Seminar Report on

HYDROGEN AS AN ALTERNATIVE FUEL

in partial fulfillment of the requirements for the award of the degree

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DEPARTMENT OF MECHANICAL ENGINEERING

ABSTRACT

Escalating apprehension about the harmful effects of widespread use of conventional fossil fuels in vehicles, has led to vast amounts of effort and capital being directed towards researching and developing sustainable alternative energy sources. One of the most promising and abundant of these sources is hydrogen. Hydrogen is one of the energy carriers which can replace fossil fuel and can be used as fuel in an internal combustion engines and as a fuel cell in vehicles. To use hydrogen as a fuel of internal combustion engine, engine design should be considered for avoiding abnormal combustion. As a result it can improve engine efficiency, power output and reduce NOx emissions. The scope of liquid hydrogen as a replacement for conventional fuels, in comparison to other alternatives as well as gasoline. Recommendations are made on improving methods of hydrogen generation and storage, and a major drawback is observed in the fact that hydrogen requires high amounts of energy for its extraction, but the fuel itself has a low energy density.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The current energy crisis urges us to explore a variety of alternate methods to satisfy the world's energy demands. A major market solution for the energy crisis is increasing supply and reducing demand for crude oil. By increasing the list of feasible fuel alternatives, the demand on crude oil reduces. Among all the potential environment-friendly alternative fuels of the future, hydrogen is one of the most promising in terms of practicality, long term feasibility and low pollution levels. Thus it has the capability to contribute majorly towards solving two major issues: energy security and climate change.

Hydrogen has a very low energy density when compared to gasoline. This is a disadvantage for storage, transport and safety purposes since it will need to be stored at very high pressures. In addition, hydrogen cannot be used to produce energy by combustion at temperatures below 0^0C, since the fuel requires a higher temperature to burn. Therefore the challenge becomes storing hydrogen at extremely high pressures without drastically reducing the temperature.

Hydrogen is the cleanest fuel having a heating value three times higher than petroleum. However, being man- made fuel the hydrogen is not natural source of energy, therefore, it involves production cost, which is responsible for it is three times more cost than petroleum products.

There are still problems in the realization of the renewed hydrogen from water ,but the market supply and the cost of hydrogen do not constitute the bottleneck of hydrogen vehicles today although the hydrogen used presently may not be renewed .But , hydrogen's excellent characters ,studying the availability of H_2 in internal combustion(IC) engines, and investigating the performance of hydrogen fuelled engines ,become one of the utmost important research directions for researchers.

1.1 Literature Survey

The paper "An overview of hydrogen as a vehicle fuel" by H. Fayaz, R.Saidur, N.Razali , F.S.Anuar, A.R.Saleman, M.R.Islam. published in 2012 introduced hydrogen as an alternative fuel. Hydrogen is one of the energy carriers which can replace fossil fuel and can be used as fuel in an internal combustion engines and as a fuel cell in vehicles. For this purpose engine design should be considered for avoiding abnormal combustion, which gives better engine efficiency, power output and reduced NO_x emission. The production of hydrogen can be ‘carbon-free’ only if it is generated by employing genuinely carbon-free renewable energy sources.

The paper "An investigation of engine performance parameters and artificial intelligent emission prediction of hydrogen powered car" by Tien Ho, Vishy Karri, Daniel Lim, Danny Barret. published in 2008 compares operating parameters and performance of a Toyota Corolla four cylinder 1.8L engine running on gasoline as well as hydrogen. The emission characteristics also discussed.

2. HYDROGEN AS A FUEL IN INTERNAL COMBUSTION ENGINES

The use of hydrogen as a fuel in internal combustion engine will be discussed further. The discussion includes properties of combustive hydrogen ,abnormal combustion in hydrogen engine, engine components ,thermal efficiency ,emission production, power output ,emissions and cost ,hydrogen production plant, people acceptability of hydrogen fuelling station and lifecycle of hydrogen

2.1. Engine concept

Hydrogen can be used in SI engine by three methods :

(i) By manifold induction :

Cold hydrogen is introduced through a valve controlled passage into the manifold.
(ii)By direct introduction of hydrogen into the cylinder :

Hydrogen is stored in the liquid form ,in a cryogenic cylinder. A pump sends this liquid through a small heat exchanger where it is converted into cold hydrogen gas .The metering of hydrogen is also done in this unit .The cold hydrogen helps to prevent pre-ignition and also reduces NOx formation. The arrangement of liquid hydrogen storage and details of hydrogen induction into the SI engine cylinder can be seen in Fig1.
(iii) By supplementing gasoline :

Hydrogen can also be used as an add-on fuel to gasoline in SI engine. In this system ,hydrogen is inducted along with gasoline, compressed and ignited by a spark.

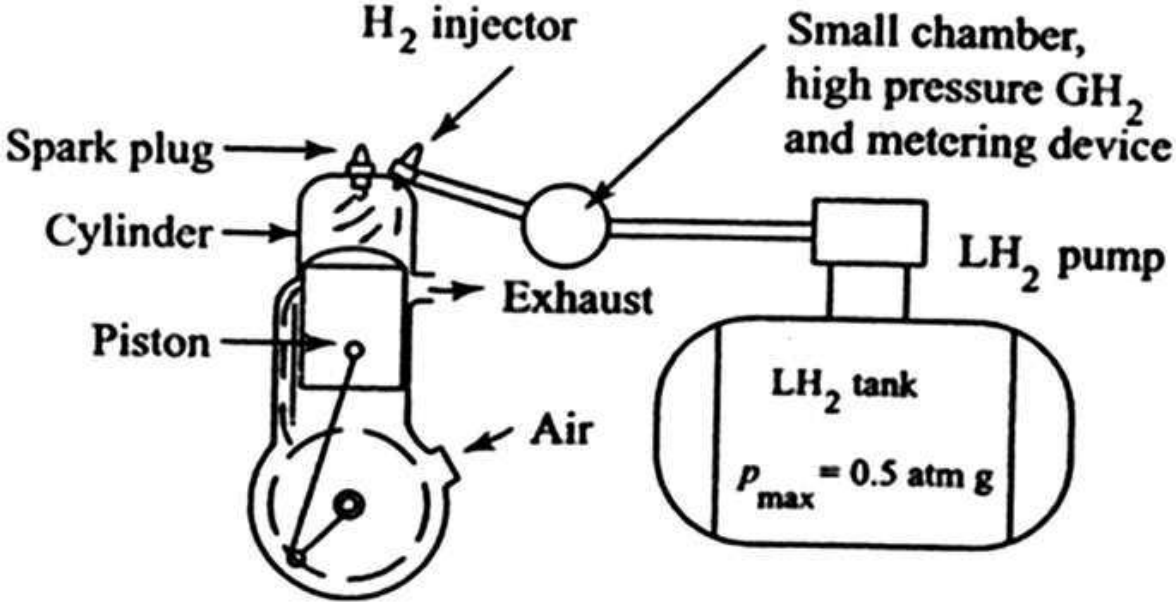


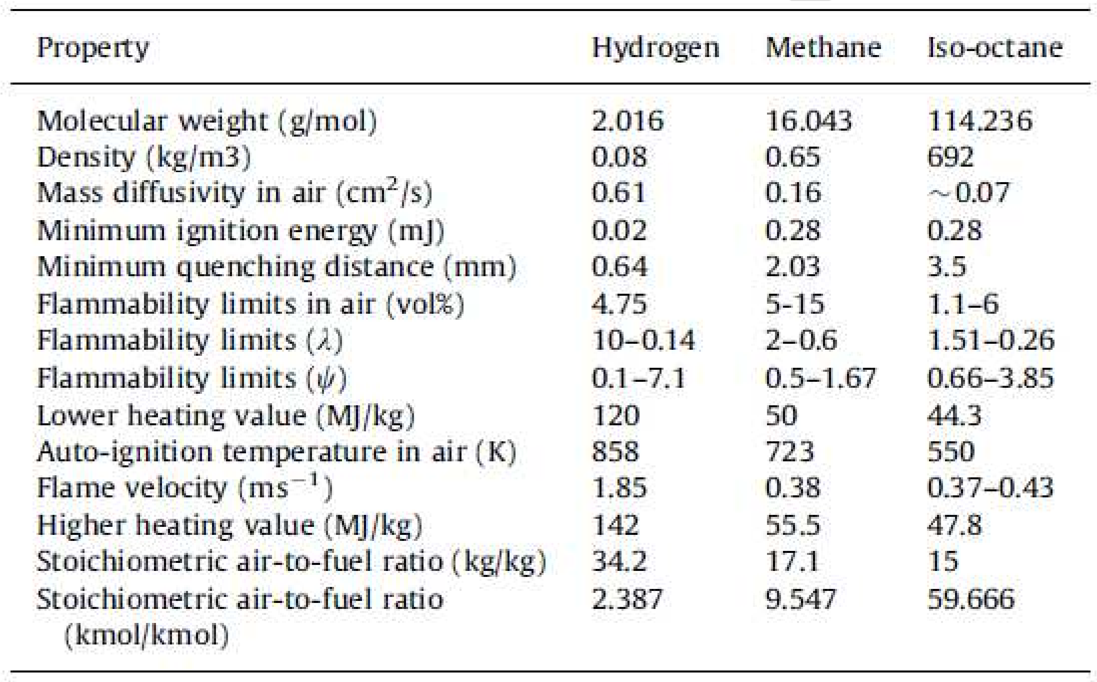
Fig.1 Liquid hydrogen storage and gaseous hydrogen injection

2.2. Combustive properties of hydrogen

A brief summary of previous literatures are reviewed and discussed based on fundamentals of hydrogen combustion, flammability, ignition energy and octane number. Details of these characteristics to hydrogen engines based on recent studies as well as on-going efforts in the development of H2ICEs and H2ICE vehicles will be discussed later. Some properties of hydrogen are listed in Table 1 in comparison with isooctane and methane ,which are representing as the natural gas and gasoline ,respectively Table 2 shows the mixture properties of hydrogen–air when operated at lean and stoichiometric mixture in comparison with iso-octane–air and methane–air at stoichiometric mixture.

