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Analysis of a hydrogen fuelled internal combustion engine

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Abstract

In the history of internal combustion engine development, hydrogen has been considered at several phases as a substitute to hydrocarbon-based fuels. Starting from the 70's, there have been several attempts to convert engines for hydrogen operation. Together with the development in gas injector technology, it has become possible to control precisely the injection of hydrogen for safe operation. Since the fuel cell needs certain improvements before it is widely used in vehicles, the conventional internal combustion engine is to play an important role in the transition. This study examines the performance characteristics and emissions of a hydrogen fuelled conventional spark ignition engine. Slight modifications are made for hydrogen feeding which do not change the basic characteristics of the original engine. Comparison is made between the gasoline and hydrogen operation and engine design changes are discussed. Certain remedies to overcome the backfire phenomena are attempted.

Keywords: Hydrogen,Dynamo meter,four stroke Gasoline,car

Introduction

Fossil fuels (i.e., petroleum, natural gas and coal), which meet most of the World's energy demand today, are being depleted rapidly. Also, their combustion products are causing global issues, such as the green house effect, ozone layer affect, acid rains and pollution, which are posing great danger for our environment, and eventually, for the total life on our planet.

Many engineers and scientists agree that the solution to all of these global problems would be to replace the existing fossil fuel system with the clean hydrogen energy system. Hydrogen is a very efficient and clean fuel. Its combustion will produce no greenhouse gases, no ozone layer depleting chemicals, and little or no acid rain ingredients and pollution. Hydrogen, produced from non-conventional energy (solar, wind, etc.) sources, would result in a permanent energy system which would never have to be changed. In addition, the pollutants emitted by fossil energy systems (e.g. CO, CO_2, C_nH_m, SO_x, NO_x, radioactivity, heavy metals, ashes, etc.) are greater and more damaging than those that might be produced by a renewable based hydrogen energy system (Winter CJ. 1987). Since the oil crisis of 1973, considerable progress has been made in the search for alternative energy sources.

Global utilization of fossil fuels for energy needs is rapidly resulting in crucial environmental problems throughout the world. Energy, economic and political crises, as well as the health of humans, animals and plant life, are all critical concerns. There is an imperative need of implementing the hydrogen technology. A worldwide conversion from fossil fuels to hydrogen would remove many of the problems and their consequences. The production of hydrogen from non-polluting sources is the ideal way (Zweig RM. 1992).

The amount of solar energy reaching the Earth is enough to supply mankind with many thousand times the energy it presently requires.

Solar hydrogen is a clean energy carrier. Electrolytic hydrogen is made from water and becomes water again. Hydrogen obtained from solar energy is ecologically responsible along its entire energy conversion chain. At only one link of the chain can a pollutant, nitrogen oxide, arise; and this occurs only if the hydrogen is not combined with pure oxygen, but using air as an oxidant, such as in reciprocating piston engines or gas turbines of automobiles or aircraft.

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Background on Hydrogen and Fuel Cells

Hydrogen is the most abundant element in the known universe. The hydrogen molecule (H_2) is a colourless gas at room temperature and, being light relative to other gases, will disperse rapidly up through the atmosphere unless it is contained. Worldwide, some 50 million metric tons of industrial hydrogen (about 9 million metric tons in the United States) are produced for use in oil refineries and in the manufacture of fertilizers and chemicals. Hydrogen is also formed through various natural processes, but it tends to accumulate only deep underground where it occurs as the result of bacteria acting on ancient vegetable and animal remains. Hydrogen has been considered as a fuel for many years, but over the past 10 to 15 years advances in fuel cell technology have spurred an enormous wave of interest in its potential energy applications, particularly for the transportation sector which—despite long-standing concerns about U.S. dependence on imported oil—remains nearly exclusively dependent on petroleum fuels. Fuel cells, which can theoretically be made in a wide range of sizes for any number of potential applications, have the ability to efficiently convert hydrogen to electricity using special membrane materials and an electrochemical rather than combustion process. In 2003, the administration announced plans to spend $1.7 billion over five years on hydrogen fuel cell vehicles and supporting fuel infrastructure as part of its Freedom CAR and Fuel Partnership program.

In this context, it is worth noting that hydrogen can also be used apart from fuel cells as a fuel for combustion engines and gas turbines in a variety of transport as well as stationary applications (potential examples include hydrogen internal combustion engine vehicles and hybrid electric vehicles; hydrogen engines and/or turbines for heavy-duty transportation applications such as forklifts or maritime vessels; and hydrogen gas turbines for power generation).

Literature Review

In the early years of the development of internal combustion engines hydrogen was not the "exotic" fuel that it is today. Water splitting by electrolysis was a well-known laboratory phenomenon. Otto, in the early 1870s, considered a variety of fuels for his internal combustion engine, including hydrogen. He rejected gasoline as being too dangerous. Later developments in combustion technology made gasoline safer.

Most early engine experiments were designed for burning a variety of gases, including natural gas and propane. When hydrogen was used in these engines it would backfire. Since hydrogen burns faster than other fuels, the fuel-air mixture would ignite in the intake manifold before the intake valve could close. Hydrogen gave less power than gasoline with or without the water.

During World War I hydrogen and pure oxygen were considered for submarine use because the crew could get drinkable water from the exhaust. Hydrogen was also considered for use in powering airship engines. At a compression ratio of 7:1, the engine achieved a peak efficiency of 43%. At compression ratio of 9.9:1, Burn stall obtained an efficiency of 41.3% with an equivalency ratio range of 0.58-0.80. After World War II, King found the cause of preignition to be hot spots in the combustion chamber from the high temperature ash, the remainder from burned oil and dust. He traced backfire to high flame velocity at high equivalency ratios.

M.R. Swain and R.R. Adt at the University of Miami developed modified injection techniques with a 1,600 cm^3 Toyota engine with a compression ratio of 9:1. The Illinois Institute of Technology converted a 1972 Vega using a propane carburettor. The Indian Institute of Technology tested spark ignition engines converted to hydrogen and has come to the following conclusions: Hydrogen permits a wide range of fuel-air mixtures. Conversion requires higher compression ratios like up to 11:1. Hydrogen is 30 to 50% more efficient than gasoline. They reduced the compression ratios from 16.5:1 to 14.5:1. Because of hydrogen's high rate of combustion only a small amount should be used mixed with diesel fuel. A second engine, a GM-Crusader V8, was then converted for hydrogen use. The first tests were done with a gas carburettor, which allowed testing with hydrogen, natural gas and hydrogen-natural gas mixtures (hythane), (Sierens R, Rosseel E. 1998).

