

The Simulation of Using Hydrogen Fuel in Gasoline Internal Combustion Engines.

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ABSTRACT

Ultimately, the use of hydrogen fuel produced from renewable energy sources could solve the air pollution, global warming, and energy security problems associated with today's fossil fuel-powered passenger vehicles. Although commercial applications of hydrogen fuel cell technology for passenger vehicles are still over a decade away, optimization of today's hybrid internal combustion engines (ICE) to run on hydrogen may provide a vital intermediary step. This paper summarizes the result of simulation of the possibility of using hydrogen as a fuel in internal combustion engines thus, this is achieved by modifying an existing design gasoline internal combustion engine to include the following parts in the intake and exhaust manifolds:

1. Installing a disk piston and flat ceiling combustion chamber.
2. Replacing the single exhaust valve with 2 valves which smaller than the single one to reduce the heat absorbed by the valve face.
3. Putting a Servo jet pulse-width-modulated electronic gas injector directly to the combustion chamber.
4. Redesigning the cooling system.

Having modified the internal combustion engine, the simulated calculated results of H₂ were compared with previously theoretical and experimental gasoline data. In general very good agreements were found to exist between our simulated calculated data and previously data especially fin efficiency, radiator efficiency, and the mass flow rates.

(Keywords: hydrogen fuel, H₂, gasoline, simulation, fuel cells, combustion chamber, servo jet, engine, ICE)

INTRODUCTION

Jordan is a lower-middle income Middle Eastern country, of about 5.8 million inhabitants, that suffers from a chronic lack of adequate supplies of natural resources including water and oil. Jordan depends heavily on imports of oil from neighboring countries as the main source of energy. Its current imports of around 100,000 barrels of crude oil per day are placing the country under extreme economic pressures.

In 2007, Jordan's consumption of primary energy [1] amounted to 7.028 million Ton Oil Equivalent (TOE). Nearly 95% of this consumption came in the form of imports of crude oil, natural gas and petroleum products. The remaining 5% came in the form of renewable energy and imported electricity. The final energy consumption for the same year amounted to 4.802 million TOE [1-3].

Hydrogen internal combustion engine vehicles present much of the same promise as hydrogen fuel cell vehicles: reduced reliance on imported oil and reduced carbon dioxide emissions. This paper examines the hydrogen ICE technology, focusing on relevant aspects such as power, fuel economy, tank size, and the state of the technology. The case for hydrogen ICE depends most on key uncertainties in the evolution of vehicle and production technology, the cost of crude oil, and the valuation of carbon dioxide emission reductions.

Hydrogen-burning internal combustion engines trace their roots back to some of the very earliest developments in internal combustion engine development. Initially, gaseous fuels like hydrogen were preferred to liquid fuels like gasoline because they were considered safer to work with, due to the low pressures used for the gaseous fuels and the quick dissipation of the

gases in the event of a leak. In 1807 Issac de Rivas built the first hydrogen internal combustion engine, and although the design had serious flaws, it was a more than 50 years ahead of the development of gasoline internal combustion engines (Taylor 1985). Technological advances in gasoline engines, such as the development of the carburetor (which allowed air and gasoline to be consistently mixed), eventually led to other fuels being largely passed over in favor of gasoline [4-11].

Alternative fuels such as methanol, ethanol, bio-diesel, propane, natural gas, and hydrogen can lower the emissions of engines when compared to gasoline emissions. Hydrogen, however, is the only one that can potentially produce no hydrocarbon, carbon monoxide, or carbon dioxide emissions.

The importance of the hydrogen fuel comes from two reasons which are; firstly it's a renewable fuel and the secondly it's environmental friendly (less pollution). A hydrogen engine is a simple internal combustion engine like those engines which we have known, but with some differences in the design of the engines.

LITERATURE SURVEY

The earliest attempt at developing a hydrogen engine was reported by Reverend W. Cecil in 1820. The engine itself operated on the vacuum principle, in which atmospheric pressure drives a piston back against a vacuum to produce power. The vacuum is created by burning a hydrogen-air mixture, allowing it to expand and then cool. Although the engine ran satisfactorily, vacuum engines never became practical.

In recent years, the concern for cleaner air, along with stricter air pollution regulation and the desire to reduce the dependency on fossil fuels have rekindled the interest in hydrogen as a vehicular fuel [12-19].

Hydrogen has been considered as a fuel for internal combustion engines for more than 100 years. In 1820, Cecil was the first to recommend the use of hydrogen as a fuel for powering engines (Cecil, 1822). In particular, just prior to and during World War II, interest in hydrogen increased. For example, in the 1930s, Rudolf Erren converted over 1000 vehicles to run on hydrogen or hydrogen/gasoline blends (Hoffman,

1981). In the 1940s, Oehmichen reported efficiencies of over 50% from an engine running solely on hydrogen (Oehmichen, 1942).