TABLE-1

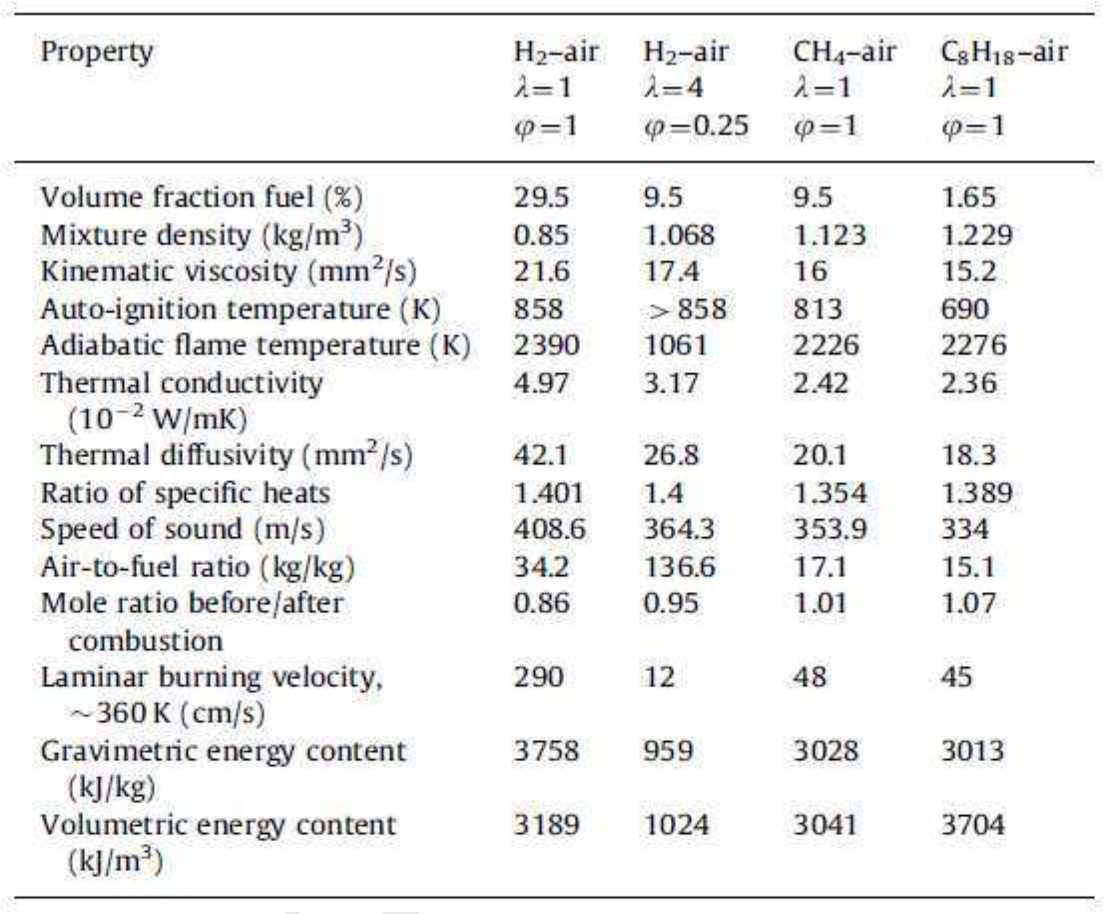
Hydrogen properties compared with methane and iso-octane properties. Data given at 300 K and 1 atm**.**



Property	Hydrogen	Methane	Iso-octane
Molecular weight (g/mol)	2.016	16.043	114.236
Density (kg/m3)	0.08	0.65	692
Mass diffusivity in air (cm^2/s)	0.61	0.16	~0.07
Minimum ignition energy (mJ)	0.02	0.28	0.28
Minimum quenching distance (mm)	0.64	2.03	3.5
Flammability limits in air (vol%)	4.75	5-15	1.1–6
Flammability limits (λ)	10–0.14	2–0.6	1.51–0.26
Flammability limits (ψ)	0.1–7.1	0.5–1.67	0.66–3.85
Lower heating value (MJ/kg)	120	50	44.3
Auto-ignition temperature in air (K)	858	723	550
Flame velocity (ms^{-1})	1.85	0.38	0.37–0.43
Higher heating value (MJ/kg)	142	55.5	47.8
Stoichiometric air-to-fuel ratio (kg/kg)	34.2	17.1	15
Stoichiometric air-to-fuel ratio (kmol/kmol)	2.387	9.547	59.666

TABLE-2

Mixture properties of hydrogen–air, methane–air, and iso-octane–air. Data given at 300 K and 1 atm (with the exception of the laminar burning velocity, given at 360 K and 1 atm).



Property	H_2–air $\lambda=1$ $\varphi=1$	H_2–air $\lambda=4$ $\varphi=0.25$	CH_4–air $\lambda=1$ $\varphi=1$	C_8H_{18}–air $\lambda=1$ $\varphi=1$
Volume fraction fuel (%)	29.5	9.5	9.5	1.65
Mixture density (kg/m^3)	0.85	1.068	1.123	1.229
Kinematic viscosity (mm^2/s)	21.6	17.4	16	15.2
Auto-ignition temperature (K)	858	>858	813	690
Adiabatic flame temperature (K)	2390	1061	2226	2276
Thermal conductivity (10^{-2} W/mK)	4.97	3.17	2.42	2.36
Thermal diffusivity (mm^2/s)	42.1	26.8	20.1	18.3
Ratio of specific heats	1.401	1.4	1.354	1.389
Speed of sound (m/s)	408.6	364.3	353.9	334
Air-to-fuel ratio (kg/kg)	34.2	136.6	17.1	15.1
Mole ratio before/after combustion	0.86	0.95	1.01	1.07
Laminar burning velocity, ~360 K (cm/s)	290	12	48	45
Gravimetric energy content (kJ/kg)	3758	959	3028	3013
Volumetric energy content (kJ/m^3)	3189	1024	3041	3704

2.2.1.Flammability limit

Flammability limit gives the proportion of combustible gases in a mixture ;between these limits, this mixture is flammable. From Table 1 it is seen that the flammability of hydrogen in air (mixture) is at 4–75% which gives hydrogen wide range of flammability as compared to other fuels. It is clear that 4% of hydrogen in air is still flammable but non-coherently and burns incompletely. The 4% value relates to configuration of one particular experiment. Therefore , the limit may vary being below 4% or above,(depending on condition) ,in real world situations . For safety considerations this limit is important where it is less important for engine combustion. Wide ranges of mixture of hydrogen permit extremely lean or rich mixture that combust with air. This makes the hydrogen engine operate at lean mixture resulting in greater fuel economy and more complete combustion reaction. Final combustion temperature will also generally lower due to lower laminar burning velocity as can be seen in Table 2. The burning velocity for hydrogen engine that operates at lean mixture is rapidly lowered as compared to hydrogen engine that runs on stoichiometric mixture which is 12cm/s (at φ=0.25) and 290cm/s (at φ=1). This absolutely will reduce amount of pollutants such as NOx.

2.2.2.Minimum ignition energy

Minimum ignition energy is the minimum amount of energy required to ignite a combustible vapour or gas mixture. At atmospheric conditions , the minimum ignition energy of a hydrogen–air mixture is an order of magnitude lower than for the mixtures of iso-octane–air and methane–air. For hydrogen concentrations of 22–26% only 0.017 MJ is obtained. Normally, capacitive spark discharge is used to measure minimum ignition energy, and thus is dependent on the spark gap. The values quoted in Table 1 are for a 0.5 mm gap. The minimum ignition energy can increase about 0.05 MJ and more or less constant for hydrogen concentrations between 10% and 50 % when using a gap of 2mm. The benefits for having minimum ignition energy to enable hydrogen engine to ignite lean mixture and ensure prompt ignition. But having minimum ignition energy will increase possibility for hydrogen air mixture in the combustion chamber to be ignited by any other source (hotspot) rather than spark plug.

