance}$$

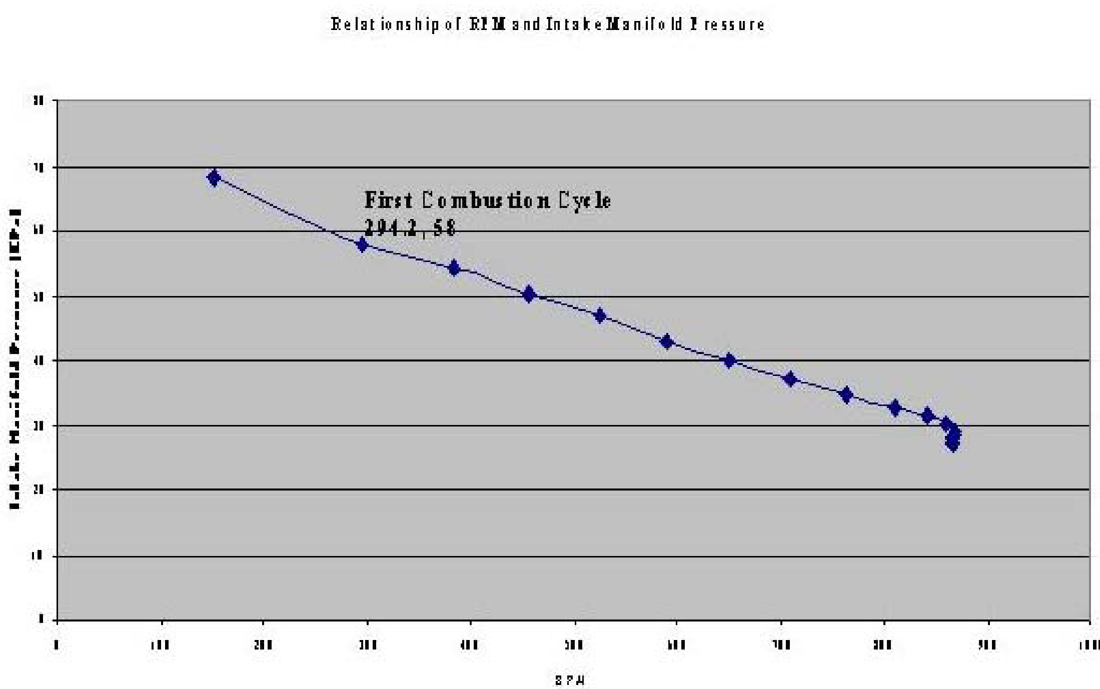
$$V_{displacement} = \pi B^2 L / 4$$

$$V_{clearance} = V_{displacement} / (r - 1)$$

The actual volumetric flow rate of hydrogen is then 8% of the calculated value or $Q_{actualH2} \cong 9.38 * 10^{-5}$ m³/s. The next step is to calculate the actual mass flow rate of hydrogen by multiplying the actual volumetric flow rate by the density of hydrogen at these same conditions. The ideal gas equation 2 is then utilized to calculate the density. The pressure and temperature values are obtained from the first firing cycle and the temperature is assumed to be 25°C. The calculation then gives the mass flow rate of hydrogen to be the following.