In order to obtain a better control of the combustion process, the engine was then equipped with a sequential timed multipoint injection system. Such an injection system, as applied to liquid fuels (gasoline, liquid LPG, etc.) has several advantages including the possibility to tune the air-fuel ratio of each cylinder to a well-defined value, increased power output and decreased cyclic variation of the combustion process in the cylinders. Timed injection also has an additional benefit for a hydrogen fueled engine, as it implies a better resistance to backfire (explosion of the air-fuel mixture in the inlet manifold).

Chapter 3

The Spark Ignition Engine

The spark ignition (SI) engine is one of the two most common reciprocating internal combustion (IC) engine types in current use. Basic SI engines have not fundamentally changed since the early 1900s with the possible exception of the introduction of the Wankel rotary SI engine in the 1960s. However, major advances in the areas of materials, manufacturing processes, electronic controls, and computer aided design have led to significant improvements in dependability, longevity, thermal efficiency, and emissions during the past decade. Electronic controls, in particular, have played a major role in efficiency gains in SI automotive engines through improved control of the fuel injection and ignition systems that control the combustion process. Electronic control of diesel fuel injection systems is also becoming more common and is producing improvements in diesel emissions and fuel economy.

IC engines may be classified by a wide variety of characteristics, the primary ones being SI vs CI, four-stroke vs. two-stroke, and reciprocating vs. rotary. Other possible categories of classification contain intake type (naturally aspirated vs. turbocharged or supercharged), number of cylinders, cylinder arrangement, cooling method (air vs. water), fuelling system (injected vs. carburetted), valve gear arrangement (overhead cam vs. pushrod), type of scavenging for two-stroke engines (cross, loop, or uniflow), and type of injection for diesel engines (direct vs. indirect).

Spark Ignition Engine Operation

The SI engine relies on a spark plug to ignite a volatile air-fuel mixture as the piston approaches top dead centre

(TDC) on the compression stroke. This mixture may be supplied from a carburettor, a single throttle-body fuel injector, or by individual fuel injectors mounted in the intake port of each cylinder. One combustion cycle involves two revolutions of the crankshaft and thus four strokes of the piston, referred to as the intake, compression, power, and exhaust strokes. Intake and exhaust valves control the flow of mixture and exhaust gases into and out of the cylinder, and an ignition system supplies a spark inducing high voltage to the spark plug at the proper time in the cycle to initiate combustion. On the intake stroke, the intake valve opens and the descending piston draws a fresh combustible charge into the cylinder. During the compression stroke, the intake valve closes and the fuel-air mixture is compressed by the upward piston movement. The mixture is ignited by the spark plug, typically somewhat before TDC.

The rapid premixed homogeneous combustion process causes a sharp increase in cylinder temperature and pressure that forces the piston down for the power stroke. Near bottom dead centre (BDC) the exhaust valve opens and the cylinder pressure drops rapidly to near atmospheric. The piston then returns to TDC, expelling the exhaust products. At TDC, the exhaust valve closes and the intake valve opens to repeat the cycle again.

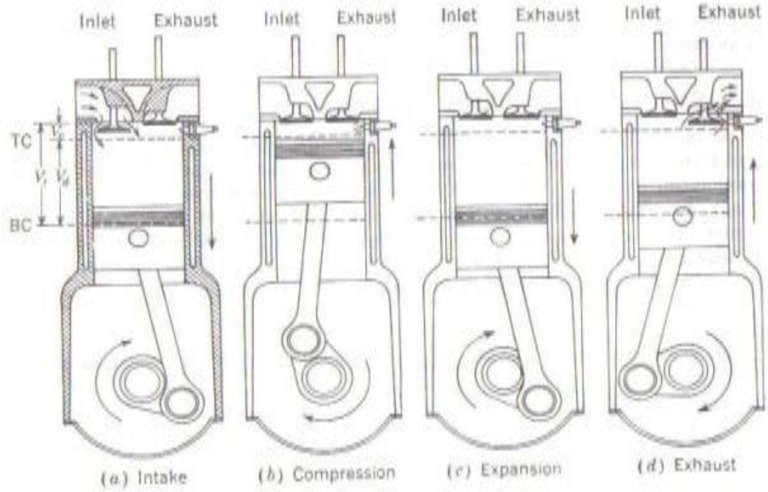


Fig 1: Schematic of a 4-stroke engine

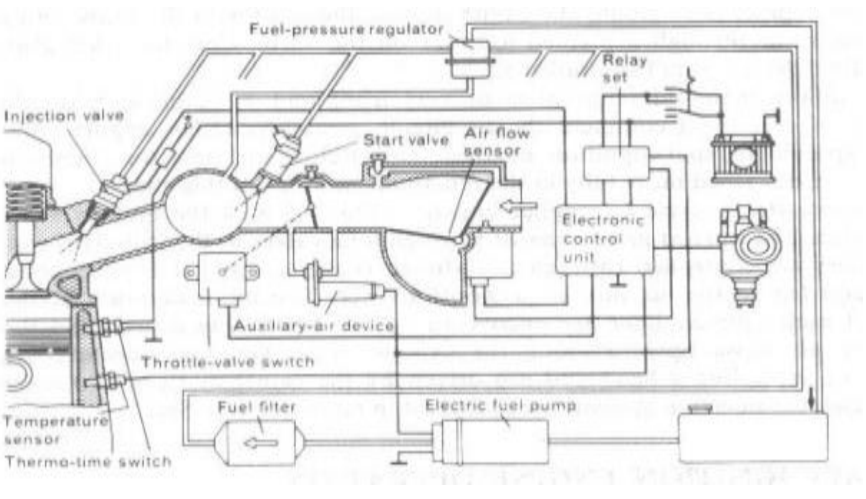


Fig 2: Schematic drawing of L-Jetronic port electronic fuel injection system (Source: Heywood 1998)

Important Engine Characteristics

An engine’s primary factors that are important to its user are its performance over the operating range, its fuel consumption within the operating range and the cost of the fuel, the engine’s noise and air pollutant emissions, its initial cost and the durability as well as reliability throughout its operating life. Geometrical relationships and other parameters characterize an engine. Engine performance, efficiency and emission characteristics are the most common considerations. Engine performance is more precisely defined by the maximum power at rated speed and maximum torque at rated speed. Rated speed is the speed at which these maximum values are reached. In general the rated speed for maximum power is close to the engines maximum allowable speed whereas the maximum torque is developed around or slightly above the half of maximum operating speed.

Engine torque is normally measured with a dynamometer. The engine is secured to a test bench where its output shaft is coupled to the dynamometer rotor. Figure 3.4.illustrates the operating principle of a dynamometer. The rotor is braked either by electromagnetic, hydraulic or mechanical friction. The energy supplied by the engine is converted to heat and therefore the dynamometer needs adequate cooling. The opposing torque exerted on the stator is measured by balancing weights, springs, pneumatic or electronic means.

