Hydrogen As a Spark Ignition Engine Fuel Technical Review

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***Abstract*-- Research is essential to be carried out to find the suitable alternative fuel to meet the energy demand with minimum environmental effect, because of fast depletion of fossil fuels. In future, the alternative energy systems be cost effective, environmental free, reliable, renewable, convenient and safe. In this review, positive features and limitations of using hydrogen as Spark ignition engine fuel is discussed in detail. Hydrogen is superior in many aspects over conventional fuels and produce satisfactory performance in engine applications. To meet the current restrictive emission norms, hydrogen will be one of the most important fuel in the near future. In this analysis, hydrogen engine fundamentals are described by examining the engine specific properties of hydrogen and the existing literature are surveyed.**

***Index Term*-- Spark ignition engine, alternative fuel, hydrogen, emissions**

1 INTRODUCTION

Today world is fraught between two major crisis, one is decreasing of fossil fuels and the second one is environmental effect due to its combustion. The hydrogen fuel is the only alternative to solve this crisis. Due to high flame speed, minimum ignition energy, higher calorific value, high auto ignition temperature it may be the best alternative to be used as fuel in IC engines. The only pollution in the exhaust is oxides of nitrogen ie NO_X and it can be minimized with lean operation[4]. Various alternative fuels such as methane, hydrogen, LPG, CNG, bio gas and producer gas have been considered to be an alternative to hydrocarbon fuels, out of these fuels hydrogen is a long term renewable and less polluting one. It has clean burning and better performance characteristics and during the combustion water only (H_2O) the product with zero level of CO_2[8]. These specialities make hydrogen as an excellent fuel which meets strict environmental control of exhaust emissions (Kareem.G.A.2003). Due to the liquid film on the walls of intake manifold, normally gasoline fuels are unevenly distributed to the cylinders (Maher et al 2003). Doping of hydrogen fuel to gasoline fuel leads to good engine performance and reduced emissions (Apostolescu and chiriac 1996, May and Gwinner,1982[7]. Energetical cycle of hydrogen is shorter than energetical cycle of fossil fuels. Introducing hydrogen technology into automobile is a high cost process and many issues has to be solved. Some of the issues are[5],

- Hydrogen production process – low cost,
- Hydrogen should be stored safely in the vehicle with adequate quantity,
- Environmental effects,
- Use with high efficiency into the combustion process.

2 Properties of Hydrogen

Following table 1&2 shows that hydrogen has the characteristics of high efficiency burning rate. Since it has wide flammability limits, high burning rate, low ignition energy etc., provides the stable combustion process for lean and very lean mixtures encouraging the wide scale use as fuel for engines[5]. The table shows some of the relevant properties of hydrogen as engine fuel compared with other fuels[5,6,9].

2.1 Wide range of flammability

Safe handling of hydrogen is very important, because it has wide flammability limits (4 - 75% vs 1.4 - 2.3 % volume in air for gasoline) over other fuels. Running an engine on a lean mixture allows greater fuel economy due to complete combustion of the fuel. Due to lower combustion temperature exhaust NO_X emissions are reduced[8]. Hydrogen has remarkably wide flammable mixture range in air to permit enormously lean or rich mixtures which supports combustion[6]. Because of wider flammability range of hydrogen, facilitates ultra lean operation of engine which results the lower value of NO_X emissions and increased brake thermal efficiency[4].

2.2 Small quenching distance

It is the distance from internal cylinder wall where the flame extinguishes. Hydrogen has the quenching distance of 0.6mm where the gasoline has 2mm. Compared with other fuels, it is more difficult to quench hydrogen flame which has the tendency of backfire, since it is ready to escape through nearly closed intake valve[8]. The burning speed of hydrogen is 2.37 - 3.25 m/s which is higher than methane or gasoline at stochiometric conditions. Hydrogen flame is relatively short lived since it fires and burn quickly[4].