2.2.3. Small quenching distance

As compared to gasoline and other fuels , hydrogen has small quenching distance. In Table 1 the quenching distance for hydrogen is about 0.64 mm compare to methane which is 2.03 mm and Iso-octane 3.5 mm. This parameter measure show close hydrogen flames can travel closer to the cylinder wall before they extinguish. The smaller the distance, more difficult to quench the flame and this will increase the tendency for backfire. Experimentally, from the relation between minimum ignitions energy and the spark gap size quenching distance can be derived or can be measured directly.

2.2.4. High auto—Ignition temperature

Referring to Table 1, taken from hydrogen has relatively high auto-ignition temperature as compared to methane and iso- octane which is 858K. This high auto-ignition is important parameter to determine engine compression ratio, since during compression, the temperature rise is pertained to the compression ratio when considering Otto cycle as shown in the Eq.(1)below.

$$T_2 = T_1 \left(r^c\right)^{k-1} \qquad (1)$$

From this equation it can be seen that compression ratio is dependent on T2 which is temperature during compression. This T2 is limited by auto-ignition temperature to prevent fuel air mixture to auto ignite before the spark, given from spark plug. Higher auto-ignition temperature will increase T2 and simultaneously increase compression ratio. As relating to thermal efficiency of the system , higher compression ratio is important.

2.2.5. High flame speed, high diffusivity and low density

At stoichiometric ratios , hydrogen acquires high flame speed as shown in Table 1, which is about 1.85 m/s compared to methane and iso-octane which is 0.38 m/s and 0.37–0.43 m/s, respectively. Having high flame speed, hydrogen engines can more be similar to the thermo dynamically ideal engine cycle. However, the flame velocity goes to decreases significantly at leaner mixture,. Hydrogen also possesses remarkably high diffusivity, which is its capability to disperse in air more than methane and iso-octane .This shows that hydrogen can form uniform mixture of fuel and air, and if hydrogen leaks, it will disperse rapidly and leaking hydrogen is not a pollutant to the environment. Low density of hydrogen will result in two problems of IC engine. Large volume needs to store more hydrogen to provide sufficient driving range and reduce power output due to low energy density.

2.3. Abnormal combustion

The main problem to use hydrogen as a fuel in internal combustion engine, is to control the undesired combustion phenomena due to low ignition energy, wide flammability range and rapid combustion speed of hydrogen that causes mixture of hydrogen and air to combust easily. In this section the main abnormal combustion in hydrogen engine which are pre-ignition, backfire, and knock in terms of cause and method to avoid will be discussed.

2.3.1.Pre-ignition

Pre-ignition is one of the undesired combustion that needs to be avoided in hydrogen engine. During the engine compression stroke, these abnormal combustion events occur inside the combustion chamber, with actual start of combustion prior to spark timing. Pre-ignition event will advance the start of combustion and produce an increased chemical heat-release rate. In turn ,the increased heat-release rate results in a rapid pressure rise, higher peak cylinder pressure, acoustic oscillations and higher heat rejection that leads to rise in-cylinder surface temperature. The start of combustion can further be advanced by latter effect, which in turn can be led to run away effect, and will cause the engine failure if unchecked.

Source of pre-ignition:

1.Hot spark plugs or spark plug electrodes.
2.Hot exhaust valves or other hot spots in the combustion chamber.
3. Residual gas or remaining hot oil particles from previous combustion events.
4.Combustion in crevice volumes

To minimize the source of pre- ignition:

1. Ignition system design with low residual charge.
2. Specific design of crankcase ventilation.
3.Sodium-filled exhaust valve.
4.Optimized design of the engine cooling passage to avoid hot spot.
5.With the use of hydrogen direct injection systems.
6.Variable valve timing for effective scavenging of exhaust residuals.
7. Proper design of spark plug.

2.3.2.Backfire

Backfire is one of the main problems to run a hydrogen fuelled engine. Backfire or flash back is the uncontrolled combustion of fresh hydrogen–air mixture during the intake stroke in the combustion chamber and /or the intake manifold. The fresh hydrogen–air mixture is aspirated into the combustion chamber with the opening of the intake valves. Backfiring is caused when combustion chamber hot sopts , hot residue gas or remaining charge in the ignition system ignite the fresh charge as hydrogen has low ignition temperature. Effect of backfire resulting in combustion and pressure rise in the intake manifold, is clearly audible as well as can also damage or destroy the intake system.

Strategies that are used to avoid backfiring:

1. Injection strategies that allow pure air to flow into the combustion chamber to cool potential hot spots before aspirating the fuel-air mixture.
2. The possibility of back firing mainly depends on the concentrations of H2 residual at intake ports in a manifold injection H2ICE, and the leaner the concentration of the residual ,the lower the possibility of the backfire.
3. Optimization of the fuel-injection strategy in combination with variable valve timing for both intake and exhaust valves allow operation of a port injected hydrogen engine at stoichiometric mixtures over the entire speed range.

2.3.3. Knock

Knock, or spark knock is defined as auto-ignition of the hydrogen–air end-gas ahead of the flame front that has originates from the spark .This follows a rapid release of the remaining energy generating high-amplitude pressure waves, mostly referred to as engine knock. Engine damage can be caused by the amplitude of the pressure waves of heavy engine knock due to increased mechanical and thermal stress. The knocking tendency of an engine is dependent on the engine design along with the fuel-air mixture properties .The high auto-ignition temperature, finite ignition delay and the high flame velocity of hydrogen mean that knock, as defined is less likely for hydrogen relative to gasoline, and hence the higher research octane number(RON) for hydrogen(RON4120) in comparison with gasoline.

Effects of knock to engine operation:

1. Increased heat transfer to the cylinder wall.
2. Excessively high cylinder pressure and temperature level sand increased emissions.
3. Undesirable engine performance and the potential damage to engine components.

2.3.4.Avoiding abnormal combustion

It is an effective measure to limit maximum fuel-to-air equivalence ratio to avoid abnormal combustion in hydrogen operation. By operation ,employing a lean-burn strategy ,the excess air in lean operation acts as an inert gas and reduces combustion temperature effectively and components temperatures consequently. Although lean operation is very effective ,it does limit the power output of hydrogen engine. Using thermal dilution technique ,pre-ignition conditions can also be curbed, such as water injection or exhaust gas recirculation(EGR).

2.4. Engine components

Some features of engines designed for or converted to hydrogen operation ,will be discussed in this section. As discussed in the previous section, the occurrence of combustion anomalies, or more particularly, the desire to prevent it, has led to most of the counter measures, which were put forwarded in the early work on H2ICEs.

2.4.1. Spark plugs

To avoid spark plug electrode temperature that exceeds the auto-ignition limit and causing backfire, cold-rated spark plugs are recommended [36]. This cold-related spark plug can be used since there are no carbon deposits to burn off. Since spark plugs with platinum electrodes can be catalyst to hydrogen oxidation, there- fore these are to be avoided.

2.4.2. Injection systems

In hydrogen engine, there are two types of injection systems, which can be used, one is port fuel injection(PFI) and other is direct injection (DI).InPFI-H2ICE, time injection is a prerequisite as what has already been discussed previously that the main problem in PFI-H2ICE is to avoid backfire. Therefore , PFI needs the programming of the injection timing such that an air cooling period is created in the initial phase of the intake stroke, and the end of injection is such that all hydrogen is inducted, leaving no hydrogen in the manifold when the intake valve closes. The advantage of using PFI system is the pressure tank for injector, which is lower as compared to DI system.

2.4.3. Hot spots

Minimizing the hot spot in combustion chamber of hydrogen engine is important to avoid abnormal combustion which is the major problem in burning hydrogen well because it will reduce power output and engine efficiency. Hot spot can act like ignition source as hydrogen needs minimum ignition energy to be ignited.

2.4.4. Piston rings and crevice volumes

Hydrogen engines have been demonstrated, run on stoichiometric mixture without any occurrence of backfire, by careful selection of crevice volumes and piston rings, without any need for timed injection or cooled exhaust valve. Therefore, it needs careful selection of piston rings and crevice volumes in order to prevent hydrogen flame from propagating into the top land.

2.4.5. Lubrication

Lubrication is an important aspect that needs to be considered when switching over to hydrogen as fuel in internal combustion engine. During engine operation, blow will always occur due to the rapid pressure rise and the low density of hydrogen gas. The exhaust gases, entering crankcase can condense, when there is no provision of proper ventilation. Water mixing into the crankcase oil (lubrication oil) reduces its lubrication ability and as a result, there occurs a higher degree of engine wear.

2.4.6. Crankcase ventilation

Using hydrogen as a fuel for spark-ignited internal combustion engines, especial attention has to be given to the crankcase ventilation as compared to gasoline engines. Carbon based deposits from the engine's lubricating oil, in the combustion chamber, on the top of the piston, in the ring grooves, and in the cylinder's squish areas are potential hot spots waiting to happen. Blow by effect can cause unburned hydrogen entering the crankcase and at certain concentration, hydrogen can combust in the crankcase due to lower energy ignition and wide flammability limits. Hydrogen should be prevented from accumulating through ventilation.

