

Use of Hydrogen in Internal Combustion Engine

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Abstract— Fast depletion of fossil fuels is urgently demanding a carry out work for research to find out the viable alternative fuels for meeting sustainable energy demand with minimum environmental impact. In the future, our energy systems will need to be renewable and sustainable, efficient and cost-effective, convenient and safe. Hydrogen is expected to be one of the most important fuels in the near future to meet the stringent emission norms. The use of the hydrogen as fuel in the internal combustion engine represents an alternative use to replace the hydrocarbons fuels, which produce polluting gases such as carbon monoxide (CO), hydro carbon (HC) during combustion. In this seminar report contemporary research on the hydrogen-fuelled internal combustion engine can be given. First hydrogen-engine fundamentals were described by examining the engine-specific properties of hydrogen and then existing literature were surveyed.

Index Terms— Internal combustion engine, hydrogen, emissions, alternative fuel

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I. INTRODUCTION

For more than a century, hydrocarbon fuels have played a leading role in propulsion and power generation. However, increase in stringent environment regulations on exhaust emissions and anticipation of the future depletion of worldwide petroleum reserves provides strong encouragement for research on alternative fuels . As a result various alternative fuels (such as liquefied petroleum gas (LPG), compressed natural gas (CNG), hydrogen, vegetable

oils, bio gas, producer gas) have been considered as substitutes for hydrocarbon-based fuel and reducing exhaust emissions.

Of these, hydrogen is a long-term renewable and less-polluting fuel. In addition hydrogen is clean burning characteristics and better performance drives more interest in hydrogen fuel. When it is burnt in an internal combustion engine, the primary combustion product is water with no CO₂. Although NO_x emissions are formed when hydrogen is used.

II. OBJECTIVES

At the completion of this module, we will understand that : -

- the combustive properties of hydrogen that relate to its use as a combustive fuel .
- the air/fuel ratio of hydrogen fuel mixtures and how it compares to other fuels.
- the types of pre-ignition problems encountered in a hydrogen internal combustion engine and their solutions .
- the type of ignition systems that may be used with hydrogen internal combustion engines .
- crankcase ventilation issues that pertain to hydrogen use in an internal combustion engine .
- the thermal efficiency of hydrogen internal combustion engines .
- the type of emissions associated with hydrogen internal combustion engines .
- the power output of hydrogen internal combustion engines .
- the effect of mixing hydrogen with other hydrocarbon fuels .

III. COMBUSTIVE PROPERTIES OF HYDROGEN

The properties that contribute to its use as a combustible fuel are its:

- wide range of flammability
- low ignition energy
- small quenching distance
- high autoignition temperature
- high flame speed at stoichiometric ratios
- high diffusivity
- very low density
- Flame velocity and adiabatic flame

A. Wide Range of Flammability

Hydrogen has a wide flammability range in comparison with all other fuels. As a result, hydrogen can be combusted in an internal combustion engine over a wide range of fuel-air

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mixtures. A significant advantage of this is that hydrogen can run on a lean mixture. A lean mixture is one in which the amount of fuel is less than the theoretical, stoichiometric or chemically ideal amount needed for combustion with a given amount of air. This is why it is fairly easy to get an engine to start on hydrogen.

Generally, fuel economy is greater and the combustion reaction is more complete when a vehicle is run on a lean mixture. Additionally, the final combustion temperature is generally lower, reducing the amount of pollutants, such as nitrogen oxides, emitted in the exhaust. There is a limit to how lean the engine can be run, as lean operation can significantly reduce the power output due to a reduction in the volumetric heating value of the air/fuel mixture.

B. Small Quenching Distance

Hydrogen has a small quenching distance, smaller than gasoline. Consequently, hydrogen flames travel closer to the cylinder wall than other fuels before they extinguish. Thus, it is more difficult to quench a hydrogen flame than a gasoline flame. The smaller quenching distance can also increase the tendency for backfire since the flame from a hydrogen-air mixture more readily passes a nearly closed intake valve, than a hydrocarbon-air flame.

C. High Autoignition Temperature

Hydrogen has a relatively high autoignition temperature. This has important implications when a hydrogen-air mixture is compressed. In fact, the autoignition temperature is an important factor in determining what compression ratio an engine can use, since the temperature rise during compression is related to the compression ratio. The temperature rise is shown by the equation:

$$T_2 = (V_1)^{\gamma-1}$$

$$T_1 = (V_2)^{\gamma-1}$$

where:

- V_1/V_2 = the compression ratio
- T_1 = absolute initial temperature
- T_2 = absolute final temperature
- γ = ratio of specific heats

The temperature may not exceed hydrogen’s autoignition temperature without causing premature ignition. Thus, the absolute final temperature limits the compression ratio. The high autoignition temperature of hydrogen allows larger compression ratios to be used in a hydrogen engine than in a hydrocarbon engine.

This higher compression ratio is important because it is related to the thermal efficiency of the system. On the other hand, hydrogen is difficult to ignite in a compression ignition or diesel configuration, because the temperatures needed for those types of ignition are relatively high.