Although interest in hydrogen fuel waned immediately following the end of World War II, some research into hydrogen vehicles continued, most notably that of R.O. King in Canada (King et al., 1955, 1956). In the 1970s, primarily as a result of the oil crisis, there was a resurgence of research into the possibility of hydrogen-fueled transportation with programs initiated in Japan, West Germany, and the United States. In the last 15 years, research on hydrogen has been reported by Mazda, BMW, and Mercedes Benz, and several university researchers (Swain et al., 1983, Koyanagi et al., 1994). A detailed review of research on hydrogen as a fuel for surface transportation is provided in Norbeck, et al. (1996).

Ford has developed a hydrogen-fueled hybrid ICE concept vehicle that is 25 percent more efficient than gasoline-fueled vehicles, and has a range of 300 miles. This vehicle—the Model U—was specifically designed with mass production and affordability in mind.

As a result of the evaluation of the prototype hydrogen-powered engine, it was determined that improvements could be implemented that would improve vehicle drivability, fuel economy, performance, and emissions.

Such improvements include increasing the compression ratio and displacement of the engine, using natural aspiration for air induction, using computer-controlled timing advance, and using an electronic fuel injection system for metering the hydrogen to the engine.

Properties of Hydrogen

There are several important characteristics of hydrogen that greatly influence the technological development of hydrogen ICE and FCVs.

- ***Wide Range of Flammability.*** Compared to nearly all other fuels, hydrogen has a wide flammability range (4-74% versus 1.4-7.6% volume in air for gasoline). This first leads to obvious concerns over the safe handling of hydrogen. But, it also implies that a wide range of fuel-air mixtures, including a *lean* mix of fuel to air, or, in other words, a fuel-air mix in which the amount of fuel is

less than the stoichiometric, or chemically ideal, amount. Running an engine on a lean mix generally allows for greater fuel economy due to a more complete combustion of the fuel. In addition, it also allows for a lower combustion temperature, lowering emissions of criteria pollutants such as nitrous oxides (NOX).

- **Low Ignition Energy.** The amount of energy needed to ignite hydrogen is on the order of a magnitude lower than that needed to ignite gasoline (0.02 MJ for hydrogen versus 0.2 MJ for gasoline). On the upside, this ensures ignition of lean mixtures and allows for prompt ignition. On the downside, it implies that there is the danger of hot gases or hot spots on the cylinder igniting the fuel, leading to issues with premature ignition and flashback (i.e., ignition after the vehicle is turned off).
- **Small Quenching Distance.** Hydrogen has a small quenching distance (0.6mm for hydrogen versus 2.0mm for gasoline), which refers to the distance from the internal cylinder wall where the combustion flame extinguishes. This implies that it is more difficult to quench a hydrogen flame than the flame of most other fuels, which can increase backfire (i.e., ignition of the engine's exhaust).

- **High Flame Speed.** Hydrogen burns with a high flame speed, allowing for hydrogen engines to more closely approach the thermodynamically ideal engine cycle (most efficient fuel power ratio) when the stoichiometric fuel mix is used. However, when the engine is running lean to improve fuel economy, flame speed slows significantly.
- **High Diffusivity.** Hydrogen disperses quickly into air, allowing for a more uniform fuel air mixture, and a decreased likelihood of major safety issues from hydrogen leaks.
- **Low Density.** The most important implication of hydrogen's low density is that without significant compression or conversion of hydrogen to a liquid, a very large volume may be necessary to store enough hydrogen to provide an adequate driving range. Low density also implies that the fuel-air mixture has low energy density, which tends to reduce the power output of the engine. Thus when a hydrogen engine is run lean, issues with inadequate power may arise (College of the Desert 2001).

Table 1 shows the physical and chemical properties of hydrogen and gasoline fuel.

Table 1: The Properties Hydrogen and Gasoline.

Property	Hydrogen	Gasoline
Molecule mass	2.016	107-114.2
Density, (at 20 c0, 760 mm Hg)	83.764e ⁻⁵	0.7-0.75
Dynamic viscosity [g.s/cm]	8.7e ⁻⁵	0.002
Range of combustion in air in volume[%]	4-75	-7.6
Minimum ignition energy in air [mJ]	0.02	0.24
Self ignition temperature [k]	858	510-744
Flame temperature in air [k]	2318	2470
Combustion speed in air [cm/s]	265-325	37-43
Diffusion coefficient in air [cm ² /s]	0.61	0.05
Equivalence ratio	0.1-7.1	0.6-3.5
Air / fuel ratio (in unit of weight)	364.8-4.8	25-4.3
Air / fuel ratio (in unit of volume)	24-0.3	100-16.7
Specific gravity	3.185	3.914

COMPARISON OF VEHICLE TECHNOLOGIES

Table 2 and Figures 1 and 2 present the most important characteristics of the four most relevant types of vehicles: gasoline ICE, gasoline hybrids, hydrogen.