2.4.7. Compression ratio

It is the similar choice of the optimal compression ratio to that for any fuel; for increasing engine efficiency it should be chosen as high as possible, with the limit given by increased heat losses or the occurrence of abnormal combustion (in the case of hydrogen, primarily surface ignition). The choice may be dependent on the application, as the optimum compression ratio for highest engine efficiency might be different from the optimum compression ratio for highest power output. Compression ratios used in H2ICEs range from 7.5:1 to 14.5:1.

2.4.8. In-cylinder turbulence

Low turbulence combustion chamber can be used due to high flame speeds of hydrogen. Low radial and tangential velocity components can be reduced by the use of disk-shaped combustion chamber (flat piston and chamber ceiling) can help produce and does not amplify inlet swirl during compression. This will be beneficial for engine efficiency by increase in the volumetric efficiency and decrease heat loses. The overall trends are such that turbulence increases auto-ignition delay times and accordingly the ignition length and pressure further contribute to this delay.

2.5. Thermal efficiency

The theoretical thermodynamic efficiency of an Otto cycle engine is based on the compression ratio of the engine as shown in Eq. (2)

$$\eta_{th} = 1-\left(\frac{1}{r^{c}}\right)^{\gamma-1} \tag{2}$$

The higher compression ratio r^c and/or the specific heat ratio γ, indicated the thermo dynamic efficiency of the engine. Hydrogen(γ=1.4) has much simpler molecular structure than gasoline and therefore its specific heat ratio is higher than that of gasoline (γ =1.1).As a result, theoretically, hydrogen engine can have higher thermal efficiency compared to gasoline engine. The high RON and low-flammability limit of hydrogen provides the necessary elements to attain high thermal efficiencies in an internal combustion engine. In DI-H2ICE, hydrogen injection at later stage of compression stroke can achieve the thermal efficiency higher than 38.9% and the brake mean effective pressure 0.95MPa.

2.5.1. Thermodynamic analysis

Using test data from different operating modes, the engine efficiencies and the losses of the working cycle can be calculated. Fig. 2 shows the efficiencies and losses for gasoline and hydrogen operation with both port injection and direct injection. The data for all fuels were collected on a single-cylinder research engine at an engine speed of 2000 RPM and indicated mean effective pressures of 2 bar and 6 bar. Table 3 shows summary of the analysis.

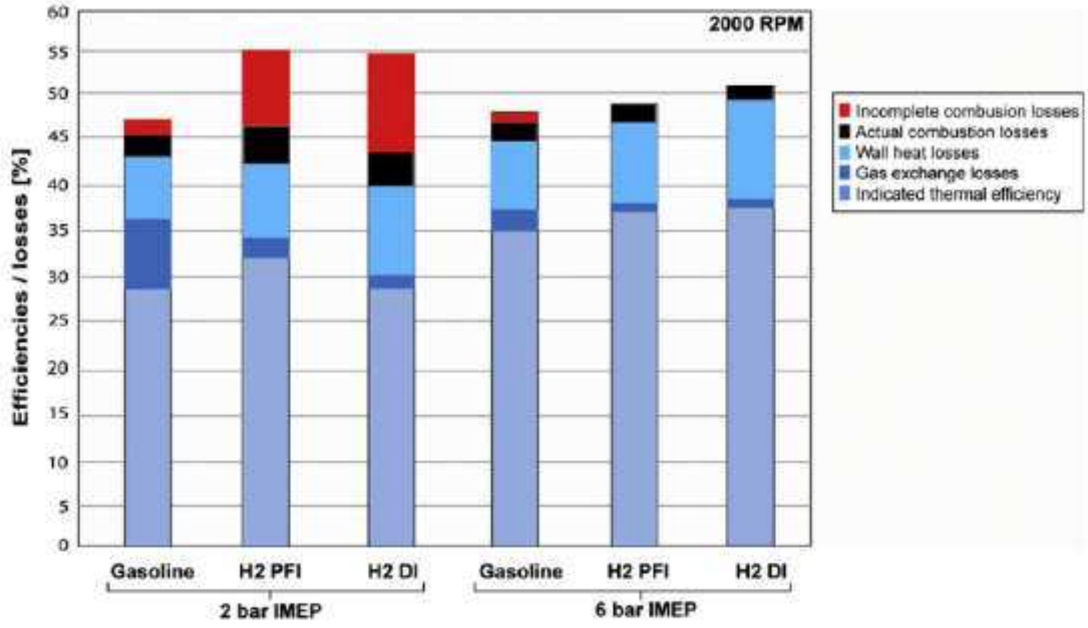
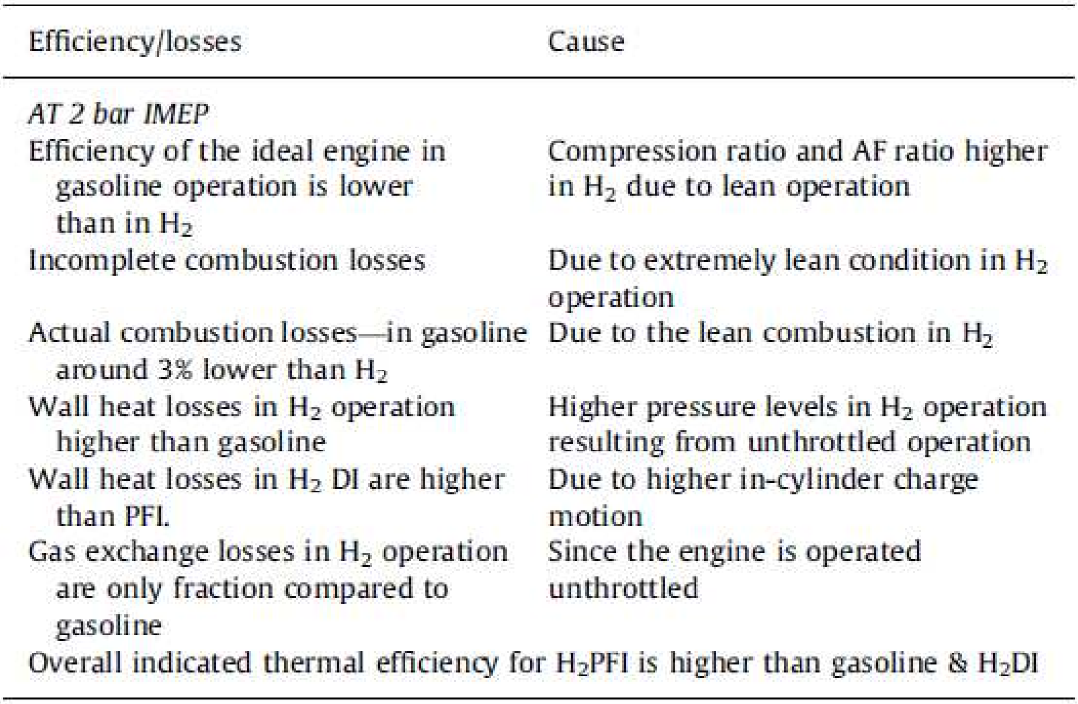


Fig.2. Analysis of losses compared to the theoretical engine cycle; gasoline versus hydrogen (PFI and DI) ,at two loads

Comparative combustion characteristics of gasoline and hydro- gen fuel, in internal combustion engine have been done. The ability of elucidating the potential performance and efficiency of a hydrogen fuelled ICE compared to a gasoline fuelled ICE was achieved in the analysis of the comparative combustion characteristics of hydrogen and gasoline fuelled internal combustion engine. It was noted that the hydrogen fuelled ICE had a higher thermal efficiency of approximately 6.42% due to the reasons as; less heat rejection during the exhaust stroke, less blow down during the exhaust stroke, combustion taking place closer to TDC and combustion taking place in an closer to isochoric environment. Thus, it was closer to an actual Otto cycle. An important conclusion is that improvement in H_2ICE efficiencies will require strategies to minimize heat transfer losses to the cylinder walls as higher combustion temperatures and shorter quenching distance associated with hydrogen combustion are believed to cause the greater convective heat transfer to the cylinder walls Table 4.