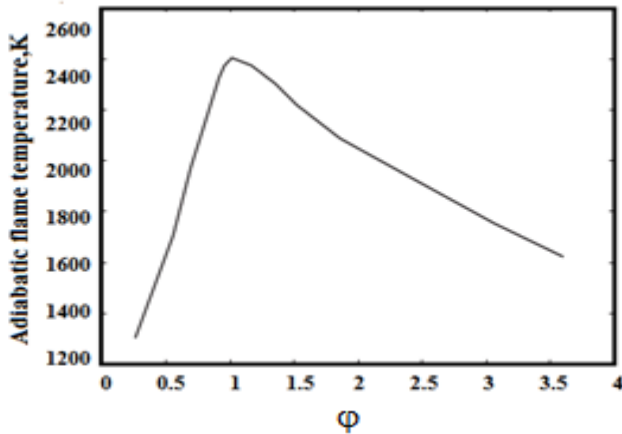
The auto ignition temperature is the minimum temperature required to initiate self-sustained combustion in a combustible fuel mixture in the absence of an external ignition. For hydrogen, the auto ignition temperature is relatively high 585°C. This makes it difficult to ignite a hydrogen-air mixture on the basis of heat alone without some additional ignition source. The auto ignition temperatures of various fuels are shown in Table 1. This temperature has important implications when a hydrogen-air mixture is compressed. In fact, the auto ignition temperature is an important factor in determining what maximum compression ratio an engine can use, since the temperature rise during compression is related to compression ratio.

Table 1. Comparison of hydrogen with other fuels

Fuel	LHV (MJ/kg)	HHV (MJ/kg)	Stoich. A.F Ratio (kg)	Combustible Range (%)	Flame Temp(°C)	Min. Ignition Energy (MJ)	Auto Ignitin Temp. (°C)
Methane	50.0	55.55	17.2	5-15	1914	0.30	540-630
Propane	45.6	50.3	15.6	2.1-9.5	1925	0.30	450
Octane	47.9	51.1	15.1	0.95-6	1980	0.26	415
Methanol	18	22.7	6.5	6.7-36	1870	0.14	460
Hydrogen	119.9	141.6	34.3	4-75	2207	0.017	585
Gasoline	44.5	47.3	14.6	1.3-7.1	2307	0.29	260-460
Diesel	42.5	44.8	14.5	0.6-5.5	2327	-----	180-320

D. High Flame Speed

Hydrogen has high flame speed at stoichiometric ratios. Under these conditions, the hydrogen flame speed is nearly an order of magnitude higher (faster) than that of gasoline. This means that hydrogen engines can more closely approach the thermodynamically ideal engine cycle. At leaner mixtures, however, the flame velocity decreases significantly. Flame velocity and adiabatic flame temperature are important properties for engine operation and control, in particular thermal efficiency, combustion stability and emissions. Laminar flame velocity and flame temperature, plotted as a function of equivalence ratio.



E. High Diffusivity

Hydrogen has very high diffusivity. This ability to disperse in air is considerably greater than gasoline and is advantageous for two main reasons. Firstly, it facilitates the formation of a uniform mixture of fuel and air. Secondly, if a hydrogen leak develops, the hydrogen disperses rapidly. Thus, unsafe conditions can either be avoided or minimized.

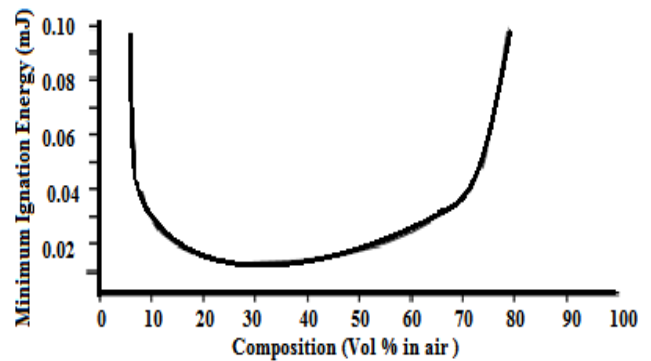
F. Low Density

Hydrogen has very low density. This results in two problems when used in an internal combustion engine. Firstly, a very large volume is necessary to store enough hydrogen to give a vehicle an adequate driving range. Secondly, the energy

density of a hydrogen-air mixture, and hence the power output, is reduced.

G. Minimum ignition source energy

The minimum ignition source energy is the minimum energy required to ignite a fuel-air mix by an ignition source such as a spark discharge. For an hydrogen-air mixture 0.02 mJ as compared to 0.24 mJ for petrol -air and is approximately constant over the range of flammability. The low minimum ignition energy of the hydrogen-air mix means that a much lower energy spark is required for spark ignition. This means that combustion can be initiated with a simple glow plug or resistance hot-wire. It also ensures prompt ignition of the charge in the combustion chamber.