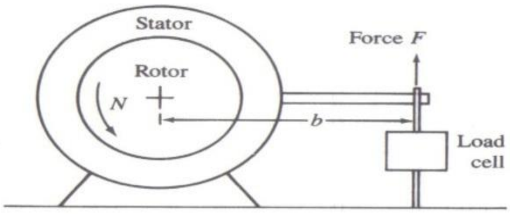


Fig 3: Schematic of a dynamometer

The load cell shown in Figure 3.4.reads the force F applied at a distance b from the centre of the rotor. The *torque* applied by the engine on the dynamometer is T:

$$T\ (Nm) = F\ (N) \times b\ (m) \qquad (3.1)$$

Torque is the engine's ability to do work, whereas power is the rate of this work done. The power P delivered by the engine and absorbed by the dynamometer is the product of the torque and angular speed:

$$P = N \times T \qquad (3.2a)$$

Using proper units Equation 3.2a becomes:

$$P\ (kW) = 2\pi\ \omega\ (rev/s) \times T(Nm) \times 10^{-3} \qquad (3.2b)$$

The value of engine power measured as described above is called brake power P_b. This is the usable power delivered by the engine to the load.

Another engine performance parameter is the mean effective pressure. Since both torque and power depend on engine size, dividing these values by the total volume swept by the cylinders of the engine, gives a more useful relative engine performance measure. The power used in the calculation is the brake power so the term is called *brake* mean effective pressure bmep.

$$mep(kPa) = \frac{P_b(kW) \times n_r \times 10^3}{V_d(dm^3) \times \omega(rev/s)} \qquad (3.$$

n_r is the number of crank revolutions for one complete cycle, 2 for the four-stroke engines and 1 for the two-stroke engines; V_d the total displaced volume of the cylinders.

In engine tests, the fuel consumption is measured as a flow rate. Again the dependence of the flow rate on engine size makes the use of a parameter called brakespecific fuel consumption necessary, the fuel flow rate per unit power output. It measures how efficiently an engine is using the fuel to do useful work.

$$bsfc(g/HP \cdot h) = \frac{\dot{m}_f(g/h)}{P_b(HP)} \qquad (3.4$$

As seen, the b_{sfc}has units. A dimensionless parameter that relates the desired engine output (power) to the necessary input (fuel flow) would be of more fundamental value. The ratio of the work produced to the amount of heat energy that can be released in the combustion process is called brake thermal efficiency.

$$\eta_{bth} = \frac{P_b(kW)}{\dot{m}_f(kg/s) \times Q_{LHV}(kj/kg)} \qquad (3.5)$$

The fuel energy supplied that can be released by combustion is given by the mass of fuel supplied m_f to the engine times the lower heating value Q_{LHV} of the fuel. The heating value of a fuel is determined in a standardized test procedure in which a known mass of fuel is fully burned with air, and the thermal energy released by the combustion process is absorbed by a calorimeter as the products cool down to their original temperature.

Combustion Stoichiometry

To develop a relation between the composition of the reactants (fuel and air) of a combustible mixture and the composition of the products, it is necessary to meter the air inlet and fuel supply rate.

The ratio of the air mass flow rate m_a to the fuel mass flow rate m_f is called the air fuel/ratio (A/F).

$$\text{Air/fuel ratio (A/F)} = \frac{\dot{m}_a}{\dot{m}_f} \qquad (3.6)$$

There is also the inverse of the above term, namely the fuel/air ratio (F/A).

$$\text{Fuel/air ratio (F/A)} = \frac{\dot{m}_f}{\dot{m}_a} \qquad (3.7)$$

The normal operating range for a conventional SI engine using gasoline fuel is 12<A/F<18.

The relation between the composition of the reactants and the composition of the products depends only on the conservation of mass of each chemical element in the reactants, only the relative elemental composition of the fuel and the relative proportions of fuel and air are needed. If sufficient oxygen is available, a hydrocarbon fuel can be completely oxidized. The carbon in the fuel is then converted to carbon dioxide CO_2 and the hydrogen to water H_2O. The general equation for the complete combustion of one mole of a hydrocarbon with air:

CaHb + (a+¼b) × (O2 +3.773 N2) => a CO2 + ½b H2O + 3.773 (a+¼b) N2 ----------- (3.8)

This is the equation for the stoichiometric (theoretical) proportions of fuel and air. That is, just enough air is present to oxidize all of the fuel. It is obvious that the stoichiometric air/fuel or fuel/air ratios depend on the chemical fuel composition. For gasoline (a reasonable approximation is $C_{7.9}H_{14.8}$) the equations becomes:

$$C_{7.9}H_{14.8} + 11.6\ O_2 + 43.767\ N_2) \Rightarrow 7.9\ CO_2 + 7.4\ H_2O + 43.767\ N2 \qquad (3.9)$$

Whereas for hydrogen H_2 it is:

$$H_2 + ½\ O_2 + 1{,}887\ N_2 \Rightarrow H_2O + 1.887\ N_2 \qquad (3.10)$$

The molecular weights of oxygen, atmospheric nitrogen, atomic carbon, and atomic hydrogen are 32, 28.16, 12.001, and 1.008 respectively. Substituting these values and a simplification y = b/a in Equation 3.7 results in the expression:

(A/F)s = (F/A)s-1 = (3.11)
Gasoline = $C_{7.9}H_{14.8}$
$(A/F)_s = 14.6$
Hydrogen = H_2 $(A/F)_s = 34.3$

$$\frac{34.56(4+y)}{12.011+1.008y}$$

Fuel-air mixtures with more than or less than the stoichiometric air requirement can be burned. With excess air or fuel-lean combustion, the extra air appears in the products in unchanged form. With less than the stoichiometric air requirement, with fuel-rich combustion, there is insufficient oxygen to oxidize fully the fuel. The products are a mixture of CO_2 and H_2O with carbon monoxide CO and hydrogen as well as N_2. Since the composition of the combustion products is significantly different for fuel-lean and fuel-rich mixtures, and because the stoichiometric fuel/air ratio depends on the fuel composition, the ratio of the actual fuel/air ratio to the stoichiometric ratio (or its inverse) is a more informative parameter for defining mixture composition. The fuel/air equivalence ratio φ:

Fuel/Air equivalence ratio

$$\phi = \frac{(F/A)_{actual}}{(F/A)_s}$$

(3.