Hydrogen ICE vehicles tend to fall in a middle ground between the higher efficiency hydrogen fuel cell vehicles and the standard gasoline ICE vehicles. In many respects, hydrogen ICE vehicles can be thought of as diesel fuel hybrid vehicles that run off of hydrogen, rather than diesel fuel. Thus a critical difference between gasoline hybrids and hydrogen ICE vehicles is that the use of a CI engine design allows for greater engine efficiency: on the order of one third greater.

Spark-ignition engines have a maximum efficiency of 32.5% under normal conditions and at low loads have a much lower efficiency than this. Note that the additional electric engine in gasoline hybrid vehicles is highly efficient at very low percent loads, and is primarily used at low load levels, so gasoline hybrids do not suffer from this loss in efficiency at low loads as much. Compression-ignition engines tend to have a maximum efficiency rough in the range of 40%, and quickly reach efficiency levels close to the maximum efficiency at low percent loads.

The greater maximum engine efficiency is in large part the reason why diesel vehicles have better fuel economy than conventional vehicles Spark-ignition engines have a maximum efficiency of 32.5% under normal conditions and at low loads have a much lower efficiency than this. Note that the additional electric engine in gasoline hybrid vehicles is highly efficient at very low percent loads, and is primarily used at low load levels, so gasoline hybrids do not suffer from this loss in efficiency at low loads as much. Compression-ignition engines tend to have a maximum efficiency rough in the range of 40%, and quickly reach efficiency levels close to the maximum efficiency at low percent loads.

Finally, Table 1 describes the current state of the technology. Gasoline hybrids have already been developed and are in the rapid market diffusion stage. On the other hand, hydrogen ICE vehicles are still for the most part on the drawing board. The few companies investing in hydrogen ICE (e.g., Ford and BMW) have made substantial progress and believe that commercialization may only be a few years away (Ford 2006). In contrast, considerable research and development effort is being focused on fuel cells today by many companies and universities, but the state of the technology is far from the market commercialization stage (Edwards 2006).

Table 2: Comparison of Different Vehicle Types.

Engine type	Gasoline ICE	Gasoline Hybrid	H2 ICE	H2 Fuel Cell
Average Engine Efficiency	~30%	~30%	~40%	~55%
Max Engine Efficiency	32.5%	32.5%	40%	65%
Transmission Type	standard	CVT/ hybrid	CVT/ likely hybrid	CVT/ likely hybrid
Transmission Efficiency	~40%	~60%	~60%	~60%
Fuel Economy (mpg equival.)	21	31	41	51
Sizeability	As much power as needed, at the cost of mpg	Efficiency improvements over gas ICEs are mostly lost with increased power	Efficiency losses or higher emission control costs to increase power	Increasing power may be expensive, requiring additional FCs
Fuel Tank Size (constant range)	Moderate	Small	Large	Large; smaller than H2 ICE
Cost of Fuel	Currently low	Currently low	Currently high; but may be slightly lower than FCVs	Currently high
Criteria Pollutant Emissions	Meets emission standards	Lower than gasoline ICE	Likely low, some NOx	Very low or none
State of Technology	Developed	Developed, and in diffusion stage	Could be developed quickly	Earlier in the research process

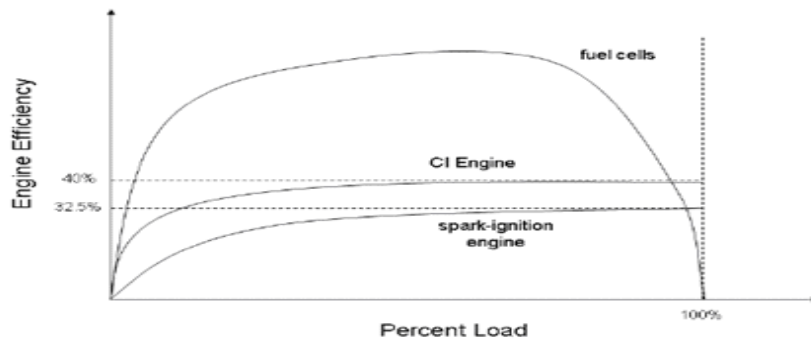


Figure 1: Engine Efficiency versus Fuel Cells, Compression Ignition, and Spark Ignition Engines (Edwards (2006)).

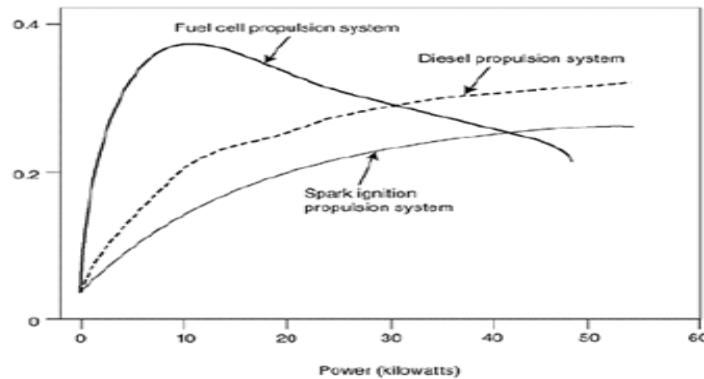


Figure 2: Comparison of Power Train Efficiency of Combustion Engine and Fuel Cell System for a Car Similar to Volkswagen Golf (Wengel and Schirrmeister (2000)).