H. Air/Fuel Ratio

The theoretical or stoichiometric combustion of hydrogen and oxygen is given as: $2H_2 + O_2 = 2H_2O$
 Moles of H_2 for complete combustion = 2 moles
 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:

$$\begin{aligned} \text{Moles of } N_2 \text{ in air} &= \text{Moles of } O_2 \times (79\% N_2 \text{ in air} / 21\% O_2 \text{ in air}) \\ &= 1 \text{ mole of } O_2 \times (79\% N_2 \text{ in air} / 21\% O_2 \text{ in air}) \\ &= 3.762 \text{ moles } N_2 \\ \text{Number of moles of air} &= \text{Moles of } O_2 + \text{moles of } N_2 \\ &= 1 + 3.762 \\ &= 4.762 \text{ moles of air} \\ \text{Weight of } O_2 &= 1 \text{ mole of } O_2 \times 32 \text{ g/mole} \\ &= 32 \text{ g} \\ \text{Weight of } N_2 &= 3.762 \text{ moles of } N_2 \times 28 \text{ g/mole} \\ &= 105.33 \text{ g} \\ \text{Weight of air} &= \text{weight of } O_2 + \text{weight of } N_2 \\ &= 32\text{g} + 105.33 \text{ g} \\ &= 137.33 \text{ g} \end{aligned}$$

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$$\begin{aligned} \text{Weight of H}_2 &= 2 \text{ moles of H}_2 \times 2 \text{ g/mole} \\ &= 4 \text{ g} \end{aligned}$$

Stoichiometric air/fuel (A/F) ratio for hydrogen and air is:

$$\begin{aligned} \text{A/F based on mass:} &= \text{mass of air/mass of fuel} \\ &= 137.33 \text{ g} / 4 \text{ g} \\ &= 34.33:1 \end{aligned}$$

$$\begin{aligned} \text{A/F based on volume:} &= \text{volume (moles) of air/volume (moles) of fuel} \\ &= 4.762 / 2 = 2.4:1 \end{aligned}$$

The percent of the combustion chamber occupied by hydrogen for a stoichiometric mixture:

$$\begin{aligned} \% \text{ H}_2 &= \text{volume (moles) of H}_2 / \text{total volume} \\ &= \text{volume H}_2 / (\text{volume air} + \text{H}_2) \\ &= 2 / (4.762 + 2) \\ &= 29.6\% \end{aligned}$$

As these calculations show, 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 are required for every pound of hydrogen. This is much higher than the 14.7:1 A/F ratio required for gasoline.

Since hydrogen is a gaseous fuel at ambient conditions it displaces more of the combustion chamber than a liquid fuel.

Consequently less of the combustion chamber can be occupied by air. At stoichiometric conditions, hydrogen displaces about 30% of the combustion chamber, compared to about 1 to 2% for gasoline. Figure 3-3 compares combustion chamber volumes and energy content for gasoline and hydrogen fueled engines.

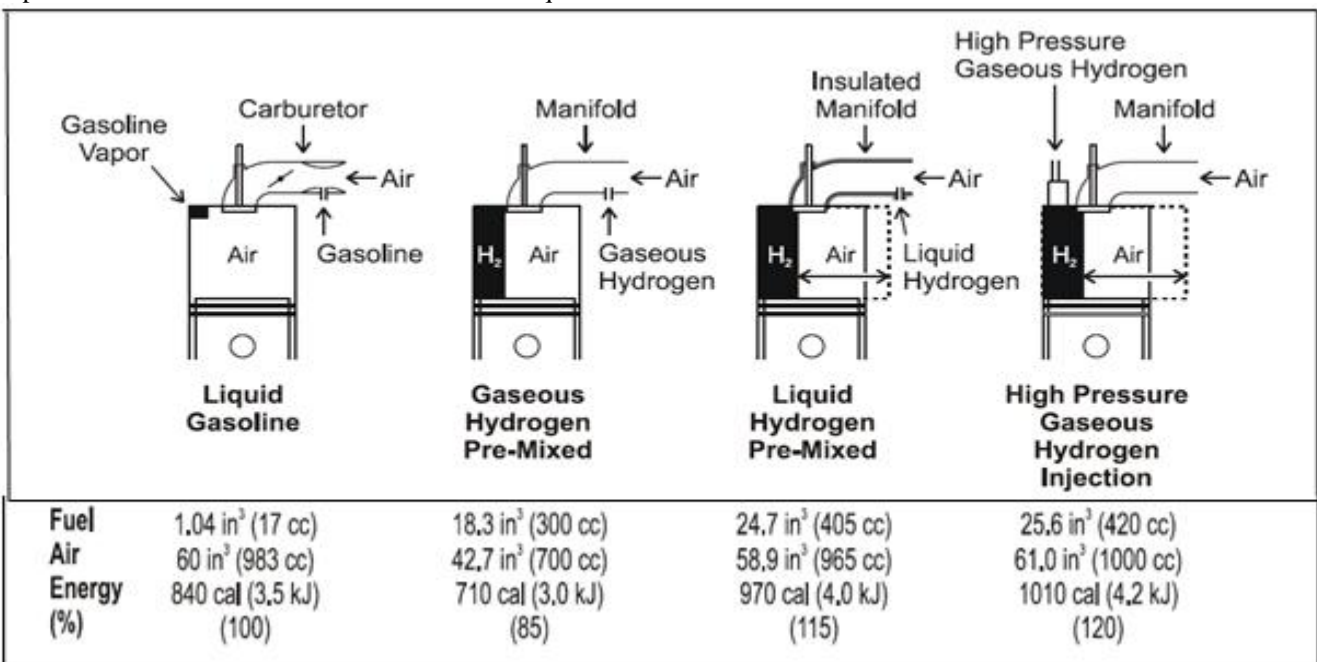


Figure 3-3 Combustion Chamber Volumetric and Energy Comparison for Gasoline and Hydrogen Fueled Engines

Depending the method used to meter the hydrogen to the engine, the power output compared to a gasoline engine can be anywhere from 85% (intake manifold injection) to 120% (high pressure injection).