The inverse of φ, the relative air/fuel ratio λ,

Relative Air/Fuel ratio

$$\phi^{-1} = \lambda = \frac{(A/F)_{actual}}{(A/F)_s} \qquad (3.13)$$

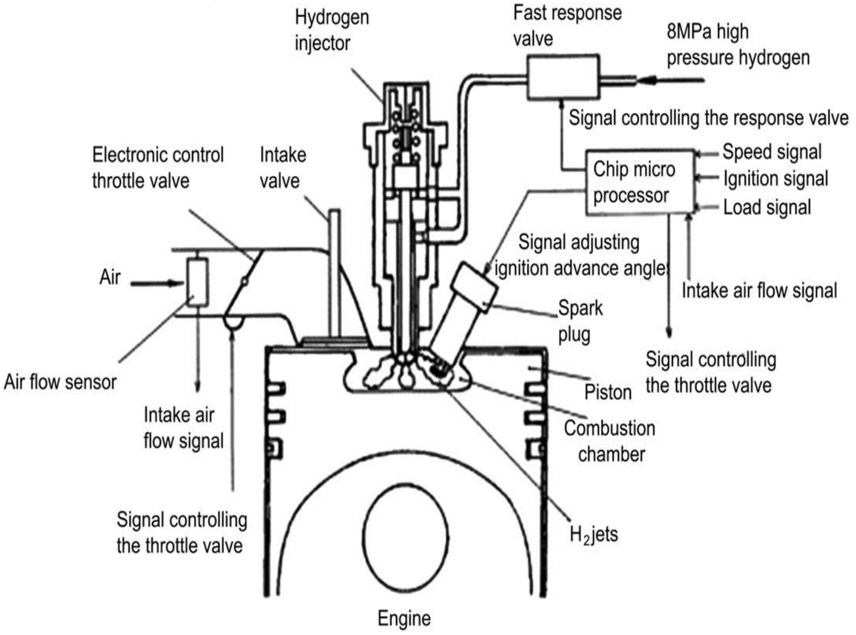
For fuel-lean mixtures: $\varphi<1, \lambda>1$
For stoichiometric mixtures: $\varphi = \lambda=1$
For fuel-rich mixtures: $\varphi >1, \lambda<1$`

In practice, although with excess air condition, the composition of the products of combustion does not occur as in Equation 3.7. At normal combustion temperatures significant dissociation of CO_2 and of H_2O occurs.

Chapter 4
Hydrogen as an Engine Fuel

There are a number of unique features associated with hydrogen that make it remarkably well suited in principle, to engine applications. Some of these most notable features are the following:

Hydrogen, over wide temperature and pressure ranges, has very high flame propagation rates within the engine cylinder in comparison to other fuels. The lean operational limit mixture in a spark ignition engine when fuelled with hydrogen is very much lower than those for other common fuels. This permits stable lean mixture operation and control in hydrogen fuelled engines.



The operation on lean mixtures, in combination with the fast combustion energy release rates around top dead canter associated with the very rapid burning of hydrogen–air mixtures results in high-output efficiency values. Of course, such lean mixture operation leads simultaneously to a lower power output for any engine size.

Varying the spark timing in hydrogen engine operation represents an unusually effective means for improving engine performance and avoidance of the incidence of knock. Also, the heat transfer characteristics of hydrogen combustion in engines are significantly different from those in engines operating on other fuels. The radiative component of heat transfer tends to be small yet the convective component can be higher especially for lean mixture operation.

4.1. Properties of Hydrogen

Table 4.1: Physical properties of hydrogen, methane and gasoline
The specific physical characteristics of hydrogen are quite

Property	Hydrogen	Methane	Gasoline
Density at 1 atm and 300 K (kg / m^3)	0.082	0.717	5.11
Stoichiometric Composition in air (% by volume)	29.53	9.48	1.65
Number of moles after combustion to before	0.85	1.00	1.058
LHV (MJ/kg)	119.7	46.72	44.79
Combustion energy per kg of stoichiometric mixture (MJ)	3.37	2.56	2.79

Table 4.2: Combustion properties of hydrogen, methane and gasoline

Property	Hydrogen	Methane	Gasoline
Flammability limits (% by volume)	4 – 75	5.3 – 15.0	1.2 – 6.0
Minimum ignition energy (mJ)	0.02	0.28	0.25
Laminar flame speed at NTP (m/s)	1.90	0.38	0.37 – 0.43
Auto ignition temperature (K)	858	813	≈ 500 – 750

Features of Hydrogen for Engine Applications

In addition to the previous unique features associated almost exclusively with hydrogen, a number of others can be cited in support of hydrogen applications in engines. To list some of the main of these features:

Less cyclic variations are encountered with hydrogen than with other fuels, even for very lean mixture operation. This leads to a reduction in emissions, improved efficiency, and quieter and smoother operation.

Hydrogen can have a high effective octane number mainly because of its high burning rates and its slow preignition reactivity.

Hydrogen has been shown to be an excellent additive in relatively small concentrations, to some common fuels such as methane.

Its gaseous state permits excellent cold starting and engine operation. Hydrogen remains in gaseous state until it reaches its condensation point around 20 K.

Hydrogen can tolerate better the presence of diluents. This would allow a better exploitation of low heating value fuel mixtures.

Hydrogen can be employed quite effectively with oxygen-enriched air such as resulting from the electrolysis of water.

The gas is highly diffusive and buoyant which make fuel leaks disperse quickly, reducing explosion hazards associated with hydrogen engine operation.

Limitations Associated with Hydrogen Engine Applications

Accordingly, the following is a listing of some features associated with hydrogen as an engine fuel that may be considered as requiring some remedial action:

Hydrogen as a compressed gas at 200 atmospheres and atmospheric temperature has merely around 5% of the energy of gasoline of the same volume. This is a major shortcoming particularly for transport applications.

Engines fuelled with hydrogen suffer from reduced power output, due mainly to the very low heating value of hydrogen on volume basis and resorting to lean mixture operation.

The mass of the intake air is reduced for any engine size because of the relatively high stoichiometric hydrogen to air ratio.

There are serious potential operational problems associated with the uncontrolled preignition and backfiring into the intake manifold of hydrogen engines.

Hydrogen engines are prone to produce excessively high cylinder pressure and to the onset of knock. The equivalent octane number of hydrogen is rather low in comparison to common gasoline and methane.

There are serious limitations to the application of cold exhaust gas recirculation for exhaust emissions control.

Hydrogen engines may display some serious limitations to effective turbo charging.

Chapter 5

Engine Modifications

SI engines are easily adaptable to gaseous fuels like propane, methane, and hydrogen. Slight modifications for the introduction of the fuel in appropriate amount are applied. A fuel supply system that can be tuned according to the engine's need is just good enough to make the engine work. In case of hydrogen there are certain additional issues concerning safety and backfire-safe operation throughout the whole operating region. The storage of the fuel is another aspect that affects the range of the vehicle operating on hydrogen. Due to its low energy per volume content, the compressed gas storage cannot compete with liquid gasoline.