Problems of the Hydrogen Engine

Several problems may be raised when we used the hydrogen as running fuel in gasoline internal combustion engine because of the following properties.

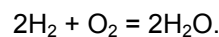
1. Low ignition energy
2. Small quenching distance
3. Low density: this results in two problems

The problems are:

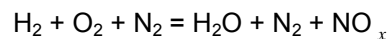
1. Pre ignition problem: The primary problem that has been encountered in the development of operational hydrogen engines is premature ignition. Premature ignition occurs when the fuel mixture in the

combustion chamber becomes ignited before ignition by the spark plug, and results in an inefficient, rough running engine.

2. Engines are usually larger than gasoline engines, and/or are equipped with turbochargers or superchargers.
3. Emissions: The combustion of hydrogen with oxygen produces water as its only product:



The combustion of hydrogen with air however can also produce oxides of nitrogen (NO_x):



The oxides of nitrogen are created due to the high

temperatures generated within the combustion chamber during combustion. This high temperature causes some of the nitrogen in the air to combine with the oxygen in the air. In addition to oxides of nitrogen, traces of carbon monoxide and carbon dioxide can be present in the exhaust gas, due to seeped oil burning in the combustion chamber.

Depending on the condition of the engine (burning of oil) and the operating strategy used (a rich versus lean air/fuel ratio), a hydrogen engine can produce from almost zero emissions (a few ppm) to high NO_x and significant carbon monoxide emissions.

Problem Solutions

As a result of these problems, we suggest the following changes in the design of our engine, and give solutions to work appropriately with the hydrogen fuel, and these solutions are:

1. Installing a suitable ignition system and carefully selecting its components, because ignition systems that use a waste spark system should not be used for hydrogen engines. These systems energize the spark each time the piston is at top dead center whether or not the piston is on the compression stroke or on its exhaust stroke. For gasoline engines, waste spark systems work well and are less expensive than other systems. For hydrogen engines, the waste sparks are a source of pre-ignition.

Spark plugs for a hydrogen engine should have a cold rating and have non-platinum tips. Platinum-tip spark plugs should also be avoided since platinum is a catalyst, causing hydrogen to oxidize with air.

2. Crankcase ventilation is even more important for hydrogen engines than for gasoline engines. As with gasoline engines, unburned fuel can seep by the piston rings and enter the crankcase. Since hydrogen has a lower energy ignition limit than gasoline, any unburned hydrogen entering the crankcase has a greater chance of igniting. Hydrogen should be prevented from accumulating through ventilation.

Ignition within the crankcase can be just a startling noise or result in engine fire. When hydrogen ignites within the crankcase, a sudden

pressure rise occurs. To relieve this pressure, a pressure relief valve must be installed on the valve cover.

Exhaust gases can also seep by the piston rings into the crankcase. Since hydrogen exhaust is water vapor, water can condense in the crankcase when proper ventilation is not provided. The mixing of water into the crankcase oil reduces its lubrication ability, resulting in a higher degree of engine wear.

The modification of the intake and the exhaust manifolds:

Redesign the engine is the most effective means of controlling the pre-ignition, specifically the combustion chamber and the cooling system.

a. First suggestion: - install a disk piston and flat ceiling combustion chamber, but we have faced some problems and the most important one is the mixing process between air and hydrogen inside the combustion chamber. This solution can be used to produce low radial and tangential velocity components and does not amplify inlet swirl during compression. Knowing that the density of air in the compression stroke inside the combustion chamber is about 23kg/m^3 so the mixing process is going to be hard.

Now instead of the high diffusivity for hydrogen which will help in the mixing we have put a steel blades in the intake manifold just before the entrance to the combustion chamber and the point is to force the air to enter in non uniform way, we can say as a vortices so in this way we assure a best mixing for fuel and air inside the engine so the efficiency and the performance will increase as well.

b. The second problem in our design is the backfire and pre-ignition of hydrogen because the hot spots and hot gases inside the combustion chamber.

We suggested two solutions as follows:

i) Replacing the single exhaust valve with two valves and they must be smaller than the single one to reduce the heat absorbed by the valve face, the heat will be distributed uniformly in the two faces of the two valves and their face area will be smaller than the single one.

ii) Installing a steel bars in the exhaust manifold right after the exit of the combustion chamber to

decrease the exit area a little bit and in that way the rejection of exhaust gases will be better and the residual gases inside the chamber will be removed or its quantity will be less in that way leading to decrease the temperature in the combustion chamber.

▪ **Injection Modification:**

An injector is a device which used to deliver the fuel to the combustion chamber as a form of atomized particles and this can be done by making the injector works under very high pressure. Because Hydrogen stores much less energy per unit of volume than gasoline; therefore, gasoline fuel injectors are inadequate for metering fuel in an engine. we are used the direct injection system.