Because of hydrogen's wide range of flammability, hydrogen engines can run on A/F ratios of anywhere from 34:1 (stoichiometric) to 180:1. The A/F ratio can also be expressed in terms of equivalence ratio, denoted by phi (Φ). Phi 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 phi equals unity (one). For lean A/F ratios, phi will be a value less than one. For example, a phi of 0.5 means 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.

IV. PRE-IGNITION PROBLEMS AND SOLUTIONS

The primary problem that has been encountered in the development of operational hydrogen engines is premature ignition. Premature ignition is a much greater problem in hydrogen fueled engines than in other IC engines, because of hydrogen's lower ignition energy, wider flammability range and shorter quenching distance.

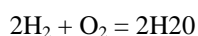
Premature ignition occurs when the fuel mixture in the combustion chamber becomes ignited before ignition by the spark plug, and results in an inefficient, rough running engine. Backfire conditions can also develop if the premature ignition occurs near the fuel intake valve and the resultant flame travels back into the induction system.

A number of studies have been aimed at determining the cause of pre-ignition in hydrogen engines. Some of the results suggest that pre-ignition are caused by hot spots in the combustion chamber, such as on a spark plug or exhaust valve, or on carbon deposits. Other research has shown that backfire can occur when there is overlap between the opening of the intake and exhaust valves.

It is also believed that the pyrolysis (chemical decomposition brought about by heat) of oil suspended in the combustion chamber or in the crevices just above the top piston ring can contribute to pre-ignition. This pyrolysed oil can enter the combustion chamber through blow-by from the crankcase (i.e. past the piston rings), through seepage past the valve guide seals and/or from the positive crankcase ventilation system (i.e. through the intake manifold).

V. HYDROGEN AS A FUEL

Hydrogen produces only water after combustion. It is a non-toxic, non-odorant gaseous matter and also can be burn completely. When hydrogen is burned, hydrogen combustion does not produce toxic products such as hydrocarbons, carbon monoxide, and oxide of sulphur, organic acids or carbon dioxides shown in Equation below, except for the formation of NO_x.



Due to these characteristics, researchers are focusing their attention on hydrogen as an alternative fuel in internal combustion engines. The properties of hydrogen are given in **Table 2**. Combustion of hydrogen is fundamentally different from the combustion of hydrocarbon fuel. Hydrogen has some peculiar features compared to hydrocarbon fuels, the most significant being the absence of carbon. The burning velocity is so high that very rapid combustion can be achieved. The limit of flammability of hydrogen varies from an equivalence ratio (ϕ) of 0.1 to 7.1 hence the engine can be operated with a wide range of air/fuel ratio.

The minimum energy required for ignition of hydrogen-air mixture is 0.02 mJ only. This enables hydrogen engine to run well on lean mixtures and ensures prompt ignition. The density of hydrogen is 0.0838 kg/m³, which is lighter than air that it can disperse into the atmosphere easily. Hydrogen has the highest energy to weight ratio of all fuels. The flame speed

of hydrogen is 270 cm/s that may cause a very high rate of cylinder pressure rise. The diffusivity of hydrogen is 0.63 cm²/s. As the hydrogen self-ignition temperature is 858 K, compared to diesel of 453 K, it allows a larger compression ratio to be used for hydrogen in internal combustion engine. But it is not possible to achieve ignition of hydrogen by compression alone. Some sources of ignition have to be created inside the combustion chamber to ensure ignition.

Table 2. Properties of hydrogen

Properties	Diesel	Unleaded gasoline	Hydrogen
Formula	C _n H _{1.8n}	C _n H _{1.87n}	—
Auto-ignition Temperature (K)	530	533-733	858
Min. ignition energy (mJ)	—	0.24	0.02
Flammability limits(vol. % in air)	0.7-5	1.4-7.6	4-75
Stoichiometric air fuel ratio on mass	14.5	14.6	34.3
Limits of flammability (equivalence ratio)	—	0.7-3.8	0.1-7.1
Density at 16 °C and 1.01 bar (kg/m ³)	833-881	721-785	0.0838
Net heating value (MJ/kg)	42.5	43.9	119.93
Flame velocity (cm/s)	30	37-43	265-325
Quenching gap in NTP air (cm)	—	0.2	0.064
Diffusivity in air (cm ² /s)	—	0.08	0.63
Octane number	—	92-98	130
Cetane number	44-55	13-17	—

VI. HYDROGEN USE IN INTERNAL COMBUSTION ENGINE

A. Hydrogen use in diesel engines :-

There are several reasons for applying hydrogen as an additional fuel to accompany diesel fuel in the internal combustion (IC) compression ignition (CI) engine.