Table I
Comparative properties of hydrogen with other fuels

S No	Property	Hydrogen	Methane	Gasoline
1	Kinematic viscosity at 300K (mm^2/sec)	110	17.2	1.18
2	Thermal conductivity at 300K (MW/mK)	182	34	11.2
3	Diffusion coefficient into air at NTP (cm^2/s)	0.61	0.189	0.05
4	Molecular mass [kg/kmol]	2.016	16	114
5	Density (gas) at 0°C and 760 mm Hg [kg/m^3]	0.0899	0.717	5.11
6	Density (liquid) [kg/lit]	0.071	0.42	0.73
7	Octane number	› 130	› 120	90 - 98
8	Lower heating value (gas at 0°C and 760 mm Hg) (MJ/m^3)	10.22	33.95	216.38
9	Lower heating value (gas at 0°C and 760 mm Hg) (kJ/kg)	119600	53000	42690
10	Higher heating value (MJ/m^3)	12.10	37.71	233.29
11	Higher heating value (kJ/kg)	141600	52680	48290
12	Normal boil. point (K)	20.3	111.6	310 - 478
13	% age thermal energy radiated from flame to surrounding	17 - 25	23 - 33	30 - 42
14	Theoretical air fuel ratio (kg/kg comb.)	34.32	17.2	14.5

Table II
Comparative combustion Properties of hydrogen with other fuels

S No	Property	Hydrogen	Methane	Gasoline
1	Flammability limits in air at 20°C and 760 mm Hg (% by volume)	4.1 - 75.6	5.3 - 15.0	1.48 - 2.30
2	Minimum ignition energy in air (mJ)	0.017	0.30	0.2 - 0.3
3	Laminar flame speed at NTP (m/s)	1.90	0.38	0.37 - .43
4	Adiabatic flame Temperature (k)	2318	2148	2470
5	Auto ignition temperature (k)	848 - 853	813	501 - 744
6	Quenching gap at NTP (mm)	0.64	2.03	2.0
7	Stochiometric air fuel ratio (kg/kg)	34.3	17.2	15.08
8	Combustion energy/kg of stochiometric mixture (mJ)	3.37	2.56	2.79

2.3 Flame velocity

Hydrogen engines are more closely approach thermodynamically ideal cycle engine because it burns with high flame speed when stochiometric fuel mix is used. Flame speed will be reduced when engine runs with lean operation in order to obtain fuel economy. The properties like adiabatic flame temperature and flame velocity influence the engine parameters like thermal efficiency, combustion stability, emissions and etc.,[8]. The graph is plotted between adiabatic flame temperature, flame velocity with equivalence ratio as shown in the following figures 1 and 2.

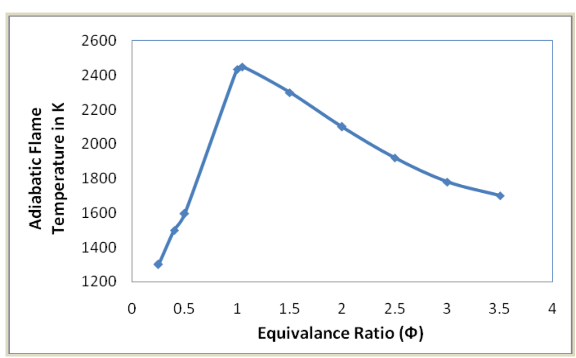

Fig. 1. Adiabatic flame temperature Vs Equivalence ratio for hydrogen - air mixture[8]

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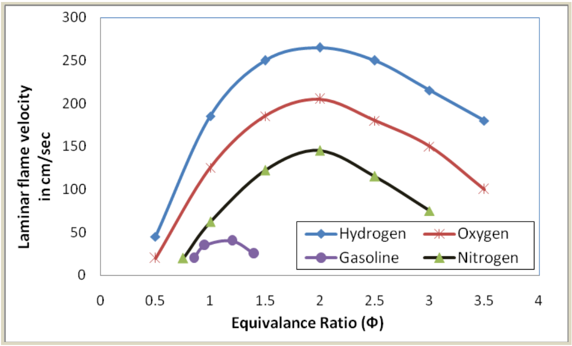

Fig. 2. Laminar flame velocity Vs equivalence ratio for hydrogen, oxygen and nitrogen mixture and gasoline, air mixture[8]

High speed operation can be achieved due to fast burning characteristics of hydrogen, which in turn increased power output with penalty of lean operation[6].