Compared to gasoline, hydrogen's low energy per unit volume produces less energy in the cylinder. An engine running on hydrogen produces less power than with gasoline. Supercharging may help remedy this by compressing the incoming fuel/air mixture before it enters the cylinder. This increases the amount of energy per volume of fuel. Additional weight and complexity is added to the engine by such modifications. But the power gain and backfire resisting property (by cooling the cylinder with more air) compensates for the mentioned drawbacks.

Addition of spray nozzles for water is essential to provide backfire free operation. Although very simple in structure, it is important to supply the right amount of water according to load, engine speed and temperature.

If cryogenic hydrogen is to be supplied, material selection for the injectors, fuel supply line, tank and metering devices must be made accordingly. Since much progress has been made in the safe handling and storage of liquid hydrogen in space industry, the remaining focus needs to be done on applying this know-how to small vehicle systems.

Preignition and Backfire

Hydrogen burns quickly and has a low ignition temperature. This may cause the fuel to be ignited by hot spots in the cylinder before the intake valve closes. It may also cause backfire, preignition, or knock. These problems are particularly more with high fuel-air mixtures. Uncontrolled preignition resists the upward compression stroke of the piston, thereby reducing power. Remedies for backfire include: timed port injection, delayed injection to make sure the fuel detonates only after the intake valve is closed; water injection, 1.75 water to hydrogen, by weight (Peavey 2003). An appropriately designed timed manifold injection system can overcome the problems of backfiring in a hydrogen engine.

Fuel Mixing

Keeping the air and fuel separate until combustion is an important strategy for controlling the difficulties arising from the fast-burning properties of hydrogen. The low flammability limits and low energy required for ignition of hydrogen cause preignition and backfire when using hydrogen fuel. Ignition occurs when a fuel-air mixture ignites in the combustion chamber before the intake valve closes. Preignition can cause backfire when ignited fuel-air mixture explodes back into the intake system. It is most present at higher loads and at higher fuel-air mixtures near open throttle.

Preignition is not a necessary precursor to backfiring and probably not occurs under normal circumstances at moderate compression and equivalence ratios. Because of the low volumetric energy content of hydrogen, higher compression ratios or higher fuel delivery pressures are needed to avoid reduced power. Supercharging spark ignition engines compresses the fuel-air mixture before being inducted into the cylinder.

Direct fuel injection involves mixing the fuel with air inside the combustion chamber. The fuel and air are kept separate until then. If the fuel and air are mixed before entering the combustion chamber; the arrangement is called external mixing. A carburettor usually accomplishes this.

Mixture Formation and Engine Operation

The extreme physical properties of hydrogen at ambient and cryogenic conditions are of beneficial influence on combustion as well as on mixture formation. In contrast to conventional fuels, the hydrogen fraction in a stoichiometric mixture at ambient temperature is about 30% of the mixture volume. The volumetric heat value of the hydrogen-air mixture (2890 J/l) results in a corresponding power loss at the engine compared to conventional fuel (3900 J/l). The wide flammability range of H_2-air mixtures enables very lean operation with substantially reduced NO_x emissions much more easily than with conventional fuels. Also, hydrogen offers a considerable reduction of air throttle and cylinder charge intake flow losses. In this point hydrogen differs considerably from other gaseous fuels such as natural gas or propane.

Chapter 6

Experimental Setup

Tests were performed at the Engines Laboratory of the University of DokuzEylül, Izmir. The laboratory consists of test banks involving water (Froude) and eddy current type dynamometers, exhaust emission analyzers, fuel metering devices and support equipment. The dynamometer and supporting electrical equipment were calibrated a few days before the tests began. To avoid temperature and pressure variations as far as possible, experiments with gasoline were immediately followed by hydrogen experiments with the engine already warmed up to operating temperature.

Compressed hydrogen at 200 bar from 50 l steel bottles was dropped down to 3 bar in the first stage regulator. The fuel line is a copper tube connected to a hydrogen flow meter. The second stage regulator supplies the gaseous hydrogen to the mixer according to the inlet manifold pressure.

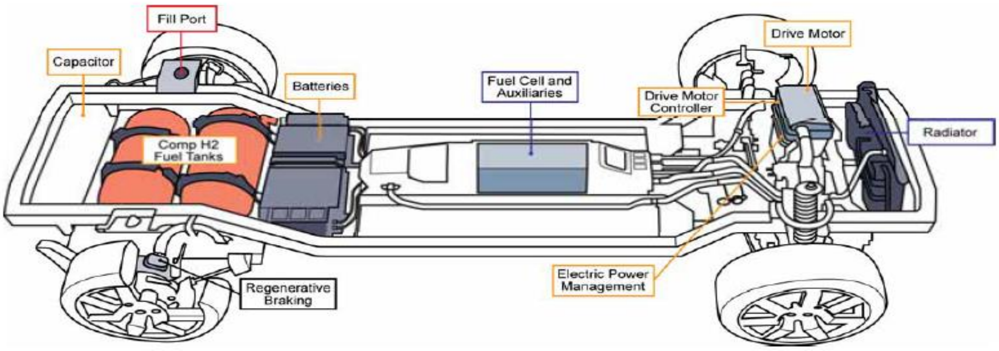


Fig 6.1: Schematic arrangement of hydrogen fuel car

The engine is coupled to the dynamometer with its gearbox. The 4th gear has a ratio of 1:1 so the rotational speed measured at the dynamometer is exactly the same as the engine speed. Besides the engine itself; flywheel, starting motor, alternator, fuel pump, fuel tank, dashboard assembly and exhaust assembly are mounted to the required parts and places.

At the exhaust outlet, there is a standard muffler and a final silencer muffler. Exhaust temperature was measured between the two muffler positions and emission values were obtained just after the final silencer.

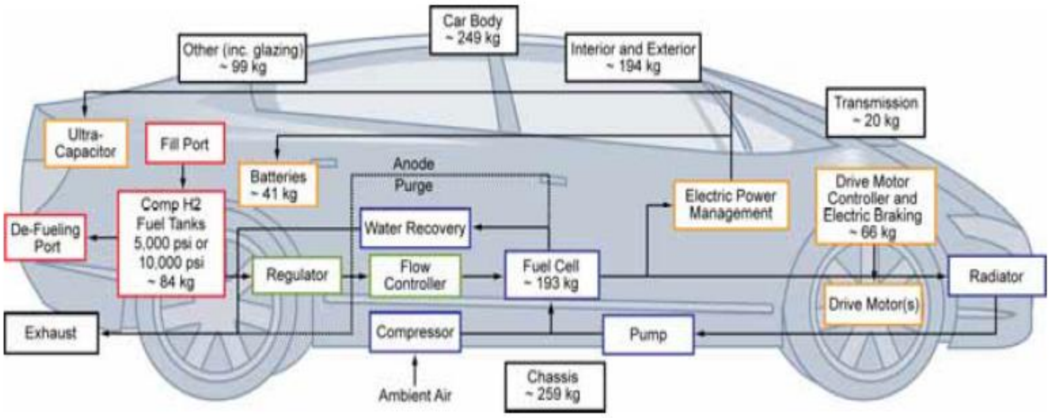


Fig.6.2: schematic diagram of arrangement of parts

Description of the Test Rig

Figure 6.3.illustrates the basic setup of the test bench. The engine is coupled with its original shaft to the dynamometer. The control panel of the dynamometer is placed at a safe distance from the setup but is easily accessible. Ambient pressure and temperature as well as engine speed and torque values are easily read from the large size gauges. Load is varied by two knobs that change the current in the stator of the eddy current dynamometer. Basically three types of loading are possible, constant speed, variable speed and a combination of these.