Firstly, it increases the H/C ratio of the entire fuel.

Secondly, injecting small amounts of hydrogen to a diesel engine could decrease heterogeneity of a diesel fuel spray due to the high diffusivity of hydrogen which makes the combustible mixture better premixed with air and more uniform. Hence the formation of hydrocarbon, carbon monoxide, and carbon dioxide during the combustion can be completely avoided; however a trace amount of these compounds may be formed due to the partial burning of lubricating oil in the combustion chamber. However hydrogen cannot be used as a sole fuel in a compression ignition (CI) engine, since the compression temperature is not enough to initiate the combustion due to its higher self-ignition temperature. Hence hydrogen cannot use CI engine without the assistance of a spark plug or glow plug. This makes hydrogen unsuitable for a diesel engine as a sole fuel.

B. Hydrogen use in spark ignition (SI) engines :-

Hydrogen can be used as a fuel directly in an internal combustion engine, almost similar to a spark-ignited (SI) gasoline engine. Most of the past research on H₂ as a fuel focused on its application in SI engines. Hydrogen is an excellent candidate for use in SI engines as a fuel having some unique and highly desirable properties, such as low ignition energy, and very fast flame propagation speed, wide operational range. The hydrogen fuel when mixed with air produces a combustible mixture which can be burned in a conventional spark ignition engine at an equivalence ratio below the lean flammability limit of a gasoline/air mixture. The resulting ultra lean combustion produces low flame temperatures and leads directly to lower heat transfer to the walls, higher engine efficiency and lower exhaust of NO_x emission.

Therefore, the extensive research pure H₂ as fuel has led to the development and successful marketing of hydrogen engine. For example, Ford developed P2000 hydrogen engine, which was used to power Ford's E-450 Shuttle Bus. BMW developed a 6 liter, V-12 engine using liquid H₂ as fuel. With an external mixture formation system, this engine has a power out about 170 kW and an engine torque of 340 Nm

C. Natural gas-hydrogen mixtures engines :-

Natural gas is considered to be one of the favorable fuels for engines and the natural gas fueled engine has been realized in both the spark-ignited engine and the compression-ignited engine. However, due to the slow burning velocity of natural gas and the poor lean-burn capability, the natural gas spark ignited engine has the disadvantage of large cycle-by-cycle variations and poor lean-burn capability, and these will decrease the engine power output and increase fuel consumption.

Due to these restrictions, natural gas with hydrogen for use in an internal combustion engine is an effective method to improve the burn velocity, with a laminar burning velocity of 2.9 m/s for hydrogen versus a laminar burning velocity of 0.38 m/s for methane. This can improve the cycle-by-cycle variations caused by relatively poor lean-burn capabilities of the natural gas engine. Thus, natural gas engines can reduce the exhaust emissions of the fuel, especially the methane and carbon monoxide emissions. Also, the fuel economy and thermal efficiency can also be increased by the addition of hydrogen. The thermal efficiency of hydrogen enriched natural gas is covered.

There are some challenges when it comes to using the hydrogen-natural gas mixture as a fuel. One of the biggest challenges using HCNG as a fuel for engines is determining the most suitable hydrogen/natural gas ratio. When the hydrogen fraction increases above certain extent, abnormal combustion such as pre-ignition, knock and backfire, will occur unless the spark timing and air-fuel ratio are adequately adjusted. This is due to the low quench distance and higher burning velocity of hydrogen which causes the combustion chamber walls to become hotter, which causes more heat loss

to the cooling water. With the increase of hydrogen addition, the lean operation limit extends and the maximum brake torque (MBT) decreases, which means that there are interactions among hydrogen fraction, ignition timing and excess air ratio

VII. HYDROGEN INTERNAL COMBUSTION ENGINES FUEL INDUCTION TECHNIQUES

As far as the development of a practical hydrogen engine system is concerned, the mode of fuel induction plays a very critical role. Two different fuel induction mechanisms are observed

1. Fuel Carburetion Method (CMI)
2. Direct Cylinder Injection (DI)
3. Port Injection Systems

The engine was operated using all these fuelling modes.

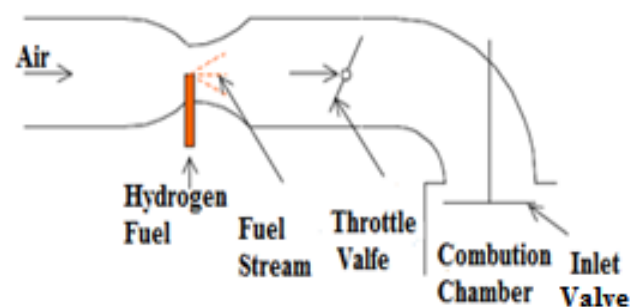
A. Fuel carburetion method (CMI) :-

Carburetion by the use of a gas carburetor has been the simplest and the oldest technique. This system has advantages for a hydrogen engine. Firstly, central injection does not require the hydrogen supply pressure to be as high as for other methods.