2.4 Minimum ignition source energy

It is the minimum energy required to ignite the fuel - air mixture like spark discharge. Hydrogen - air mixture requires low ignition source compared to gasoline air mixture, it requires 0.02MJ whereas gasoline mixture requires 0.24 MJ. So hot gases and hot spots in the combustion chamber act as ignition source which create premature ignition and flash back. This is explained in the following figure.

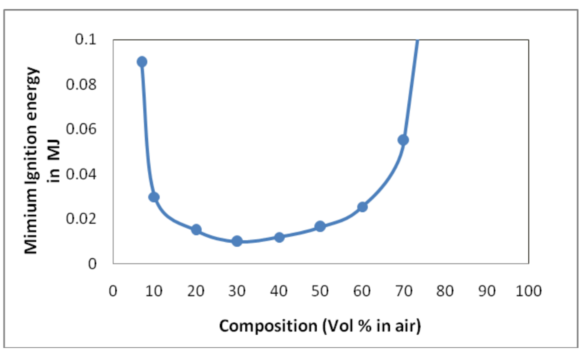

Fig. 3. Ignition source energy Vs compositition

Because of low minimum ignition source, low energy spark is required to initiate the ignition. A glow plug or resistance hot wire can initiate the combustion process[8]. As the requirement of low ignition energy hydrogen engines meet uncontrolled pre - ignition problems. Spark ignition characteristics have to be optimized in terms of energy, spark plug gap size, material, plug geometry, electrical insulation and etc.,[6].

2.5 High diffusivity

Hydrogen has very high diffusivity, its ability of disperse into air is superior than gasoline. Because of this feature it has two advantages, mixture formation is excellent and during the leakage, it quickly disperses into the air, in fact avoid and minimize the unsafe conditions[8]. The gas is highly diffusive and buoyant which make quick dispersant of fuel during leaks, reducing the fire and explosion hazards associated with hydrogen engine operation[6].

2.6 Low density

Without compressing or converting into liquid, large volume of hydrogen gas cannot be stored for automobile propulsion. This is the most important implication of hydrogen's low density. It means fuel - air mixture has low energy density which in turn power output reduces[8]. Hydrogen at 200bar, at atmospheric pressure and temperature has mainly around 5% of the energy of gasoline of the same volume. This is the major setback for transport applications. Since the density of hydrogen is lesser than air, calorific value of hydrogen - air mixture reduces. So the homogeneous mixture formation is not efficient, storage and refilling of cylinder with fresh mixture is difficult (insufficant refilling)[6].

2.7 High auto ignition temperature [AIT]

It is defined as the minimum temperature required to initiate the combustion of fuel air mixture without the aid from external ignition source. The auto ignition temperature of hydrogen fuel is 585°C and comparatively higher than other fuels. It makes difficult to ignite hydrogen - air mixture with heat alone and an external source of ignition is also required. AIT is the important factor for finout the maximum compression ratio of the engine, because temperature rise during the compression process is related to compression ratio only. Larger compression ratio can be used in hydrogen engine than hydrocarbon engine because of its high AIT[8].

3 Stochiometric air fuel ratio

The composition of air and fuel which provides the chemically precise amount of oxidant to completely burn all the fuel is known as stochiometric composition. The stochiometric combustion equation for hydrogen and air is expressed in the following steps. The actual mass ratio of air to fuel $\dot{m}_a/\dot{m}_f$ can be expressed as excess ratio – the relative amount of mass of air over that required for stochiometric combustion, given by

$$(\dot{m}_a/\dot{m}_f)_{actual} = \lambda \text{ x } (\dot{m}_a/\dot{m}_f)_s = \lambda\sigma \quad \text{--- (1)}$$

$(\dot{m}_a/\dot{m}_f)_s \rightarrow$ Stochiometric air fuel ratio (σ)