$$m_{hydrogen} \cong 4.42 * 10 ^ {-6} \text{ kg/s}$$

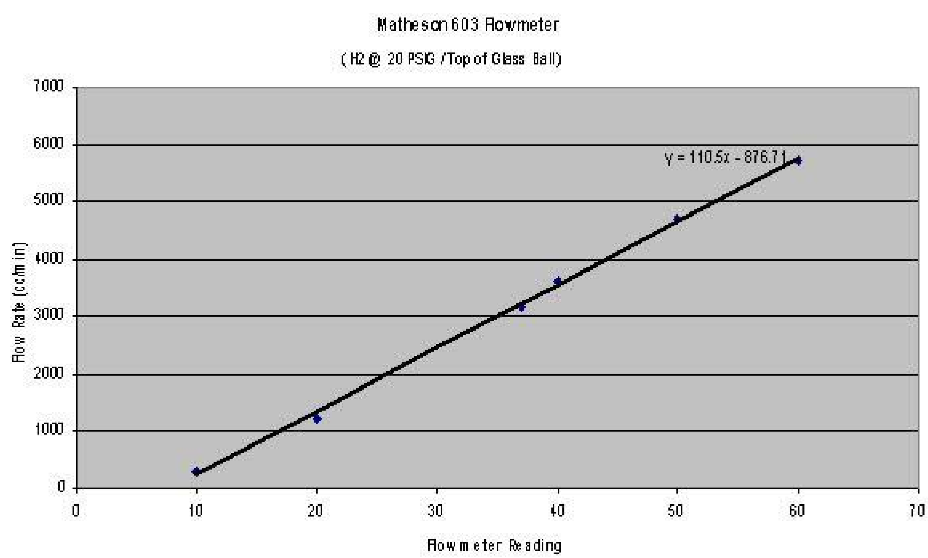
Figure 1: First Combustion Cycle Values



Flow Meter Selection

Once the mass flow rate of hydrogen was calculated, the next step was to select a flow meter. The flow meter catalog provides the volumetric flow rate at different standard conditions of each meter. The mass flow rate is equal to the density times the volumetric flow rate. The mass flow rate of hydrogen is already known and the density can be calculated from the standard conditions provided by the catalog. The volumetric flow rate of hydrogen would now be calculated utilizing different standard conditions. The catalog classifies the flow meters according to their volumetric flow rate in units of standard cubic centimeters per minute (sccm). Therefore, a unit conversion of the volumetric flow rate is required. Since the volumetric flow rate is in units of m^3/s, a factor of 6.0 * 10^7 would need to be applied to convert to sccm. The volumetric flow rate was calculated to be 3,176 sccm. The flow meter best suitable for this flow rate was chosen to be Matheson Model 603. The flow meter was calibrated and Figure 2 was then made to obtain the actual mass flow rates. This figure displays the flow meter reading on the x-axis and the actual flow rate on the y-axis.

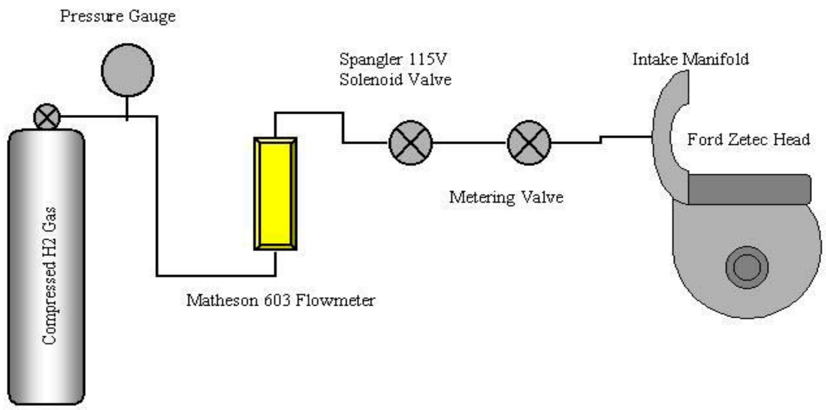
Figure 2: Flow Meter Actual Readings



Description of Hydrogen Supply System

The hydrogen is supplied by the system illustrated in Figure 3. The tank contains compressed hydrogen gas and a pressure valve regulates it at 20 psig. The hydrogen flow rate is controlled by the flow meter and it is activated once the solenoid valve is triggered. The metering valve serves as a regulator for the amount of hydrogen that supplies the intake manifold per unit of time.

Figure 3: Hydrogen System



Test Plan

The testing was achieved in multiple engine runs to simulate an engine cold start. The cold start operating conditions are listed in Table 2. The engine speed and manifold pressure were obtained from the first firing cycle. The injection and ignition timings were acquired by performing timing scans for best engine performance. The fuel component utilized was chosen for its similar performance characteristics of gasoline. Also, the amount of fuel supplied to the engine was reduced when hydrogen was added so that the equivalence ratio was kept at 1. Each run included an initial motoring stage that was followed by an actual 50 firing cycle test. After the 50 cycles, a cool down period of about 30 minutes followed to reach the initial cold start conditions. Five engine runs were conducted with and without the supply of hydrogen.

Table 2: Cold Start Operating Conditions

Speed	294 RPM
Manifold Absolute Pressure	58 kPa
Intake Air Temperature	25 deg C
Air Flow Rate	2.0 SCFM
Air-Fuel Ratio	Stoichiometric
Injection Timing / Ignition Timing	100 ATDC / 35 BTDC
Fuel	70% iso-octane / 30% 4-Heptanone

Results and Discussion

Figure 4 shows the average performance results taken without the supply of hydrogen. The results are illustrated by performance measurements such as the Gross Indicated Mean Effective Pressure (GIMEP), the Coefficient of Variation (COV) of GIMEP, the HC emissions and the Location of Peak Pressure (LPP). The GIMEP is obtained by dividing the work per cycle by the cylinder volume displaced per cycle [6]. The COV of GIMEP is obtained by dividing the standard deviation of GIMEP by the mean GIMEP [4]. In short terms, GIMEP is the engine's ability to do work and the COV of GIMEP shows the stability of engine combustion.

Based on the GIMEP of Figure 5, there existed several misfires between cycle 1 and 5 and several partial burns between cycles 5 and 10. The complete combustion cycles did not occur until after cycle 10. The peak of the HC emission indicates unburned hydrocarbons in the exhaust port that may have been caused by cycles with partial burn. Because of their characteristics, these first 45 cycles are referred to as the start-up transient. After this region, a quasi-steady state is reached as indicated in cycle 45 through 50.