Secondly, central injection or carburetors are used on gasoline engines, making it easy to convert a standard gasoline engine to hydrogen or a gasoline/hydrogen engine.

The disadvantage of central injection in international combustion engine, the volume occupied by the fuel is about 1.7% of the mixture whereas a carbureted hydrogen engine, using gaseous hydrogen, results in a power output loss of 15%. Thus, carburetion is not at all suitable for hydrogen engine, because it gives rise to uncontrolled combustion at unscheduled points in the engine cycle. Also the greater amount of hydrogen/air mixture within the intake manifold compounds the effects of pre-ignition. If pre-ignition occurs while the inlet valve is open in a premixed engine, the flame can propagate past the valve and the fuel-air mix in the inlet manifold can ignite or backfire. In a carbureted hydrogen engine, a considerable portion of the inlet manifold contains a combustible fuel-air mix and extreme care must be taken to ensure that ignition of this mix does not occur. Serious damage to the engine components can result when back fire occurs [4-6].

A schematic diagram illustrating the operation of fuel carburetion method.



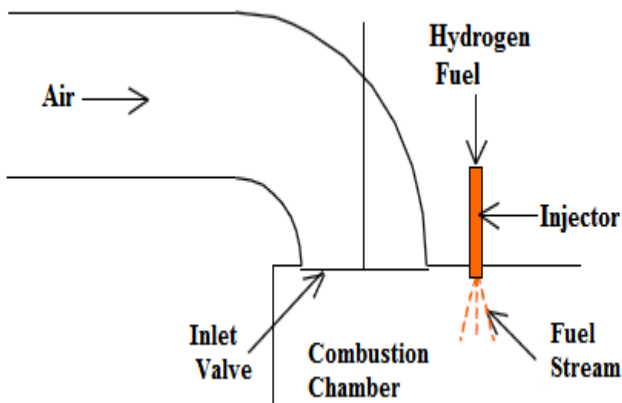
B. Direct injection systems:-

In direct in-cylinder injection, hydrogen is injected directly inside the combustion chamber with the required pressure at the end of compression stroke. As hydrogen diffuses quickly the mixing of hydrogen takes flame instantaneously. For ignition either diesel or spark plug is used as a source.

During idling or part load condition the efficiency of the engine may be reduced slightly. This method is the most efficient one compared to other methods of using hydrogen. The power output of a direct injected hydrogen engine was 20% more than for a gasoline engine and 42% more than a hydrogen engine using a carburetor. With hydrogen directly injected into the combustion chamber in a compression ignition (CI) engine, the power output would be approximately double that of the same engine operated in the pre-mixed mode. The power output of such an engine would also be higher than that of a conventionally fuelled engine since the stoichiometric heat of combustion per standard kilogram of air is higher for hydrogen (approximately 3.37 MJ for hydrogen compared with 2.83 MJ for gasoline).

While direct injection solves the problem of pre-ignition in the intake manifold, it does not necessarily prevent pre-ignition within the combustion chamber. In addition, due to the reduced mixing time of the air and fuel in a direct injection engine, the air/fuel mixture can be non-homogenous. Studies have suggested this can lead to higher NOx emissions than the non-direct injection systems. Direct injection systems require a higher fuel rail pressure than the other methods.

A schematic diagram illustrating the operation of direct injection is shown:-



Two types of injectors are available for use in D.I. systems. One is a low-pressure direct injector (LPDI) and the other one is a high pressure direct injector (HPDI). Low-pressure direct injector injects the fuel as soon as the intake valve closes when the pressure is low inside the cylinder. The high-pressure direct injector injects the fuel at the end of the compression stroke.

C. Port Injection Systems:-

The port injection fuel delivery system injects fuel directly into the intake manifold at each intake port, rather than drawing fuel in at a central point. Typically, the hydrogen is injected into the manifold after the beginning of the intake stroke. At this point conditions are much less severe and the probability for premature ignition is reduced.

In port injection, the air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool any hot spots. Since less gas (hydrogen or air) is in the manifold at any one time, any pre-ignition is less severe. The inlet supply pressure for port injection tends to be higher than for carbureted or central injection systems, but less than for direct injection systems.

The constant volume injection (CVI) system uses a mechanical cam-operated device to time the injection of the hydrogen to each cylinder. The CVI block is shown on the far right of the photo with four fuel lines exiting on left side of the block (one fuel line for each cylinder).

The electronic fuel injection (EFI) system meters the hydrogen to each cylinder. This system uses individual electronic fuel injectors (solenoid valves) for each cylinder and are plumbed to a common fuel rail located down the center of the intake manifold. Whereas the CVI system uses constant injection timing and variable fuel rail pressure, the EFI system uses variable injection timing and constant fuel rail pressure.