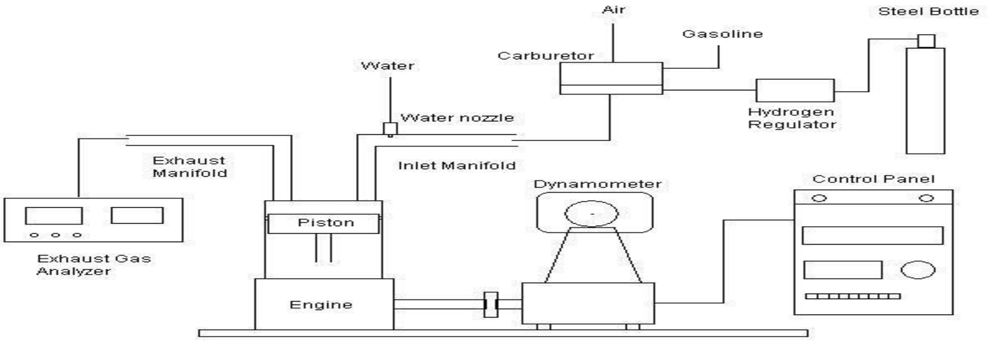


Fig 6.3: Block Diagram of Test Setup

A 3-way switch is installed on the dashboard assembly that allows immediate switching from gasoline to hydrogen. This switch controls the solenoid valves on the gasoline line and hydrogen regulator. In this way, switching between fuels is possible without stopping the engine.

Figure 6.4.gives an overview of the engine. There is an extra cooling fan installed for adequate cooling which is used throughout high load sessions.

Chapter 7

Results and Discussions

For the purpose of detailed analysis, as many as possible operating points were recorded. Much experimentation has been done to avoid backfire. Firstly the mixer was placed above the throttle valve, level with the air filter housing. In this arrangement the engine's tendency to backfire was considerably high. For this reason it was placed between the carburettor body and inlet manifold afterwards. At idling and no load speeds, no backfire occurred. When load was applied, a practical limit of about 20 Nm prevented further loading no matter how much water was given as a fine mist into the inlet manifold. At speeds below 2600 rpm serious backfire caused sudden loss of power and therefore the operating range for hydrogen was set between 2600 rpm and 3800 rpm (the upper limit is due to the rated speed of the dynamometer).

Sample calculation for power, thermal efficiency and mean effective pressure is as follows: For 3000 rpm,

Gasoline T=22 Nm

P (kW) = 2π ω (rev/s) × T(Nm) × 10^{-3}

P = 2 π × (3000 × 1 / 60) × 22 × 10^{-3}

P = 6.9 kW

Hydrogen T = 19 Nm

P (kW) = 2π ω (rev/s) × T(Nm) × 10^{-3}

P = 2 π × (3000 × 1 / 60) × 19 × 10^{-3}

P = 6.0 kW

Gasoline $P_b = 6.9$ kW

$$\eta_{bth} = \frac{P_b\,(kW)}{\dot{m}_f\,(kg/s) \times Q_{LHV}\,(kj/kg)}$$

t = time for 100 ml of fuel, t = 74 s

QLHV = 44000 kJ / kg

m = 760 kg/m3 × 10-6 m3/ml × 100 ml / 74s

m = 1.027 × 10-3 kg / s

ηbth = 15.3 %

Pb = 6.0 kW

Hydrogen $P_b = 6.0$ kW

$$\eta_{bth} = \frac{P_b\,(kW)}{\dot{m}_f\,(kg/s) \times Q_{LHV}\,(kj/kg)}$$

QLHV = 120000 kJ / kg

m = 0.084 kg/m3 × 10-3 l/m3 × 139 l/min × 1/60 min/s

m = 1.946 × 10-4 kg /s

ηbth = 25.5 %

Gasoline

Pb = 6.9 kW

Vd = 1.197

dm3, nr = 2 (4-stroke engine)

$$mep(kPa) = \frac{P_b\,(kW) \times n_r \times 10^3}{V_d\,(dm^3) \times \omega(rev/s)}$$

ω = 3000 rev/min × 1/60 min/s

ω = 50 rev /s

mep = 231 kPa

Hydrogen

Pb = 6.0 kW

Vd = 1.197 dm3, nr = 2 (4-stroke engine)

$$mep(kPa) = \frac{P_b\,(kW) \times n_r \times 10^3}{V_d\,(dm^3) \times \omega(rev/s)}$$

ω = 3000 rev/min × 1/60 min/s

ω = 50 rev /s

mep = 199 kPa

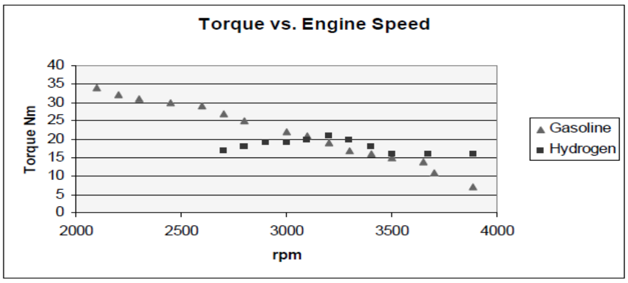


Fig 7.1: Torque comparison between gasoline and hydrogen

The variation of brake torque, which is read directly from the dynamometer, with engine speed can be clearly seen in Figure 7.1. At a speed of about 3100 rpm hydrogen achieves the torque values for gasoline and exceeds them at greater speeds. Since hydrogen has fast burning characteristics, it is expected to show better results at high speed operation. Figure 7.2.shows the brake power for both fuels. At low speeds hydrogen suffers power but competes well within the second operating speed range (3000 rpm – 4000 rpm).