TABLE 3

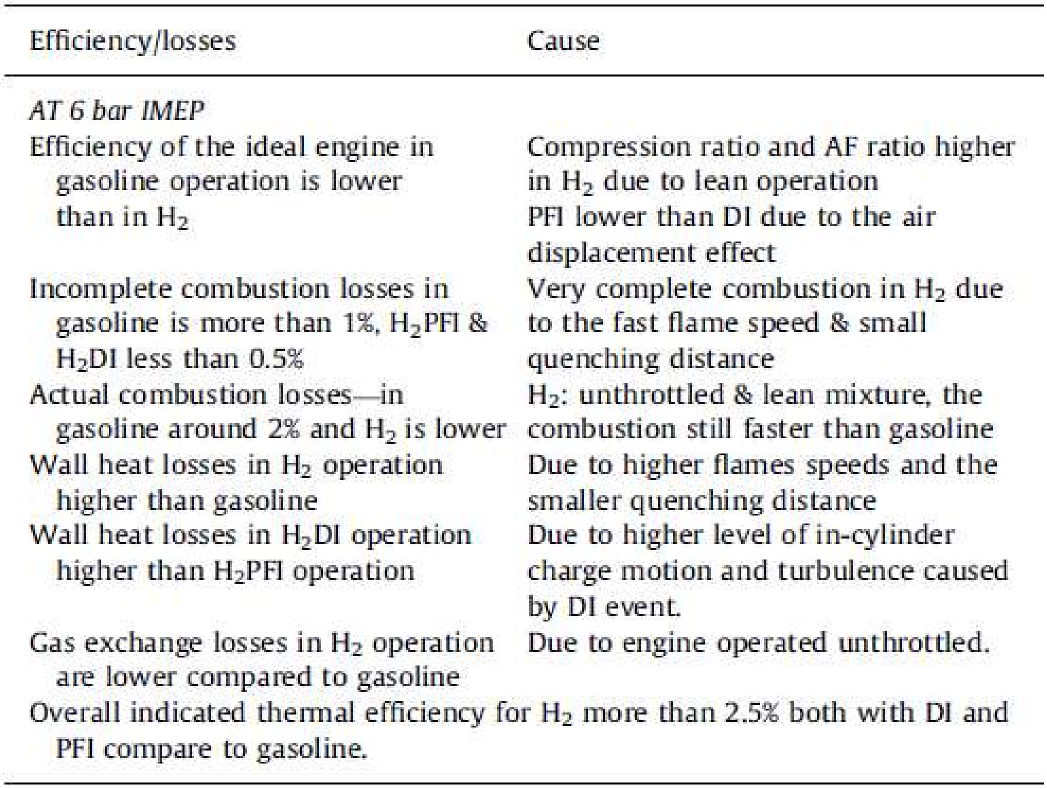
Result analysis of losses compared to the theoretical engine cycle at load 2bar IMEP.



Efficiency/losses	Cause
AT 2 bar IMEP	
Efficiency of the ideal engine in gasoline operation is lower than in H_2	Compression ratio and AF ratio higher in H_2 due to lean operation
Incomplete combustion losses	Due to extremely lean condition in H_2 operation
Actual combustion losses—in gasoline around 3% lower than H_2	Due to the lean combustion in H_2
Wall heat losses in H_2 operation higher than gasoline	Higher pressure levels in H_2 operation resulting from unthrottled operation
Wall heat losses in H_2 DI are higher than PFI.	Due to higher in-cylinder charge motion
Gas exchange losses in H_2 operation are only fraction compared to gasoline	Since the engine is operated unthrottled
Overall indicated thermal efficiency for H_2PFI is higher than gasoline & H_2DI	

TABLE 4

Result analysis of losses compared to the theoretical engine cycle at load 6bar IMEP.



Efficiency/losses	Cause
AT 6 bar IMEP	
Efficiency of the ideal engine in gasoline operation is lower than in H_2	Compression ratio and AF ratio higher in H_2 due to lean operation PFI lower than DI due to the air displacement effect
Incomplete combustion losses in gasoline is more than 1%, H_2PFI & H_2DI less than 0.5%	Very complete combustion in H_2 due to the fast flame speed & small quenching distance
Actual combustion losses—in gasoline around 2% and H_2 is lower	H_2: unthrottled & lean mixture, the combustion still faster than gasoline
Wall heat losses in H_2 operation higher than gasoline	Due to higher flames speeds and the smaller quenching distance
Wall heat losses in H_2DI operation higher than H_2PFI operation	Due to higher level of in-cylinder charge motion and turbulence caused by DI event.
Gas exchange losses in H_2 operation are lower compared to gasoline	Due to engine operated unthrottled.
Overall indicated thermal efficiency for H_2 more than 2.5% both with DI and PFI compare to gasoline.	

2.6. Emission production

Because of the reasons that hydrogen can be produced form any kind of energy source and it is combusted without emitting carbon dioxide or soot, it is considered as an ideal alternative fuel to conventional hydrocarbon fuels The only potential emissions are the nitrogen oxides (NO_X) as pollutants from hydrogen combustion, hence it becomes crucial to minimize the (NO_X) emissions from the combustion of hydrogen. Eqs.(3) and (4) show the exhaust gas emission from hydrogen which is water and NO_x.

$$2H_2 + O_2 = 2H_2O \tag{3}$$

$$H_2 + O_2 + N_2 = H_2O + N_2 + NO_x \tag{4}$$

The formation of nitrogen oxides occurs, because the higher temperatures are generated within the combustion chamber during combustion. These higher temperatures cause some of the nitrogen and oxygen to combine, present in the air. The technique of rich-lean combustion or staged combustion is used to reduce NO_x formation in continuous combustion burners such as gas turbine sand boilers. Where ,water injection in the compression ignition engine helps to control combustion temperature and pressure. Hence, it is beneficial in controlling unwanted emissions .Many researchers have demonstrated the effect with conventional hydro carbon fuels.

The amount of NO_x formed depends on :

1. The air/fuel ratio.
2. The engine compression ratio.
3. The engine speed.
4. The ignition timing.
5. Thermal dilution is utilized or not.

2.7. Power output

Volumetric efficiency, fuel energy density and pre-ignition primarily determine the H_2ICE peak power output. The volumetric efficiency has been proved to be the limiting factor for determining the peak power output for most of the practical applications. The displacement of intake air by the large volume of hydrogen in the intake mixture is the reason for PFI-H_2ICEs to inherently fusser from volumetric efficiency. For example, about 30% of hydrogen is possessed by mixture of hydrogen and air by volume, where as a 2% gasoline is possessed by stoichiometric mixture of fully vaporized gasoline and air by volume. The higher energy content of hydrogen partially offsets the corresponding power density loss. The stoichiometric heat of combustion per standard kg of air is 3.37MJ and 2.83 MJ for hydrogen and gasoline, respectively. It follow that approximately 83% is the maximum power density of a pre-mixed or PFI-H2CE, relative to the power density of the gasoline operated identical engine. For applications where peak power output is limited by pre- ignition, H_2ICE power densities, relative to gasoline operation ,can significantly be below 83%. For direct injection systems, which mix the fuel with the air after the intake valve closes (and thus the combustion chamber has 100% air), the maximum output of the engine can be approximately 15% higher than that for gasoline engines. Therefore, depending on how the fuel is metered, the maximum output for a hydrogen engine can be either 15% higher or 15% less than that of gasoline if a stoichiometric air/fuel ratio is used.

However, at a stoichiometric air/fuel ratio, the combustion temperature is very high and as a result it will form a large amount of nitrogen oxides (NO_X), which is a criteria pollutant. Since one of the reasons for using hydrogen is low exhaust emissions, therefore hydrogen engines are not normally designed to run at a stoichiometric air/fuel ratio. At this air/fuel ratio, the formation of NOx is reduced to near zero. Unfortunately, this also reduces the power output. To make up the power loss, hydrogen engines are usually larger than gasoline engines, and/or are equipped with turbo chargers or superchargers.

3. EXPERIMENTAL SETUP

For analysing engine performance parameters of hydrogen powered car a four cylinders manual Toyota Corolla was successfully converted to use hydrogen as a fuel in its internal combustion engine. Certain characteristics of hydrogen make it unique for application as an automotive fuel. The wide flammability limits of hydrogen allow for a larger range of air to fuel mixtures to be used at different engine operating conditions. This means that very lean mixtures may be used for lower emissions while enriched mixtures could be used when additional power is required. Hydrogen also has a very high flame propagation rate even with lean mixture providing a very sharp rise in pressure immediately after spark ignition.

The design and construction of the hydrogen conversion based on the following seven basic systems of the conversion:

1. Hydrogen storage system - Consist of two E-size cylinders, with a total hydrogen capacity of 0.5 kg.
2. Hydrogen re-fuelling system - Consist of cylinder adapter hoses along with lock - off valve, on-return valves and bleed valves.
3. Hydrogen piping system - it is a stainless steel solid tube
4. Pressure regulation system - Consist of CIG Weld dual stage high flow industrial hydrogen gas regulator.
5. Fuel delivery system - Hydrogen is injected into the air entering the engine piston cylinder.
6. Fuel and engine management system - it control the fuel delivery system ,that is mass of hydrogen required to the engine's cylinders at the precise taming.
7. Safety system -consist of leak detection system , fuel shut-off switch and solenoid valve, flashback arrestor, pressure relief valves and filtration.

4. RESULT AND DISCUSSION

This experiment is used to measure various essential engine operating parameters, such as the engine's rotational speed, power output, levels of the various exhaust gas emissions, fuel flow rate, and fuel mixture formation. The results obtained were used to discuss ;

1. Effect of hydrogen as a fuel compared with gasoline on engine parameters.
2. Effect of hydrogen as a fuel compared with gasoline on emission characteristics.