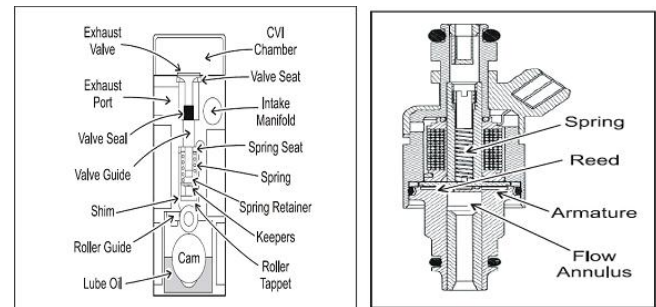
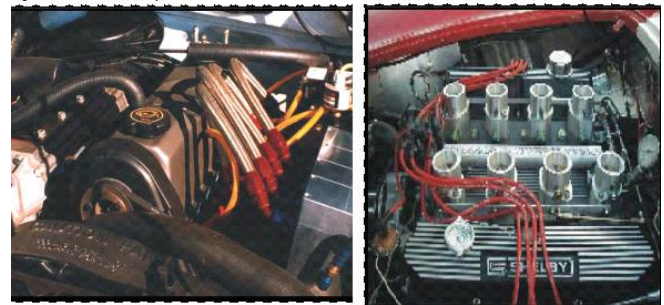


Figure 3-4 Constant Volume Injector

Electronic Fuel Injector



VIII. ENGINE DESIGN

The most effective means of controlling pre-ignition and knock is to re-design the engine for hydrogen use, specifically the combustion chamber and the cooling system.

A disk-shaped combustion chamber (with a flat piston and chamber ceiling) can be used to reduce turbulence within the chamber. The disk shape helps produce low radial and tangential velocity components and does not amplify inlet swirl during compression.

Since unburned hydrocarbons are not a concern in hydrogen engines, a large bore-to-stroke ratio can be used with this engine. To accommodate the wider range of flame speeds that occur over a greater range of equivalence ratios, two spark

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plugs are needed. The cooling system must be de-signed to provide uniform flow to all locations that need cooling.

Additional measures to decrease the probability of pre-ignition are the use of two small exhaust valves as opposed to a single large one, and the development of an effective scavenging system, that is, a means of displacing exhaust gas from the combustion chamber with fresh air.



Hydrogen Internal Combustion Engine

IX. IGNITION SYSTEMS

Due to hydrogen's low ignition energy limit, igniting hydro-gen is easy and gasoline ignition systems can be used. At very lean air/fuel ratios (130:1 to 180:1) the flame velocity is reduced considerably and the use of a dual spark plug sys-tem is preferred.

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. A cold-rated plug is one that transfers heat from the plug tip to the cylinder head quicker than a hot-rated spark plug. This means the chances of the spark plug tip igniting the air/fuel charge is reduced. Hot-rated spark plugs are designed to maintain a certain amount of heat so that carbon deposits do not accumulate. Since hydrogen does not contain carbon, hot-rated spark plugs do not serve a useful function.

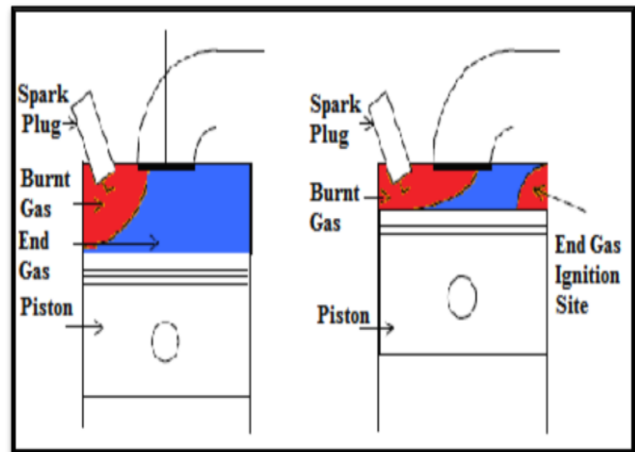
Platinum-tip spark plugs should also be avoided since platinum is a catalyst, causing hydrogen to oxidize with air.

X. AUTO-IGNITION AND KNOCK

When the end gas conditions (pressure, temperature, time) are such that the end gas spontaneously auto-ignites, there follows a rapid release of the remaining energy generating high-amplitude pressure waves, mostly referred to as engine knock.

The amplitude of the pressure waves of heavy engine knock can cause engine damage due to increased mechanical and thermal stress. The tendency of an engine to knock depends on the engine design as well as the fuel-air mixture properties .

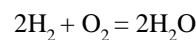
Knocking combustion is a common problem found in hydrogen-fuelled engines. It is detectable by the human ear as an audible knocking sound and by oscillations in pressure during combustion. There are many theories about how knock occurs and different types of knocking combustion have been categorized. The most common, detonation knock, describes an effect due to the self-ignition and explosion of the end gas - the unburned gas ahead of the flame.