The equivalence ratio is given by

$$\Phi = \lambda^{-1} \quad \text{-------- (2)}$$

It is the relative amount of mass of fuel over that required for stochiometric combustion.

$$(\dot{m}_f/\dot{m}_a)_{actual} = \lambda \text{ x } (\dot{m}_f/\dot{m}_a)_s = \Phi \text{ x } \sigma^{-1} \quad \text{--- (3)}$$

Atmospheric air contains 20.95% O_2 and 79.05% N_2 by volume basis. Since 1 kmol of any perfect gas occupies the same volume ($22.4m^3$) this corresponds to 79.05/20.95 = 3.773 moles of N_2 per one mole of O_2 in the atmospheric air. The stochiometric combustion equation of hydrogen and oxygen is given by,

$$H_2 + 1/2(O_2 + 3.773N_2) \rightarrow H_2O + 1.886N_2 \quad \text{----- (4)}$$

Expressing the above equation by the number of moles of each species,

$$1 + 1/2(1+3.773) \rightarrow 1 + 1.887 \quad \text{-------- (5)}$$

or

$1 + 2.387 \rightarrow 1 + 1.887$ -------- (6)

So from the equation 5, we clearly understood that 2.387 moles of air is required for one mole of hydrogen to completely burn. This corresponds to a stochiometric volume percentage of hydrogen in air as (1/3.387) x 100 = 29.52%. For the mass stochoiometric air fuel ratio (Φ) express the above equation in terms of relative mass by multiplying by the molecular weights of species, for air(28.96kg/kmol), nitrogen(28.16kg/kmol) and water (18.02 kg/kmol) respectively and given as

$(1x2.016) + (2.387x28.96) \rightarrow$

$(1x18.02) + (1.887x28.16)$ ------- (7)

Dividing the above equation by 2.016

$1 + 34.29 \rightarrow 8.94 + 26.36$

So stochimetric air fuel ratio of H_2 ie Φ_{H2} = 34.29 kg of air per kg of fuel. Since the density of hydrogen is 0.09 kg/m^3 at NTP, its energy content on volume basis is low.

4 Hydrogen as a fuel

During the combustion hydrogen produces only water and it burns completely. It is a non-toxic, non- odorant matter and does not produce toxic compounds such as CO_2, CO, hydro carbons, oxides of sulphur, organic acids during the combustion except the formation of NO_X.

$2H_2 + O_2 \rightarrow 2H_2O$ ------ (6)

Due to these aspects, reasearchers are focusing their attention to use hydrogen as alternative fuel for IC engines and the important character of hydrogen is that it does not have carbon. The combustion of hydrogen differs from hydro carbon fuels, its equivalence ratio varies from 0.1-7.1, wide range of air fuel ratio can be adopted. As the minimum energy required for ignition of hydrogen - air mixture is 0.02MJ, the engines can be operated on lean mixtures and due to high flame speed (1.9m/s) high rate of cylinder pressure rise reached. Larger compression ratio can be allowed in engine because it has higher self ignition temperature compared with other fuels. Ignition process carried out by compression alone is not possible, some sources of ignition can be provided in the combustion chamber in order to obtaining prompt ignition[8]. Investigation by C.A.Maccarley et. al prove that chances of back fire can be minimized by using direct injection of hydrogen fuel into the cylinder. By experiment, timed manifold injection is best suited for reducing the back fire and obtain smooth engine operation. It improves the thermal efficiency and reduces NO_x level for neat hydrogen operation[4]. The low boiling temperature of hydrogen leads to cold weather operational problems. It has high octane number because of its high burning rates. Due to fast burning characteristics, hydrogen is more amenable for high speed engine operation[6]. On volume basis the least amount of air is required for stochiometric combustion (2.39 moles), where as iso - octane requires 59.6 moles and on mass basis hydrogen requires highest amount of air (34.3 kg of air / kg of fuel). Its heating value is high on mass basis where is low on volume basis and energy released by combustion per unit mass of stochiometric mixture is one of the highest. Hydrogen engine produces low power output due to lower heating value on volume basis which induces lean mixture operation. High amount of decibels and vibrations occur due to high rate of pressure rise from fast burning flame. A hydrogen engine requires 40 - 50% larger in size of gasoline engine for obtaining the same power output. In order to avoid pre - ignition and back firing, direct injection into the cylinder is preferable, water injection also may be provided [9].