4.1 Effect of hydrogen as a fuel compare with gasoline on engine parameters

4.1.1 Engine Power

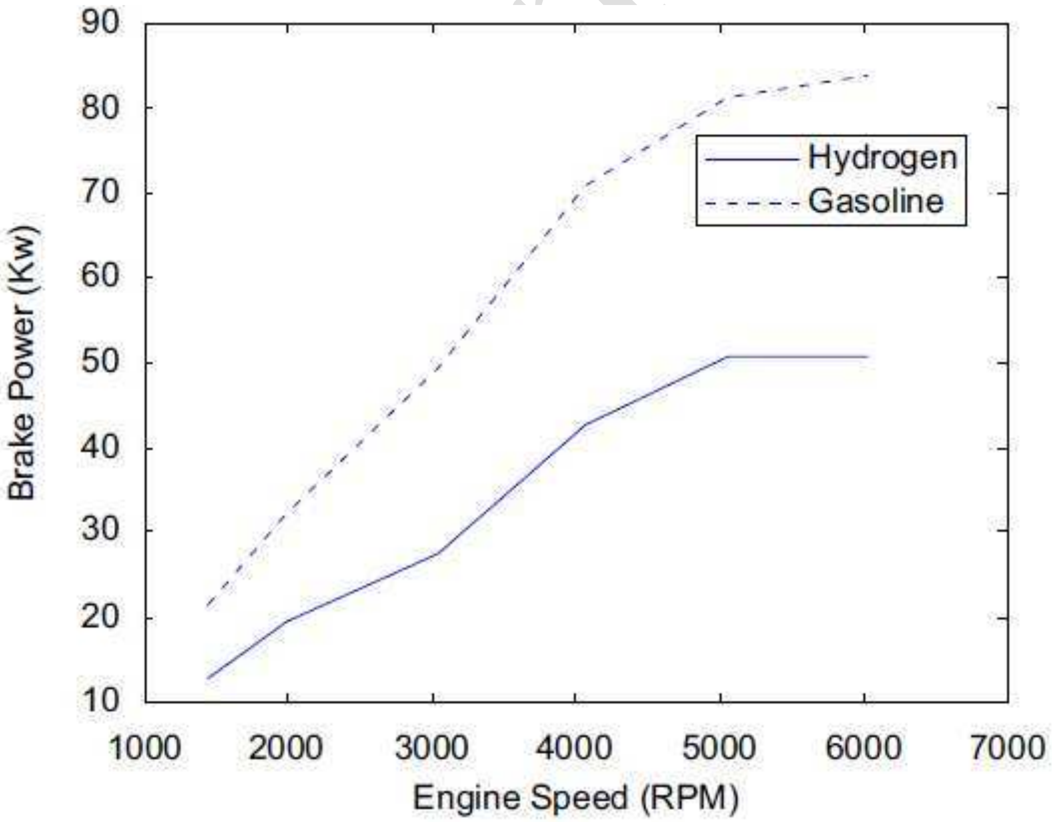


fig 3. Effect of hydrogen as a fuel compare with gasoline on brake power at various engine speed at WOT

From the experimental result it is seen that the engine output while fuelled by hydrogen was found to be around half of that of the engine while fuelled by gasoline .But, at 5000RPM and Wide opening throttle, the power output for hydrogen operation was as high as 63% of that of gasoline operation. This is due to the increased fuel delivery of the hydrogen engine's calibration around these conditions.

From fig 3 it is seen that the brake power vs engine speed curves are similar in shape for both hydrogen and gasoline. There is some deficiency in power output for the hydrogen powered engine as compared to gasoline. This is mainly due to two reason. First reason is that injection of hydrogen into the inlet manifold displaces approximately one third of the air within the inlet manifold, while vaporized gasoline only displaces around 1% of the air within the inlet manifold. The proportion of the air which is displaced by hydrogen decreases as the fuel and air mixture is weakened. This reduction of the quantity of fuel directly reduces the energy input into the engine. This, in turn, directly decreases the power output from such an engine. This is the second major reason.

4.1.2 Engine Torque

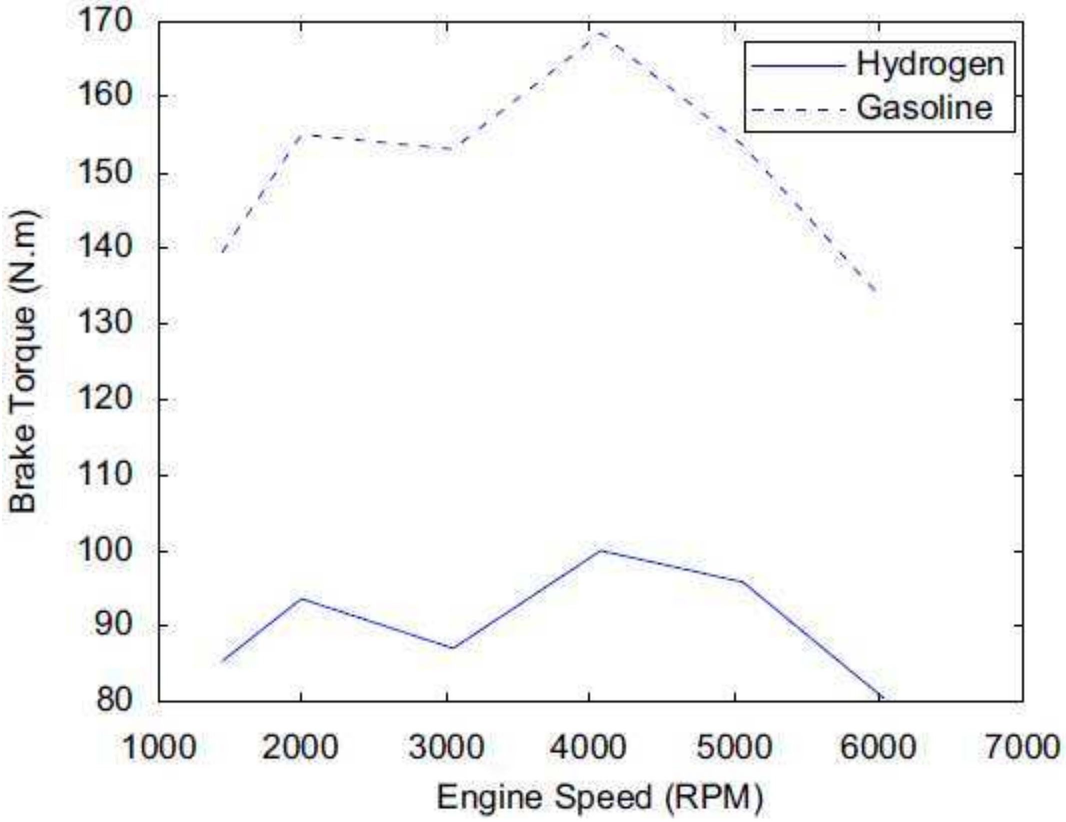


Fig.4 Effect of hydrogen as a fuel compare with gasoline on brake power at various engine speed at WOT

The brake power of an engine is directly proportional to the torque and engine speed. For this reason, it is not surprising to find that the engine's torque output shows the same proportional characteristics as were present for its power output. The gasoline-fuelled engine has a peak torque of 168.3Nm at an engine speed of 4000 RPM, with a secondary peak of 155Nm at 2000 RPM. This is compared to hydrogen operation, having 100.1 and 93.7Nm at the same engine speeds, respectively, as shown in Fig. 4

4.1.3 Break mean effective pressure

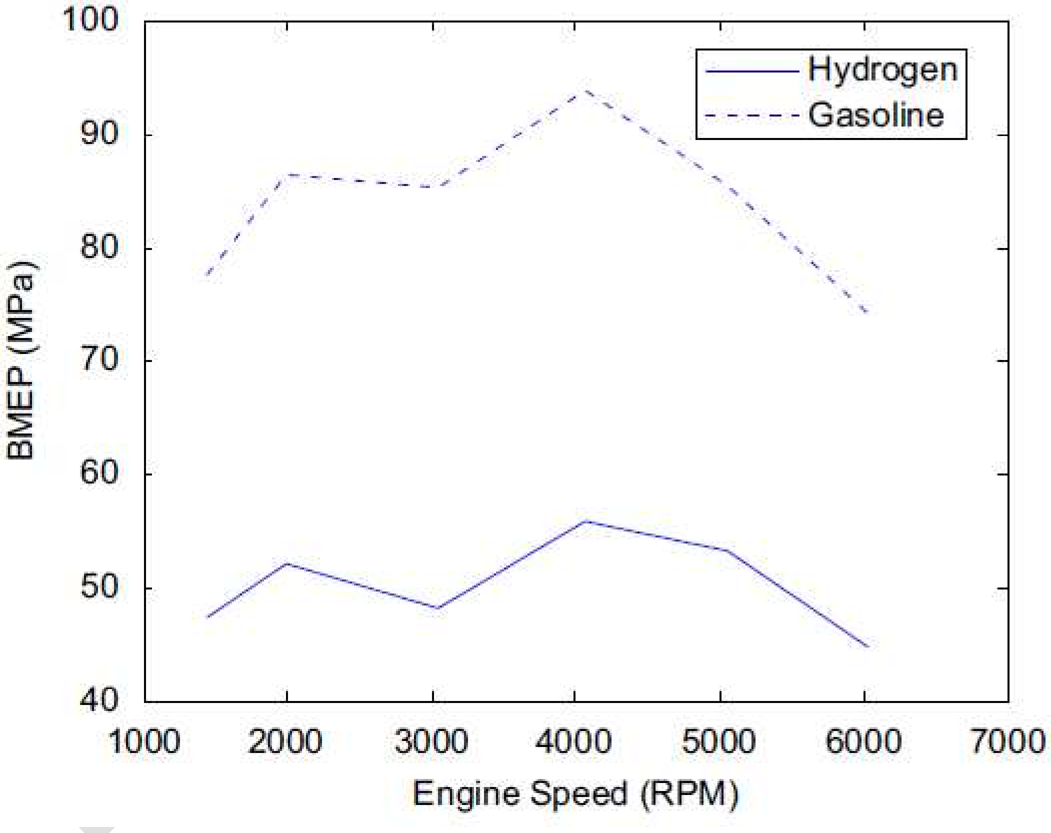


fig.5 Effect of hydrogen as a fuel compare with gasoline on brake torque at various engine speed at WOT