Figure 5 illustrates the average performance results taken with the supply of hydrogen. According to the GIMEP, complete combustion occurred in the first cycle, which is significantly earlier than in the case without hydrogen. With the supply of hydrogen, there exist no HC peak. This result could indicate that most of the hydrocarbons were burned properly. In both quasi-steady state regions, while the HC measurements are equal, the GIMEP and LPP average values are different. The LPP of the hydrogen case could be adjusted for a more accurate comparison of both performance values. Another reasonable action would be to perform engine runs with decreasing percentages of hydrogen. These tests should provide with more noticeable effects of hydrogen in the cold start phase.

Conclusions

1. The supply of hydrogen did have a significant effect on the GDI cold start performance especially during the engine transient phase.

2. In the hydrogen case, the LPP mean value was significantly earlier than the case without the hydrogen supply. The LPP could be adjusted by retarding the ignition timing to have a more fair comparison between both case results.

Figure 4: Performance Results Without Hydrogen

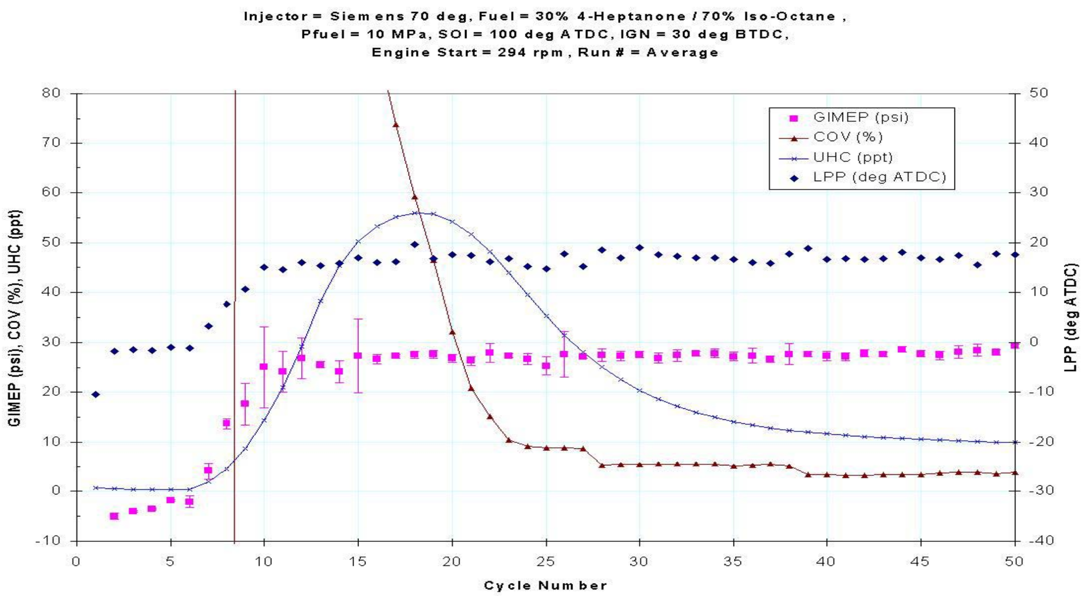
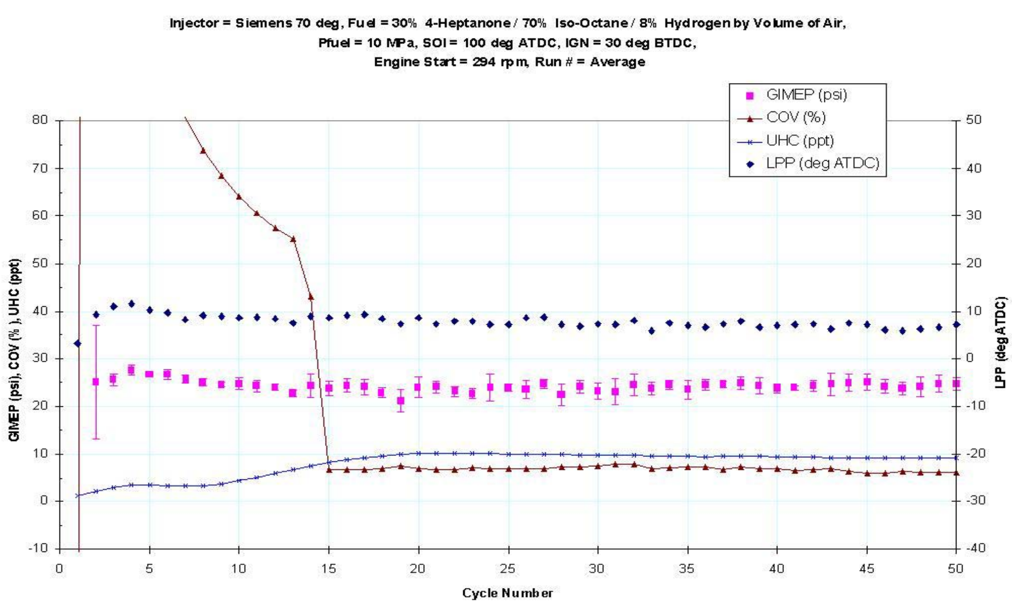


Figure 5: Performance Results With Hydrogen



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