▪ **Hydrogen injector description**

The Servo jet pulse-width-modulated electronic gas injector is a two ways, normally closed, solenoid operated valve. Designed with corrosion resistant materials, it meters gaseous fuels into the intake system of internal combustion engines. The injector is a cartridge design for easy installation. These injectors are typically pulse-width-modulated to meter fuel quantity at any operating frequency, even above 100 Hz. With sonic flow across the valve inlet when fully open, mass flow is approximately proportional to the supply pressure.

▪ **Injector Basic Design and Function**

The basic design of the gas injector was derived from the fast responding solenoid valve which is described in detail by Barkhimer et al. (1983). The injectors are composed of a solenoid coil and valve assembly. The coil assembly consists of solenoid winding and electrical connection. The valve assembly is comprised of the valve body which holds the solenoid armature, ball poppet and seat.

Figure 3 shows the operating concept of the injector. The cross-section of the actual injector is shown in Figure 4. With the solenoid de-energized, the supply pressure, assisted by a spring, forces the solenoid ball poppet on its seat, prohibiting gas flow. When the solenoid is energized, the ball poppet is lifted off the seat and held against the stop. Gas then passes through the valve seat and outlet port of the injector. The solenoid is a low resistance coil designed for rapid response, and is typically actuated by a current to 4 amperes, then reduced and held at 1

ampere to conserve energy for the duration of the energized time (pulse-width).

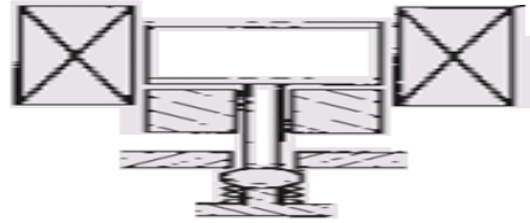


Figure 3. Operating Concept of the Hydrogen Injector (Barkhimer et al., 1995).

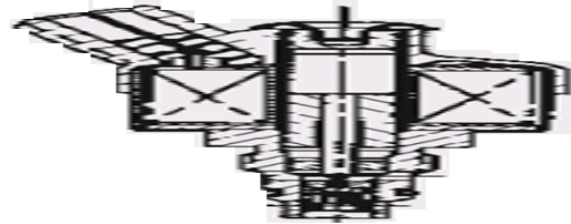


Figure 4: Injector Cross-Section (Barkhimer et al., 1995).

Cooling System Modification

The cooling system composed of:

- The Radiator: It's composed of the fins, the tubes which pass through it, and the header and water container in the top and bottom of the radiator.
- Pressure cap and expansion reservoir.
- Pump: It's necessary for forced circulation, the pump is mounted at the front end of the engine, and it's normally of the centrifugal type, and it's driven by a V-belt from the crank shaft.
- Thermostat and Fan.

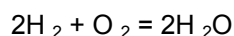
So finally modifying the cooling system in a hydrogen fuelled engine is very important due to the problems we are facing like auto ignition and back fire and these problems are caused as a result of the high temperatures. Table 3 shows the specifications of hydrogen modified engine.

Table 3 : The Specifications of Hydrogen Modified Engine.

Engine Type	4-stroke / Four cylinder
Combustion Chamber Shape	Flat Ceiling
Displacement	2.2 L
Bore	84.8 mm
Stroke	95.3 mm
Compression Ratio	10:1

Hydrogen Combustion Theory [20-26]

Fundamental Equation for the Combustion Hydrogen and Air:



Number of moles of H_2 for complete combustion = 2 moles

Number of moles of O_2 for complete combustion = 1 mole

Because air is used as the oxidizer instead oxygen, the nitrogen in the air needs to be included in the calculation:

Number of moles of N_2 in air

$$= \# \text{ of moles of } \text{O}_2 \times (79\% \text{ N}_2 \text{ in air}/21\% \text{ O}_2 \text{ in air}) \quad (1)$$

$$= 1 \text{ mole of } \text{O}_2 \times (79\% \text{ N}_2 \text{ in air}/21\% \text{ O}_2 \text{ in air}) \\ = 3.762 \text{ moles N}_2$$

Number of moles of air

$$= \text{moles of } \text{O}_2 + \text{moles of N}_2 \quad (2)$$

$$= 1 + 3.762 = 4.762 \text{ moles of air}$$

$$\text{Weight of } \text{O}_2 = 1 \text{ mole of } \text{O}_2 \times 32 \text{ g/mole} \\ = 32 \text{ g} \quad (3)$$

$$\text{Weight of N}_2 = 3.762 \text{ moles of N}_2 \times 28 \text{ g/mole} \\ = 105.33 \text{ g} \quad (4)$$

$$\text{Weight of air} = \text{weight of } \text{O}_2 + \text{weight of N}_2 \quad (5)$$

$$= 32\text{g} + 105.33 \text{ g} = 137.33 \text{ g}$$

$$\text{Weight of } \text{H}_2 = 2 \text{ moles of } \text{H}_2 \times 2 \text{ g/mole} \\ = 4 \text{ g} \quad (6)$$