The brake mean effective pressure (BMEP) of an engine is equivalent to the engine’s torque, divided by its displacement. For this reason, the BMEP curve for a given engine is simply a scaled version of the torque curve. Maximum BMEP for the gasoline-fuelled engine was found to be 93.8MPa at 4000 RPM, while it was 55.8MPa at the same engine speed for the hydrogen-fuelled engine as shown in fig 5.

4.1.4 Brake specific fuel consumption

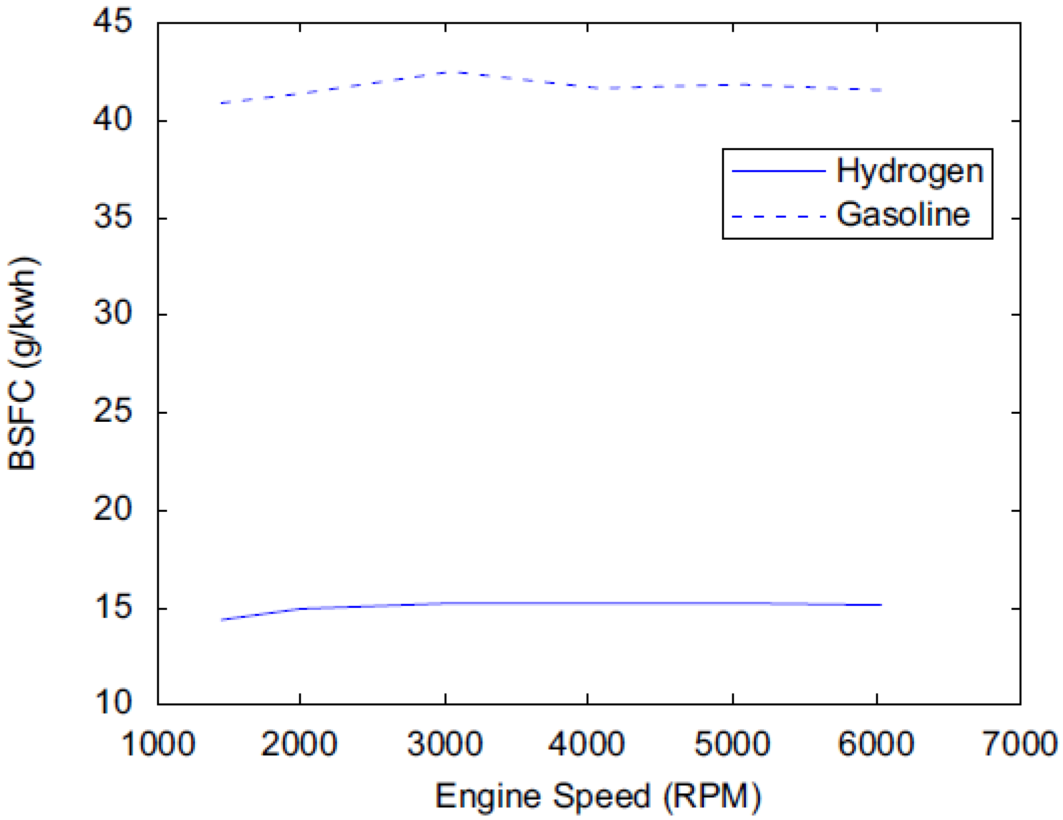


fig.6. Effect of hydrogen as a fuel compare with gasoline on brake specific fuel consumption at various engine speed at WOT

At WOT, the BSFC for the gasoline-fuelled engine ranges between 40.9 and 42.5g/kWh (average 41.6g/kWh), while for the hydrogen-fuelled engine it ranges between 14.4 and 15.2g/kWh (average 15.0g/kWh) as shown in Fig.6. This gives a ratio of gasoline BSFC to hydrogen BSFC of 2.77. This was fully expected, as hydrogen's lower calorific value (LCV) is 119.9 MJ/kg, compared to 44.5 MJ/kg for gasoline (a ratio of hydrogen LCV to gasoline LCV being 2.69).

4.1.5 Engine efficiency

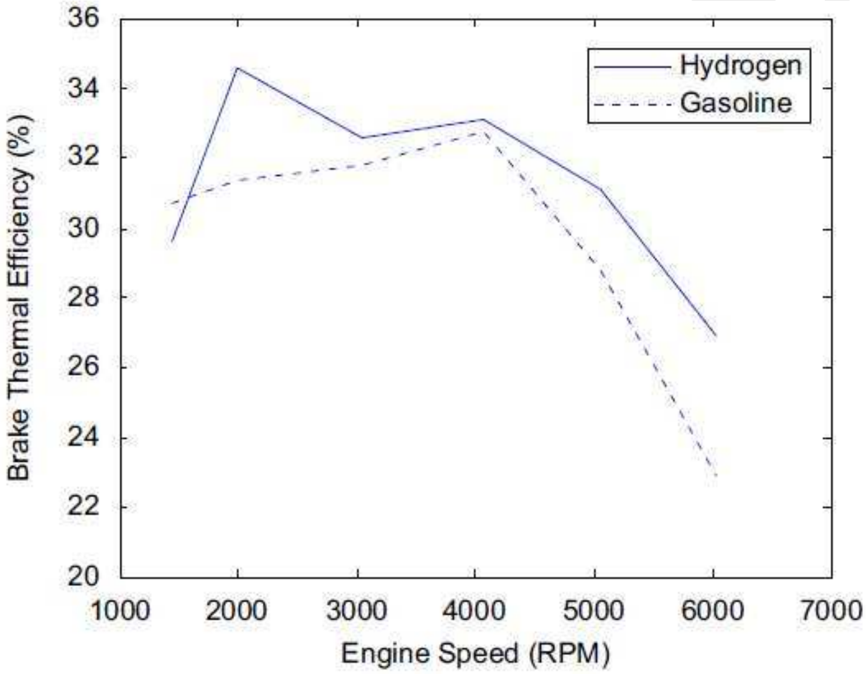


fig.7. Effect of hydrogen as a fuel compare with gasoline on brake thermal efficiency at various engine speed at WOT

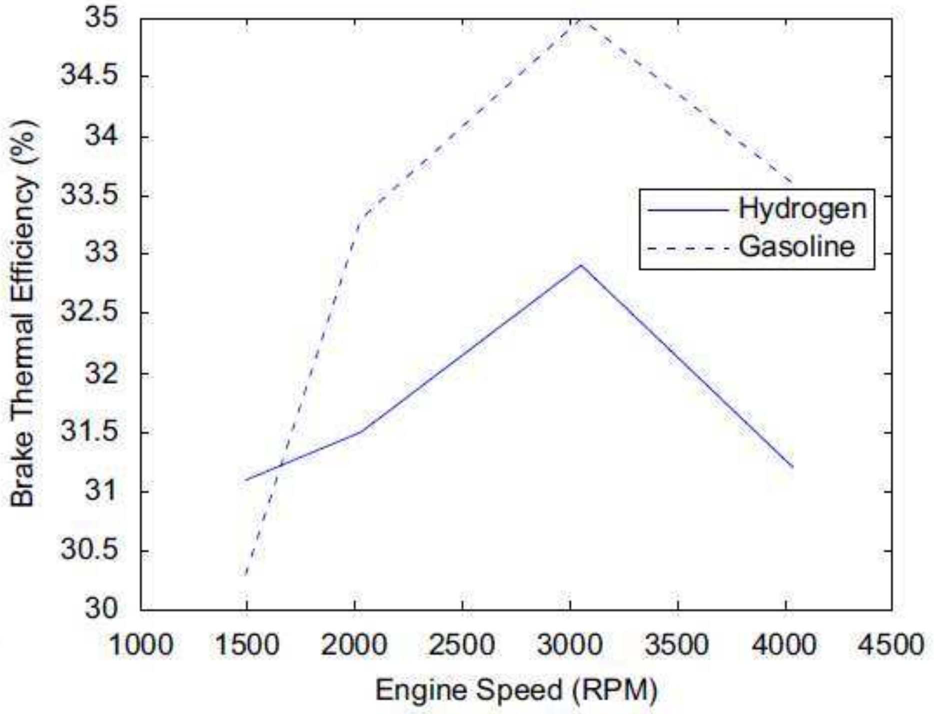


fig.8. Effect of hydrogen as a fuel compare with gasoline on break mean effective pressure at various engine speed at 75% throttle opening.