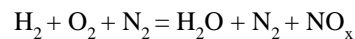
Knock - end gas ignition

XI. 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):

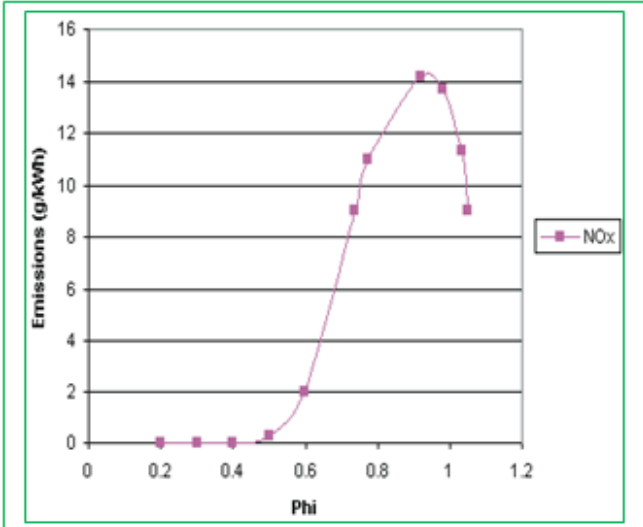


The oxides of nitrogen are created due to the high temperatures generated within the combustion chamber during combustion. This high temperature causes some of the nitrogen in the air to combine with the oxygen in the air. The amount of NO_x formed depends on:

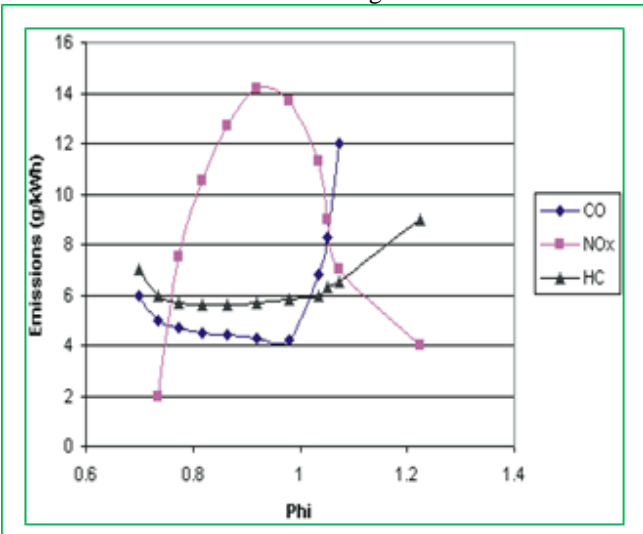
- the air/fuel ratio
- the engine compression ratio
- the engine speed
- the ignition timing
- whether thermal dilution is utilized

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 (as low as a few ppm) to high NO_x and significant carbon monoxide emissions.



Emissions For A Hydrogen Engine Emissions For A Gasoline Engine



BMW's Hydrogen-Powered Internal Combustion Vehicle
As Figure shows, the NO_x for a gasoline engine is reduced as phi decreases (similar to a hydrogen engine). However, in a gasoline engine the reduction in NO_x is compromised by an increase in carbon monoxide and hydro-carbons.

XII. CURRENT STATUS

A few auto manufacturers have been doing some work in the development of hydrogen-powered vehicles (Ford has recently announced that they have developed a "production ready" hydrogen-powered vehicle using an ICE and BMW has completed a world tour displaying a dozen or so hydro-gen-powered 750i vehicles). However, it is not likely that any hydrogen-powered vehicles will be available to the

public until there is an adequate refueling infrastructure and trained technicians to repair and maintain these vehicles.

Like current gasoline-powered vehicles, the design of each hydrogen-powered vehicle will most likely vary from manufacturer to manufacturer and model to model. One model may be simple in design and operation, for example, a lean-burning fuel metering strategy using no emission control systems such as EGR, catalytic converter, evaporate fuel canister, etc. Another model may be very sophisticated in design and operation, for example, using an EGR fuel meter-ing strategy with a catalytic converter, multiple spark plugs, etc.

Until such time that a hydrogen infrastructure exists, hydrogen/natural gas fuel blends provide a logical transition to fully hydrogen-powered vehicles. These vehicles can operate on either fuel, depending on availability.



BMW's Hydrogen-Powered Internal Combustion Vehicle

XIII. CONCLUSIONS

Hydrogen can be used in both the spark ignition as well as compression ignition engines without any major modifications in the existing systems. An appropriately designed timed manifold injection system can get rid of any undesirable combustion phenomena such as backfire and rapid rate of pressure rise.

- 1) Internal combustion engine powered vehicles can possibly operate with both petroleum products and dual-fuels with hydrogen.
- 2) Because of hydrogen has a wide range of ignition, hydrogen engine can be used without a throttle valve. By this way engine pumping losses can be reduced.
- 3) Direct injection solves the problem of pre-ignition in the intake manifold; it does not necessarily prevent pre-ignition within the combustion chamber.
- 4) An appropriate DI system design specifically on the basis of hydrogen's combustion characteristics for a particular engine configuration ensures smooth engine operational characteristics without any undesirable combustion phenomena.
- 5) Backfiring is limited to external mixture formation operation and can be successfully avoided with DI operation. Proper engine design can largely reduce the occurrence of surface ignition.

- 6) Optimizing the injection timings can also control the onset of knock during high hydrogen flow.
- 7) Hydrogen engine may achieve lean-combustion in its actual cycles.

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