Stoichiometric Air/Fuel (A/F) ratio for H_2 and air
Based on mass: A/F

$$= \text{mass of air/mass of fuel} \quad (7) \\ = 137.33 \text{ g}/4 \text{ g} = 34.33:1$$

Based on volume: A/F = volume (moles) of air/volume (moles) of fuel = (8)

$$= 4.762/2 = 2.381:1$$

Percent of combustion chamber occupied by H_2 for a stoichiometric mixture:

$$\% \text{ H}_2 = \text{volume (moles) of } \text{H}_2 / \text{total volume} \quad (9)$$

$$= \text{volume (moles) of } \text{H}_2 / (\text{volume (moles) of air} + \text{volume (moles) of } \text{H}_2) = 2 / (4.762 + 2) = 29.57\%$$

As shown in these calculations, the stoichiometric or chemically correct A/F ratio for the complete combustion of hydrogen in air is about 34:1 by mass. This means that for complete combustion, 34 pounds of air is required for every pound of hydrogen. This is much higher than the 14.7:1 A/F ratio required for gasoline.

Injection Calculations

Injector Gas Flow Characteristics in electronically controlled fuel-injection systems, solenoid operated injectors are used for fuel entering. Gaseous fueling consistency between injectors and cycles is just as important as with liquid injectors. The static gaseous flow rate is defined by the following formula:

$$Q_{\text{static}} = C_d \cdot A \cdot V_t$$

For sonic flow, the velocity of gas through the orifice is given by:

$$V_t = \sqrt{\frac{\gamma * Pt}{\rho t}}$$

The static mass flow rate becomes:

$$Q_{static} = \frac{KAP_1}{\sqrt{T_1}}$$

Provided that, $\frac{P_2}{P_1} \leq r$ where

$$r = \left[\frac{2}{\gamma} + 1 \right]^{\frac{\gamma-1}{\gamma}}$$

Therefore, it is recommended the ratio of manifold absolute pressure to absolute supply pressure not exceed the critical pressure ratio to maintain the sonic flow characteristic.

Induction Period at Maximum Speed for the Constant Speed Engine:

Using 3,500 rpm as the top engine speed for the constant speed engine, the crankshaft will complete one revolution in 17 ms

($1 \frac{\text{min}}{3500 \text{ rev}} \times 60 \frac{\text{s}}{\text{min}}$) of the 360 ° of crank

rotation during one revolution, 145 ° is used for hydrogen induction. This leaves only 6.90 ms (17

ms x $\frac{145^\circ}{360^\circ}$) available for hydrogen induction at

maximum engine speed.

Hydrogen Flow Rate Calculations:

From Equation (9) above, an engine operating at a stoichiometric mixture of hydrogen and air, the hydrogen will occupy approximately 30% of the combustion chamber. For an engine operating on hydrogen fuel, however, it is preferred to operate the engine with a very lean (excess air) A/F ratio to reduce the combustion chamber temperature and thus the amount of NO_x formation. Operating with a lean A/F ratio will result in less hydrogen being injected into the engine, which in turn corresponds to the hydrogen occupying less of the combustion chamber.

For the purpose of this work, the degree of air-to-fuel leanness will be expressed using equivalence ratio (ER) or phi (Φ). ER (Φ) is equal to the stoichiometric A/F ratio divided by the actual A/F ratio.

For a stoichiometric mixture, the actual A/F ratio is equal to the stoichiometric A/F ratio and thus the ER (Φ) equals one. For lean A/F ratios, ER (Φ) will be a value less one.

For example, an ER (Φ) of 0.5 mean that there is only enough fuel available in the mixture to oxidize with half of the air available. Another way of saying this is that there is twice as much air available for combustion than is theoretically required.

This value is calculated below:

$$ER(\phi) = \frac{\frac{A}{F_{stoich}}}{\frac{A}{F_{Actual}}} \quad \text{or}$$

$$\frac{A}{F_{Actual}} = \left[\frac{\frac{A}{F_{Actual}}}{\phi} \right] = \frac{34.33}{0.4} = 85.825 \quad (10)$$

By definition, $\frac{A}{F_{Actual}} = W_t$ of $\frac{air}{W_t}$ of fuel

From equation (5) above, the weight of air was found to be equal to 137.3g.