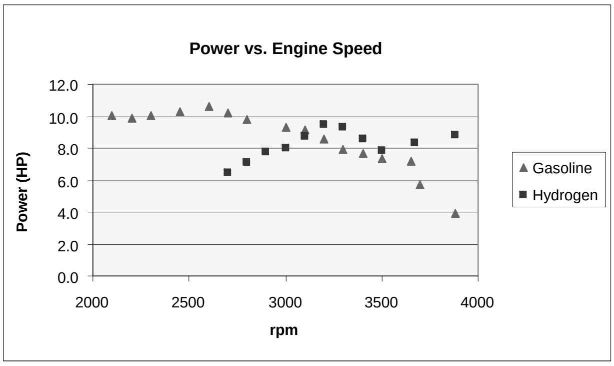


Fig 7.2: Power vs. engine speed

Due to its low energy content per unit volume, an externally mixed hydrogen engine has less power than a conventional gasoline fueled engine. This drawback can be overcome by supercharging. In this way more air can be charged in the cylinder and more fuel as well. It also helps to cool down the cylinder avoiding preignition.

Hydrogen has a wide flammability range (4-75 %). Certain non-homogeneity in the fuel air mixture has no considerable effect on its combustion. The mixture burns completely and thermal efficiency tends to be higher. With external mixture formation non-homogeneity is lower than internal mixture formation. This is also the reason for the high backfire tendency when external mixing is applied. There is fuel air mixture ready to burn flowing into the cylinder through the manifold. At any time this mixture can be ignited by a hot spot within the cylinder.

Comparison of brake thermal efficiency of gasoline and hydrogen operation is made in Figure 7.3. Obviously hydrogen has a higher brake thermal efficiency. It is known for gasoline engines that they show their effective efficiency at greater part loads whereas hydrogen can operate even at low part loads with better efficiency.

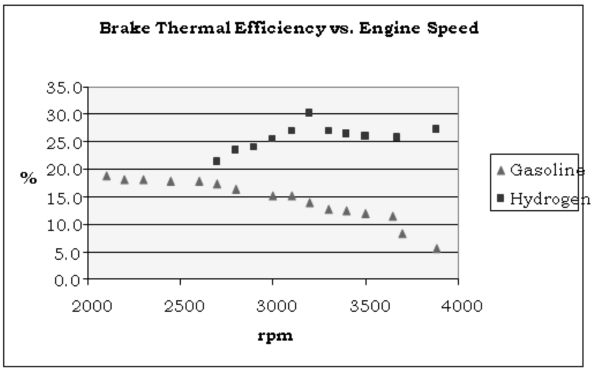


Fig 7.3: Brake thermal efficiency vs. engine speed

Plot of another performance parameter, the brake mean effective pressure is shown in Figure 7.4. Again at speeds below 3000 rpm the gasoline engine is more effective. Hydrogen operation shows a slightly better effectiveness at speeds above 3200 rpm.

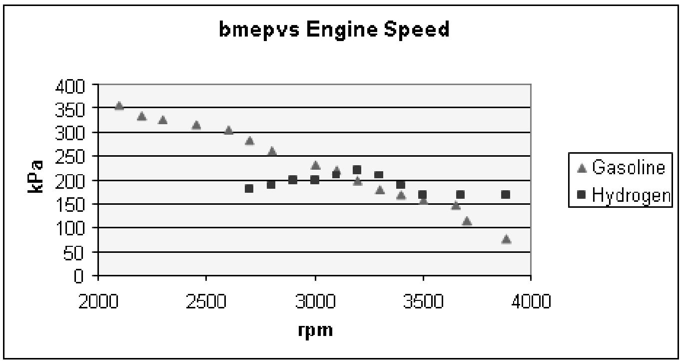


Fig 7.4: Brake mean effective pressure vs. engine speed

Temperature analysis of the exhaust gas can be made in Figure 7.5. As soon as the hydrogen engine gets into the high speed range, the exhaust temperature starts to increase significantly. The cooling effect of water that is added with hydrogen is observed. But fast burning that occurs at increased speed during hydrogen operation results in temperature rise.

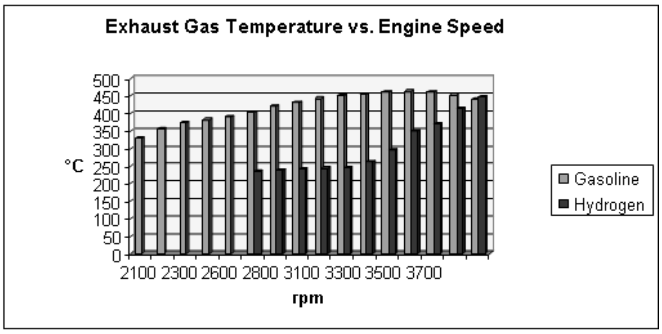


Fig 7.5: Exhaust gas temperature of gasoline and hydrogen engine

Figure 7.6.Portrays the NO_x levels of both engines in ppm. Significant decrease in NO_x emissions is observed with hydrogen operation. Almost a 10-fold decrease can easily be noted. The cooling effect of the water inducted plays an important role in this reduction. Also operating the engine with a lean mixture kept the emissions low.

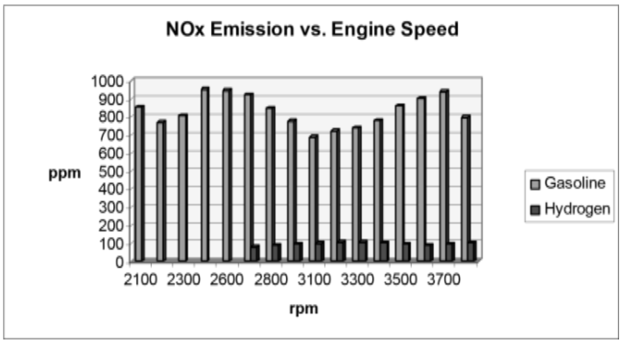


Fig 7.6: NO_x levels vs. engine speed

Although more air than required for complete combustion is present in the cylinder (fuel lean operation), the engine is not capable of burning the total amount of fuel. Carbon monoxide emissions are due to incomplete combustion of fossil fuels. It is expected that the hydrogen engine has zero carbon monoxide emissions since hydrogen is a carbon-free fuel. As the results in Figure 7.7.show, some amount of carbon monoxide is still present even with hydrogen. This is due to the burning of the lubricating oil film inside the cylinder. As speed increases, these emissions tend to diminish. A similar presentation of results for carbon dioxide emissions is contained in Figure 7.8. For hydrogen there is practically no emission, only very slight values again due to combustion of the lubricating oil film.

During combustion the temperature inside the cylinder is extremely high. As the piston expands, this heat evaporates a certain amount of the oil. Observing Figure 7.9., the contribution of the evaporated and incompletely burned oil to the overall emission can be guessed. Gasoline is a long-chain hydrocarbon and when not completely burned, breaks up into short chain hydrocarbons. Hydrogen is a gaseous fuel and does not dissolve the oil film on the cylinder walls. This is another advantage of it against conventional fuels. Better lubricating characteristics and longer engine life is obtained. At low speed the gasoline engine is choked and therefore more unburnt hydrocarbons are present in the exhaust gases. The only hydrocarbon emission from the hydrogen engine is due to the above mentioned oil film evaporation.