It is quite clearly seen that operation on hydrogen is generally more efficient than operation on gasoline at most engine speeds while operating at WOT as shown in Fig.7. Much of this can be attributed to the fact that the engine is fuelled by a rich air to gasoline mixture at WOT. This is for the express purpose of increasing the power output at WOT. While the air to gasoline ratio is made to be rich at WOT, the air to hydrogen ratio is still lean at WOT. The net result is that the efficiency of the gasoline fuelled engine suffers more due to enrichment than does the hydrogen-fuelled engine under the same conditions.

In contrast, the efficiency of the hydrogen fuelled engine at nearly all other tested operating points was lower than that of the gasoline fuelled engine, due to two main reasons as shown in Fig.8. (75% throttle opening). Firstly, the power output of the gasoline fuelled engine while not at WOT is significantly higher than that of the hydrogen fuelled engine. Secondly, the tuning of the gasoline engine was the culmination of potentially thousands of hours of experimental work by the manufacturer of the engine.

4.2 Effect of hydrogen as a fuel compare with gasoline on emission characteristics :

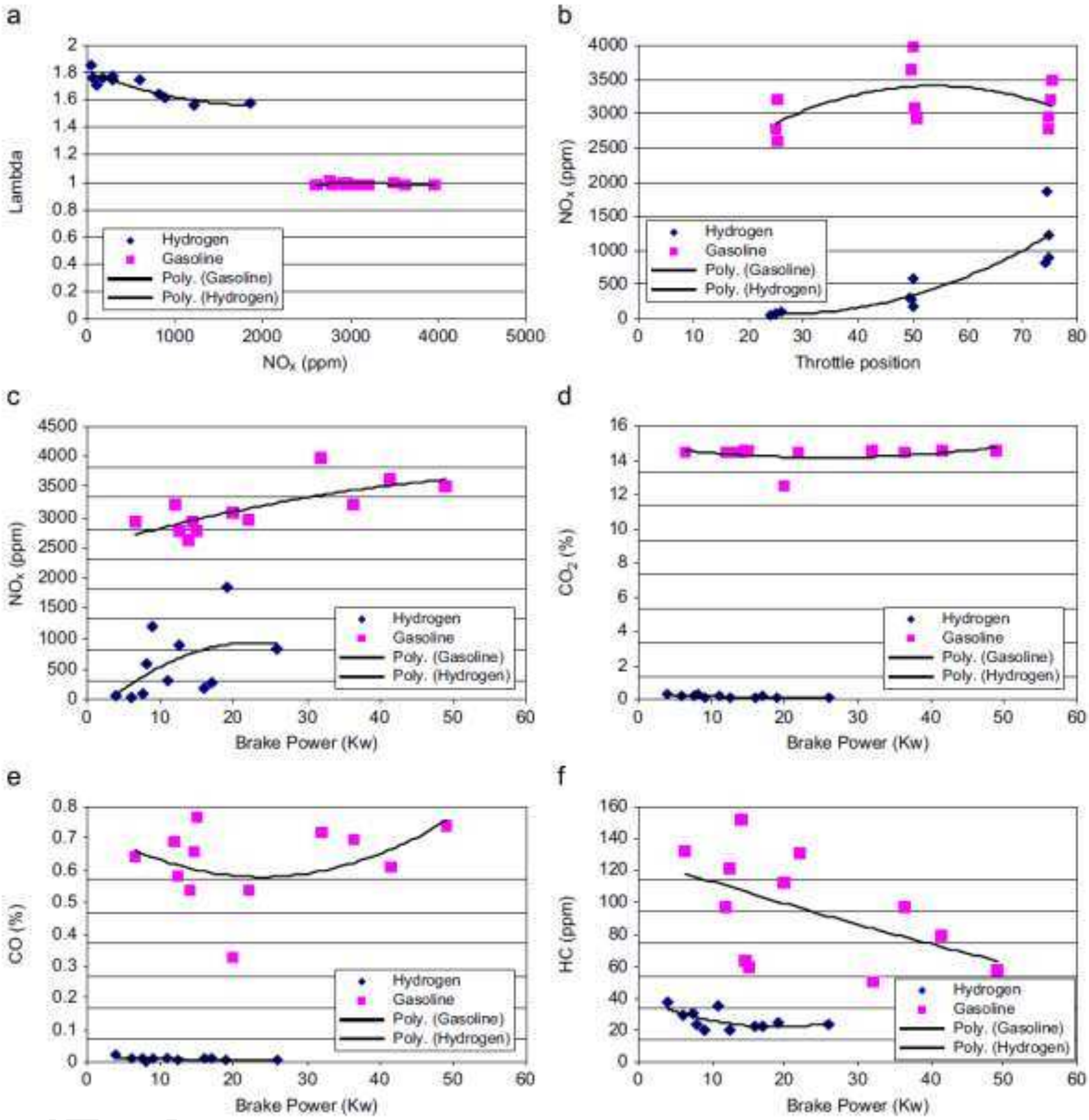


Fig. 9 – Effect of hydrogen as a fuel compare with gasoline on emission characteristics; (a) Lambda versus NOx at 25% throttle position; (b) throttle position versus NOx; (c) brake power versus NOx; (d) brake power versus CO2; (e) brake power versus CO; and (f) brake power versus HC.

4.2.1. Emission of oxides of nitrogen

The emission of NO_x increases markedly as the lambda value decreases toward unity, and has a minimum at a lambda value of around 1.87 as shown in Fig. 9(a). In addition, at no point in time did the emission of NO_x from the hydrogen fuelled engine exceed that from the gasoline fuelled engine as shown in Figs. 9(a)–(c). The results can be seen most markedly at operating conditions with small (25%) throttle position. This can be attributed to the fact that the hydrogen fuelled engine was always operated at a lean air to fuel ratio, which has been shown to result in low emissions of NO_x gases.

4.2.2. Emission of carbon dioxide

The reduction in the emission of carbon dioxide is a major advantage of hydrogen-fuelled engines over gasoline-fuelled engines. The hydrogen-fuelled engine does not emit absolutely zero carbon dioxide. However, the emission of carbon dioxide is virtually negligible, being between 0.05% and 0.29%, compared with between 14.44% and 14.58% from the gasoline-fuelled engine as shown in Fig. 9(d). The emission of carbon dioxide from the hydrogen fuelled engine can be attributed to two factors. Firstly, any carbon dioxide within the air before it enters the engine will remain as carbon dioxide. This is expected to be a minor contributor to the general emission of carbon dioxide. Secondly, during each cycle of the engine some lubricating oil makes its way into the combustion chamber, past the piston rings, through the crankcase ventilation system, and through the valve guides. Because of this, it is impossible to eliminate carbon dioxide emissions from hydrogen fuelled internal combustion engines.

4.2.3. Emission of carbon monoxide

The emission of carbon monoxide from hydrogen fuelled internal combustion engines is negligible in comparison with that from gasoline fuelled internal combustion engines. The emission of carbon monoxide from the hydrogen engine was extremely low, at 0.005–0.020%, compared to 0.326–0.767% for the gasoline engine as shown in Fig. 9(e).

4.2.4. Emission of hydrocarbon

The hydrocarbon emission level from the hydrogen engine was notably lower than that of the gasoline fuelled engine as shown in Fig. 5(f). In the case of a gasoline-fuelled engine, most of the hydrocarbon emissions come from un-burnt fuel passing through the exhaust system. In contrast, in a hydrogen-fuelled engine, all hydrocarbons must come from the combustion of the lubricating oil. The emission of hydrocarbon from the hydrogen engine was lower than those of gasoline engine, at 20–37 ppm, compared to 50–152ppm for the gasoline engine.

5. CONCLUSIONS

Hydrogen in internal combustion engines has many advantages in terms of combustive properties but it needs detailed consideration of engine design to avoid abnormal combustion, which is the major problem in hydrogen engine. This, as a result can improve engine efficiency, power output and reduce NOx emissions.

From the measured parameters, various engine characteristics were calculated, and compared for operation using gasoline and hydrogen as fuels, brake power and torque of the car’s engine when running on hydrogen was generally about 50–60% of that of gasoline as well as brake specific fuel consumption was in line with expectations from the respective lower calorific values of the two fuels. In addition, thermal efficiency was similar for the two fuels, hydrogen being more efficient at lower power output, and gasoline being more efficient at higher power output. Besides that, the emission of NOx was significantly lower for hydrogen operation than for gasoline operation and its lowest values were achieved with lambda value around 1.87. Similarly, the emission of carbon dioxide and carbon monoxide and hydrocarbon from the hydrogen engine was extremely low compared the gasoline engine.

6. REFERENCES

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