5 Hydrogen as a SI engine fuel

Hydrogen is an excellent fuel for SI engine due to some unique and desirable properties like fast flame propagation speed, low ignition energy and wide operational range. The hydrogen fuel and air mixed and form combustable mixture which can be burn in conventional SI engine with an equivalence ratio less than gasoline air mixture. The lean combustion produces low flame temperature which induces lower heat transfer to cylinder walls, higher thermal efficiency and lower NO_X emissions[8]. When compared to other fuels, it has wide temperature range and pressure range with very high propogation rates. These propogation rates are sufficiently high even at lean operation. The associated energy release is so fast, hence the combustion duration tends to be short[6] as in the following figure.

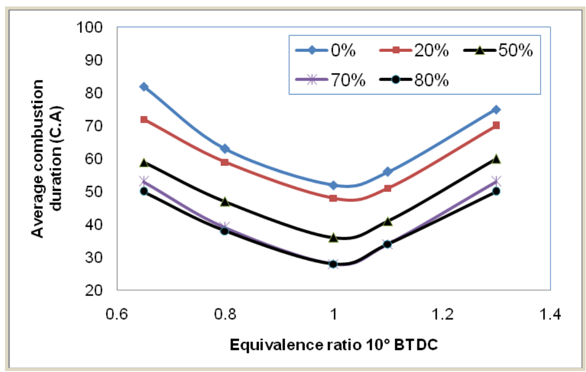

Fig. 4. typical variations in combustion duration with equivalence ratio

The lean operation limit of hydrogen fueled engine is very less compared with other fuels and is explained in the following figure for the range of compression ratios.

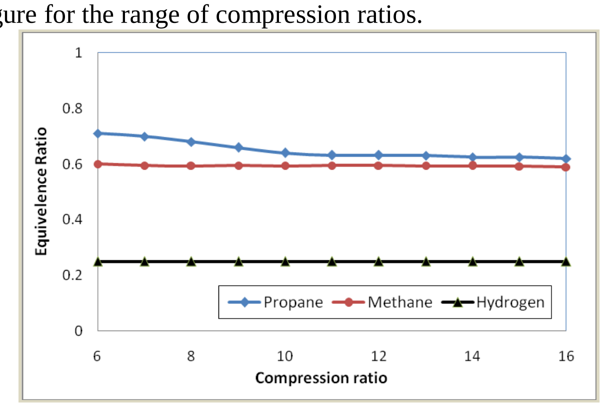

Fig. 5. Lean operation limit over various compression ratio's for different fuels at 900 RPM[6].

Hydrogen engines are associated with less undesirable emissions compared with engines operated on other fuels. There are no unburnt hydrocarbons, oxides of sulphur, carbon di oxide, carbon monoxide, smoke and particulate present in the exhaust. Hydrogen has high octane number over other fuels because of its high propagation ratios. It can be excellent additive with small range to fuels like methane. Higher compression ratio is possible with lean operation, which in turn get higher power output and thermal efficiency and is shown in the following figure 6a and 6b respectively.