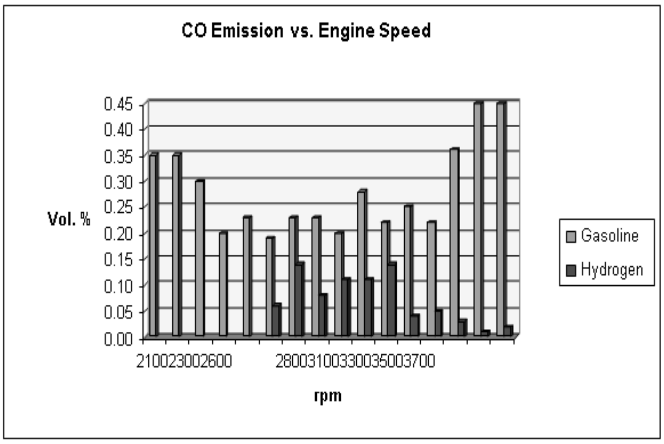


Fig 7.7: Carbon monoxide emissions

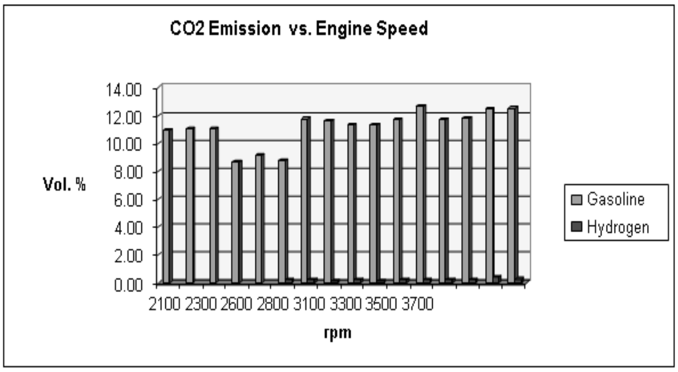


Fig.7.8. Carbon dioxide emissions

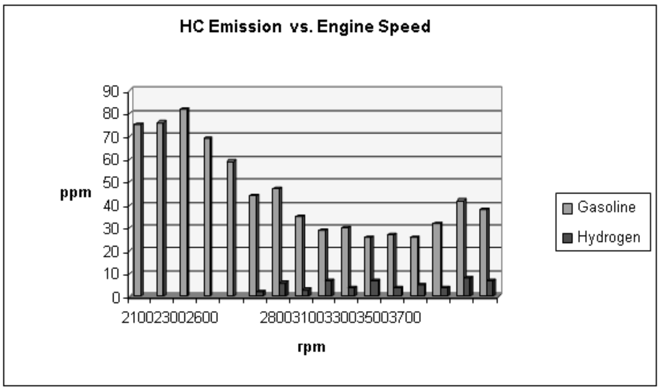


Fig 7.9: Hydrocarbon Emissions

Since the tests were performed at part load, fuel lean operation was needed. Especially to cool down the cylinder and operate the engine safely without backfire, in hydrogen operating case, mixture was leaned by following the oxygen content in the exhaust gas. Figure 7.10.shows the oxygen levels in the exhaust gas. During hydrogen operation, the engine was kept on extremely lean side.

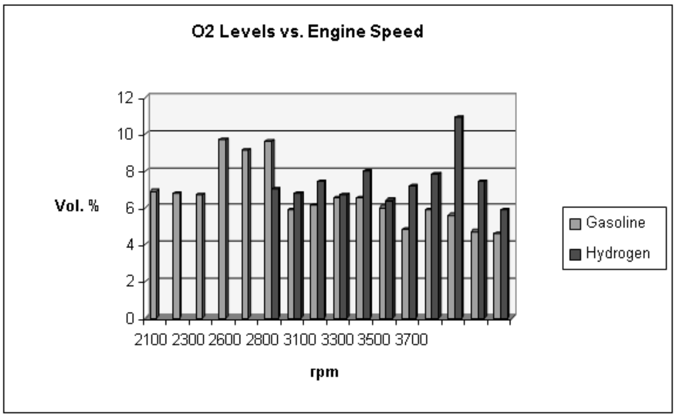


Fig 7.10: Oxygen Levels vs. engine speed

Chapter 8
Conclusions

A conventional 4 cylinder SI engine was adapted to operate on gaseous hydrogen. Compressed gas at 200 bars in steel bottles was introduced to the engine by external mixing. The first stage regulator drops the pressure to 3 bars to a copper gas supply line where a flow meter is installed. The second stage regulator supplies hydrogen to the mixing apparatus installed on the inlet manifold. Spray nozzles for water induction are placed approximately 4 cm away from the inlet valves. Ignition timing was set to 10° before TDC and fixed.

First tests were performed with the mixer installed on top of the carburettor body. This is the usual configuration in propane mixing. Serious backfire was observed with this installation. Another mixer was then put between the carburettor body and inlet manifold. Backfire was prevented in this option. Under no-load condition, the engine operated flawless with a smooth idling. When load is applied and engine speed is below 2600 rpm, serious backfire occurred and caused a sudden drop in engine power. Water mist from the spray nozzles greatly enhances the backfire-safe operation.

Specific features of the use of hydrogen as an engine fuel were analysed. Results of the tests demonstrated that there will be power loss for the low speed operation whereas high speed characteristics could compete with gasoline performance. The increase in thermal efficiency was obvious. It has been proved that hydrogen is a very bright candidate as an engine fuel.

NO_x emissions were about 10 times lower than with gasoline operation. CO and HC emissions were almost negligible as expected. Traces of these emissions were present because of the evaporating and burning lubricating oil film on the cylinder walls.

Combustion properties of hydrogen favour fast burning conditions such as in a high speed engine. Design changes that would allow the engine to greater speeds would have a beneficial effect. Appropriate changes in the combustion chamber together with better cooling of the valve mechanism, would increase the possibility of using hydrogen across a wider operating range.

Sequential injection of gaseous hydrogen instead of carburetion could greatly solve the backfire problem. Better performance could be obtained. Even further, liquid hydrogen either internally mixed or injected into the manifold could be a measure against backfire due to its extraordinary cooling effect (20 K temperature).

An electronic control unit that measures the speed, and varies the injection timing together with ignition timing installed on a supercharged, intercooled, high compression ratio, short stroke and high speed engine seems to be the most appropriate way to get the best from hydrogen’s unique properties.

Hydrogen has the potential to achieve problem-free operation in IC engines. The future advances depend on whether hydrogen can be obtained abundantly and economically.

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