Therefore:

$$\frac{A}{F_{Actual}} = \frac{137.3g}{(X_{moles} H_2 * \frac{2g}{mole})} = \frac{137.3}{(2X_{moles} H_2)} = 85.825 \quad (11)$$

Solving for X:

$$2X_{moles} H_2 = 137.3/85.825, \quad X_{moles} H_2 = 1.60/2, \quad X = 0.8 X_{moles} H_2$$

Percent of combustion chamber occupied by hydrogen for an $Er = (\phi) = 0.4 \%$

= Volume of H₂ / Total volume (12)

= Volume of H₂ / (volume of air + volume of H₂)

= 0.8 moles of H₂ / (4.762 moles of air + 0.8 moles of H₂) = 0.8/5.562 = 14%

Hydrogen Mass Flow Rate to the Injector at Maximum Speed:

The calculations of maximum hydrogen flow rate for the constant speed engine are based on a cylinder size of 538 cc. This cylinder size corresponds to a 4 cylinder engine with a displacement of approximately 2200 cc (2.2 liters). Using this cylinder displacement, the mass of hydrogen required for each intake stroke can be calculated as follows:

$$\begin{aligned} \text{Mass of H}_2 &= \text{Combustion chamber volume} \\ & * H_2 \% * \rho_{H_2} @ STP \\ &= (0.00006 * 0.14 * 0.0813) = 0.7 \text{ mg} \end{aligned}$$

Note: The mass of H₂ calculated is based on an engine with a 100% volumetric efficiency, Actual mass would be somewhat less than this amount. Using the 6.90 ms calculated above, and dividing this value into the 0.7 mg of hydrogen calculated above, the injector needs to flow 0.1014 mg of H₂/ms at the maximum engine speed.

Mass Flow Rate of Hydrogen in the Supply System:

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. From this assumption, the relationship between the volumetric flow rate, Q, of air and hydrogen is the following.

$$Q_{H_2} = 0.08 * Q_{air}$$

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, we were assumed that the hydrogen flow rate should be based on the air flow rate of the combustion cycle.

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:

$$\rho = \frac{P}{RT}$$

$$Q_{actual} = \frac{RPM}{2} V_{cylinder} = \frac{3500}{2} * 0.0006 = 1.05 \frac{m^3}{s}$$

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

$$V_{displacement} = \frac{\pi D^2 L}{4} =$$

$$\frac{\pi(0.0848)^2 * 0.0953}{4} = 0.000538 \text{ m}^3$$

$$V_{clearance} = \frac{V_{displacement}}{r - 1} = \frac{0.000538}{10 - 1} = 0.00006 \text{ m}^3$$

The actual volumetric flow rate of hydrogen is then 8% of the calculated value or (Q actual H₂ = 0.084 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. Then the following gives the mass flow rate of hydrogen:

$$m_{H_2} = Q_{H_2} * \rho_{H_2} = 0.84 * .0813 = 0.0069 \frac{Kg}{sec}$$

Cooling System Calculations:

We start by calculating the heat transfer through the cylinder wall:

$$Q = \frac{K}{x * A * \Delta T} \tag{13}$$

For carbon steel at T =1405.5, K =30.903 w/m.k
The cylinder dimensions are: Bore = 8.48 mm, Stroke= 9.53 mm
A = π * D * L= 0.02539 m² · X =0.015 m, ΔT = 1825 k

Heat transfer through one cylinder:

$$Q = 95457.68047 \text{ watt}$$

$$Q = m * C_p * \Delta T \quad (14)$$

But $C_p = 4.182 \text{ KJ/Kg.k}$ and $\Delta T = 45$
 Mass flow rate of water = 0.50724 Kg/s
 m for 4 cylinder engine = 2.02896 Kg/s

$$\dot{Q} = h * A_t * \left\{ \frac{1 - N * A_f}{A_t (1 - \eta_f)} \right\} * \theta_b \quad (15)$$

$$\theta_b = 85 - 25 = 60$$

$$\eta_f = \frac{\tanh m * I_c}{m * I_c} \quad (16)$$

Properties of air at $T = 328$ and $V = 4.2 \text{ m/s}$, $k = 28.372 * 10^{-3} \text{ w/m.k}$,

$$\nu = 18.7068 * 10^{-6} \text{ m}^3/\text{s}, \text{ Pr} = 0.70392.$$

$$\text{Re} = V L / \nu = 22451.7288 \quad (17)$$

$$\text{Nu} = 0.644 \text{ Re}^{\frac{1}{2}} \text{ Pr}^{\frac{1}{3}} = 88.505 \quad (18)$$

But, $\text{Nu} = \frac{hL}{K}$, for $L = 0.01 \text{ m}$, $h = 25.111 \text{ w/m}^2$.
 k

For the radiator which is made of pure a Aluminum $K = 238.92$ at $T = 328 \text{ k}$

For the fin,
 $t = 0.1 \text{ mm}$, $w = 600 \text{ mm}$, $P = 2w + 2t$,
 $A_c = w * t$, $P = 1.2002 \text{ m}$, $A_c = 0.00006 \text{ m}^2$

$$m = \sqrt{h * \frac{P}{K} * A_c} = 45.519 \quad (19)$$

$$L_c = L + \frac{t}{2} = 0.00755 \quad (20)$$

Substituting m and L in Equation (16) we get:
 $\eta_f = 0.96188$

The fin has dimensions of 0.6 m length and 0.1 m length and passes through it 40 pipes with a 0.01 m diameter.

$$A_b = \pi D(L - t * N) * \text{Number of tubes.}$$

$$A_b = 0.31416 \text{ m}^2$$

$$A_f = 2wL - N * A_{area}$$

$$A_f = 0.1137168 \text{ m}^2, A_t = N * A_f + A_b, A_t = 114.031 \text{ m}^2$$

By substituting in Equation (15) we get:

$$Q = 165274.7496 \text{ watt.}$$

$$\eta_{\text{radiator}} = \frac{Q_{\text{actual}}}{Q_{\text{Theo.}}} = 0.43285. \quad (21)$$

RESULTS AND DISCUSSION

Having modified the design of gasoline internal combustion engine through the following parameters:

1. Disk piston and flat ceiling combustion chamber.
2. Replacing the single exhaust valve with two valves.
3. Installing the gas injector.
4. Running the modified engine on hydrogen and performing our calculations on the two engines.