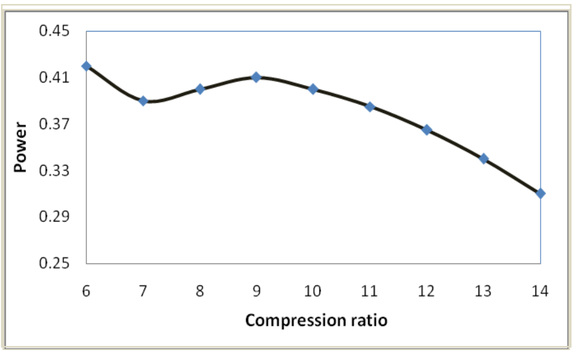

Fig. 6a. Typical variations in power output for various compression ratios [6]

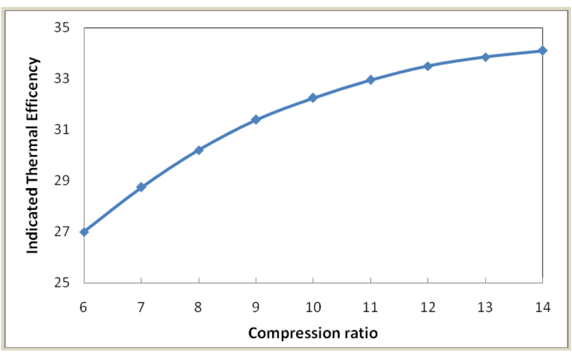

Fig. 6b. Typical variations in indicated thermal efficiency for various compression ratios[6]

When operating the engine with hydrogen, an operation range of equivalence ratio is identified for safe and stable process free from undesirable combustion phenomena. This technical review indicates that from the hydrogen engine the major pollutants come out is NO_X only. Definitely the NO_X emission from hydrogen engine is higher than gasoline engine because of its high self ignition temperature. As a result of higher combustion temperatures, the NO_X emissions are delivered when the engine is operated at or near the stochiometric fuel air ratio's. When the combustion temperature is reduced, then NO_X and fuel-air ratio was reduced which dilutes the combustion products with air. To control the NO_X level, equivalence ratio plays a significant role. It has been observed that when the engine is operated with an equivalence ratio of 0.6, the NO_X emission delivered is too low[φ=0.6]. It is concluded that hydrogen can be used in existing SI engine without doing major modifications. Higher brake thermal efficiency and improved combustion are obtained due to its higher burning velocity. The hydrocarbon and carbon monoxide emissions are almost negligible, but traces of these emissions are found out due to evaporation and burning of lubricating oil film on the cylinder walls[4]. Especially at part load operation, hydrogen engine efficiency is superior to gasoline engine due to better combustion aspects. In order to reduce NO_X emission the methods like cooled EGR, usage of catalytic converters may be adopted. The provision of direct fuel injection at the beginning of compression stroke, engine runs without abnormal combustion phenomena. The power output by using direct fuel injection technique is nearly 30% higher than conventional engine due to avoiding of inlet air quantity reduction[5]. Hydrogen is an excellent additive to methane or gasoline due to its some unique characteristics. It is capable of burn ultra lean at an equivalence ratio of 0.1. The fuels like gasoline and methane are not capable of burn less than the equivalence ratio of 0.7 & 0.53. Hydrogen mass lower heating value is three times than gasoline or methane, but on volume basis its LHV is lower than gasoline (or) methane due to low density[9].

6 Fuel Induction Techniques

In the development of hydrogen engine system, the fuel induction technique plays the major role for optimizing the fuel economy and power output. Three fuel induction mechanisms are observed in the literature. They are,

1. Direct in Cylinder Injection [DCI] or [DI]
2. Inlet Manifold and Port Injection
3. Fuel Carburetion Method [FCM] or [CMI]

6.1 Direct in cylinder injection

In this type, hydrogen is directly injected in to the combustion chamber at required pressure at the end of compression stroke. Since the hydrogen diffuses quickly, the mixing of it takes flame instantaneously and spark plug is used as source. In manifold injection power drop may occur and this will be completely eliminated in DCI system. The efficiency of engine can be slightly reduced during idling condition. This method is the most efficient one compare with other induction methods. 20% of more power will be reached by using this method over gasoline engine, also 42% of power is increased over carburetion system using hydrogen. Direct injection solve the problem of pre - ignition in the intake manifold, does not necessarily control the pre-ignition in the combustion chamber. Air - fuel mixture will be non - homogenous because of reduced time of mixing of hydrogen with air in DCI method. The following figure illustrates the working principle of DCI method[8].

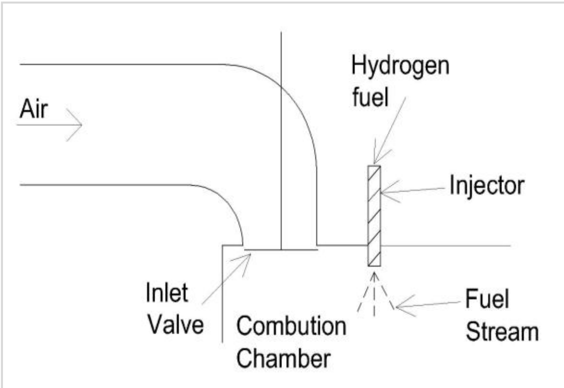

Fig. 7. Direct in cylinder injection[8]

6.2 Inlet manifold and port injection

In this type hydrogen fuel is injected into the manifold directly by mechanical or electrical operated injectors after the beginning of intake stroke. To operate under high speed conditions and regulate the injection timing and injection duration electronic injectors are preferred.

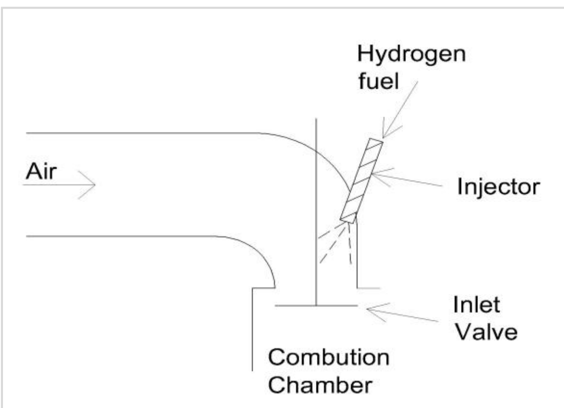

Fig. 8. Inlet manifold injection[8]

In this type air is seperatly injected at the beginning of intake stroke in order to dilute the hot residual gases and cool the hot spots of the combustion chamber. Since less gas is available at any one time pre-ignition is less severe[8]. In this method inlet supply pressure is less than direct induction system and higher than carbureted system[8]. The schematic layout of this method is shown in the above figure.

6.3 Fuel carburetion method

This is the oldest induction method, which uses gas carburetor. Central injection doesn't require as high pressure as the other methods. By using this method the conventional engine can be easily modified into the hydrogen engine or gasoline - hydrogen engine. Carburetion is not at all suitable for hydrogen engine, it gives rise to uncontrolled combustion at unscheduled points in the engine cycle. The greater amount of hydrogen air mixture within the manifold promotes the pre - ignition. If pre - ignition occurs in a pre mixed engine when inlet valve opens, the flame can propagate and past the valve and fuel air mix in the manifold can ignite or back fire takes place. In this induction type, always the possibility of considerable hydrogen air mixture present in intake manifold and extreme care should be taken that this mixture should not ignite. When backfire occurs, engine components may seriously affected. The following figure illustrates the working principle of fuel carburetion method.