In this work the simulated results will be presented, which include the following parameters for both hydrogen and gasoline engines:

1. Induction duration, amount of fuel delivery
2. Mass flow, amount of the total heat rejected
3. Fin efficiency, radiator efficiency

Thus we found the following results:

- The induction duration at maximum speed for the engine is 6.9 ms for both hydrogen and gasoline.
- The amount of hydrogen should be delivered to the injector at each power stroke is .1014 mg / ms.
- The mass flow rate in the hydrogen supply system is .069 kg / sec.
- The amount of the total heat rejected from the engine is 381.831 kw..
- The mass flow rate of water in the cooling system is 2.02896 kg / sec..
- Fins efficiency around the radiator tubes is 96.188 %.
- Radiator efficiency is 43.285%.

This work simulates the suggestion of converting a gasoline internal combustion engine to modified hydrogen internal combustion engine through installing some parts in the intake and exhaust manifolds, injector type and re-designing the cooling system.

This modification gave the modified internal combustion engine the ability of running on hydrogen as a combustible fuel. Comparing the simulation of the modified internal combustion engine works on hydrogen with the gasoline internal combustion engine, the results of the comparison show a reasonable agreement and this work shows:

1. This work shows that converting an internal combustion engine uses a gasoline fuel to a hydrogen fuelled engine is possible as a result of hydrogen properties.
2. The efficiency of the hydrogen engine is greater than the gasoline engine's efficiency and this is clear by rising the compression ratio for the modified engine.
3. These modifications will solve the problems associated when converting a gasoline engine to a hydrogen engine.

4. These modifications will enhance the combustion of fuel in this engine.
5. Reduce the CO, CO² emissions.

Economics of a Hydrogen ICE Policy [27-29]

There is enormous uncertainty surrounding the advance of the hydrogen ICE technology to the commercialization stage. Choices made by manufacturers about where to allocate R&D funds and how to deal with the tradeoffs inherent in hydrogen ICE vehicles will determine the final characteristics of a hydrogen ICE vehicle. Consumer preferences about the desirability of hydrogen ICE vehicles and the acceptability of hydrogen as a fuel will play an important role in the economic feasibility of the vehicles. And most importantly, the rate at which technological barriers are overcome, both on the vehicle and on the hydrogen production side, will dictate just how quickly costs drop, and thus how quickly hydrogen ICE vehicles could be economically marketable.

CONCLUSION

Much like hydrogen fuel cell vehicles, hydrogen ICE vehicles present a considerable promise: the chance to improve energy security. and there are significant barriers to the adoption of hydrogen ICE vehicles, involving both technological improvements so it is competitive with gasoline-based alternatives as well as implementing a hydrogen fueling infrastructure. Looking beyond those similarities, distinctions quickly arise due to the nature of the hydrogen ICE technology that differentiates it from fuel cell and gasoline vehicles.

Thus, if the policy goal is a long-term shift to hydrogen and the hydrogen infrastructure could be brought online quickly enough, hydrogen ICE vehicles may provide sufficient early term fuel savings and carbon dioxide emission reductions that they may be worth promoting as a transition strategy.

1. This work shows us that converting an internal combustion engine uses a gasoline fuel to a hydrogen fuelled engine is possible.
2. The efficiency of the hydrogen fuelled engine is greater than the gasoline engine efficiency and

that is because the compression ratio is greater in H₂ engine.

2. The most critical differences are the power produced by the engine, the fuel economy, the fuel tank size, and the state of development of the technology.

3. In this work we suggested some modifications to accommodate the use of H₂ as a fuel for this engine such as injection system modification, cooling system modification and changing some parts like selecting a suitable spark plugs and replacing a single exhaust valve with two valves.

4. With comparing our hydrogen fuelled engine with the gasoline engines we found that the hydrogen fuelled engine is better than the gasoline and that's because it is an environment friendly (the combustion product is water vapor only).

NOMENCLATURE

C_d = Coefficient of discharge

A = Area of throat at valve seat

V_t = Velocity at throat

γ : Ratio of specific heats

P_t : Pressure at throat

ρ_t : Density at throat

P_1 : Absolute inlet pressure

T_1 : Absolute inlet temperature

K = Constant

P_2 : Absolute outlet pressure

R: Critical pressure ratio (0.528 for hydrogen)

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