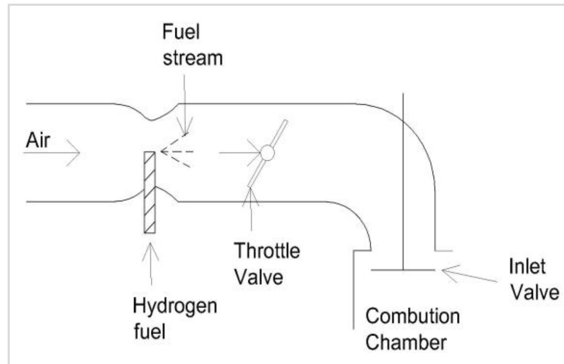

Fig. 9. Fuel carburetion method

7 Abnormal Combustion

Undesired combustion occur in hydrogen engine due to wide flammability limits, low ignition energy and high flame speeds. In fact these properties make hydrogen as a desirable fuel as well as induces abnormal combustion and the suppression of abnormal combustion is the difficult task in hydrogen engines. Steps has to be taken to avoid this which have important implications for engine design, mixture formation and load control. Three regions of abnormal combustion exist in spark ignition engines, ie pre - ignition, back fire and the knock[8]. Logically the method used for hydrogen fuel in IC engine is similar to other gaseous fuels by considering some issues. Due to large flammability limits, low ignition energy of hydrogen - air mixture intake misfire or pre - ignition develops, in turn higher cylinder pressure followed by negative effects of engine performance such as brutal running, power and efficiency drop occurs. It is important to take special precautions to eliminate the mentioned problems. Steps has to be taken for design modification in cylinder head, valve, ignition system, piston and piston rings to eliminate the uncontrolled ignition. Direct injection of hydrogen into the combustion chamber at the beginning of compression stroke eliminate the chances of abnormal combustion[5]. Hydrogen engines are prone to produce excess high cylinder pressure which follows knock as shown in the following figure10. While operating near the stochiometric mixture range, hydrogen engines produce higher cylinder pressure and temperature which in turn delivers high output of oxides of nitrogen. Due to high rate of pressure rise resulting from fast burning engine operation may be associated with increased noise and vibrations. Material compatibility problem with hydrogen should be avoided[6].

7.1 Pre - ignition

Because of low ignition energy and wide flammability limit of hydrogen, pre - ignition is often happened in the hydrogen engines. When hydrogen - air mixture approaches stoichiomtric level, pre ignition is more pronounced. Also increased engine speed, engine load are more prone to the formation of pre - ignition due to higher gas and component temperatures.

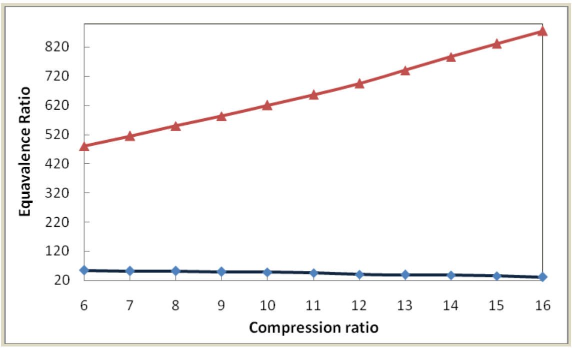

Fig. 10. Variations of operational limits for ignition and knock with compression ratio changes for hydrogen operation[6]

8 Conclusions

- Without any major modifications in the existing system hydrogen can be used in both SI and CI engines. Internal combustion engine powered vehicles can possibly operate with both petroleum products and dual - fuels with hydrogen.
- Direct injection system solve the problem of pre - ignition in the intake manifold, not necessary to prevent the pre - ignition inside the combustion chamber.
- Hydrogen engines can be operated without the throttle valve since it is having wide range of ignition, ultimately pumping losses may be reduced.
- In external mixture formation process back firing is possible and can be avoided in DCI operation, optimizing the injection timing is the best way of controlling the knock.
- In its actual cycle, hydrogen engine may achieve lean combustion[8]. In its lean mixture operation NO_X level is much lesser than gasoline engine. The exhaust gases does not contain CO_2, CO, lead components and particles, but traces of the CO and HC emission is there because of evaporation and burning of lubricating oil film on the cylinder walls[4].
- Excellent scope is there to promote satisfactory SI engine operation with hydrogen as the fuel[6]. Specifically at part load operating conditions, hydrogen engine efficiency is superior to gasoline engine due to better combustion aspects.
- If we inject the hydrogen at the beginning of compression stroke by using DCI technique, engine runs at stochiometric range without abnormal combustion phenomena's. 20% power rise occur in hydrogen DCI system over gasoline engine due to avoiding of inlet air quantity reduction.
- Due to its properties, hydrogen has proved to be an excellent fuel for IC engines and signifies a reliable option to the fossil fuels replacement[5].
- The power loss of hydrogen operated engine is compensated by using super charging and it is more effective than gasoline, iso - octane and methane fuelled engines for the same operating conditions[7].

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