Available online at www.academicpaper.org

Academic @ Paper

International Journal of Automotive Engineering and Technologies
Vol. 1, Issue 1, pp. 1 – 15, 2012

International Journal of Automotive Engineering and Technologies

http://www.academicpaper.org/index.php/IJAET

HYDROGEN USE IN INTERNAL COMBUSTION ENGINE: A REVIEW

Murat CİNİVİZ[1], Hüseyin KÖSE[1*]

[1]Technical Education Faculty, Mechanical Education Department, Selçuk University, 42003 Konya, Turkey

Accepted 14 July, 2011

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 paper contemporary research on the hydrogen-fueled 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.

Keywords: Internal combustion engine, hydrogen, emissions, alternative fuel

* Corresponding author

Tel.: +90 332 223 33 39; fax: +90 332 241 21 79.

E-mail address: huseyin@selcuk.edu.tr (H. Köse).

1. 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 [1]. 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 CO_2. Although NO_x emissions are formed when hydrogen is used [2,7].

1.1. Combustive Properties of Hydrogen

There are several important characteristics of hydrogen that greatly influence the technological development of hydrogen internal combustion engine.

1.1.1. Wide range of flammability

Compared to nearly all other fuels, hydrogen has a wide flammability range (4-75% versus 1.4-7.6% volume in air for gasoline). This first leads to obvious concerns over the safe handling of hydrogen. But, it also implies that a wide range of fuel-air mixtures, including a lean mix of fuel to air, or, in other words, a fuel-air mix in which the amount of fuel is less than the stoichiometric, or chemically ideal, amount. Running an engine on a lean mix generally allows for greater fuel economy due to a more complete combustion of the fuel. In addition, it also allows for a lower combustion temperature, lowering emissions of criteria pollutants such as nitrous oxides (NO_x) [3].

1.1.2. Small quenching distance

Hydrogen has a small quenching distance (0.6 mm for hydrogen versus 2.0 mm for gasoline), which refers to the distance from the internal cylinder wall where the combustion flame extinguishes. This implies that it is more difficult to quench a hydrogen flame than the flame of most other fuels, which can increase backfire since the flame from a hydrogen-air mixture more readily passes a nearly closed intake valve, than a hydrocarbon-air flame [3, 17].

1.1.3. Flame velocity and adiabatic flame

Hydrogen burns with a high flame speed, allowing for hydrogen engines to more closely approach the thermodynamically ideal engine cycle (most efficient fuel power ratio) when the stoichiometric fuel mix is used. However, when the engine is running lean to improve fuel economy, flame speed slows significantly [3].

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, are shown in **Fig. 1.** and **Fig 2.**, respectively.

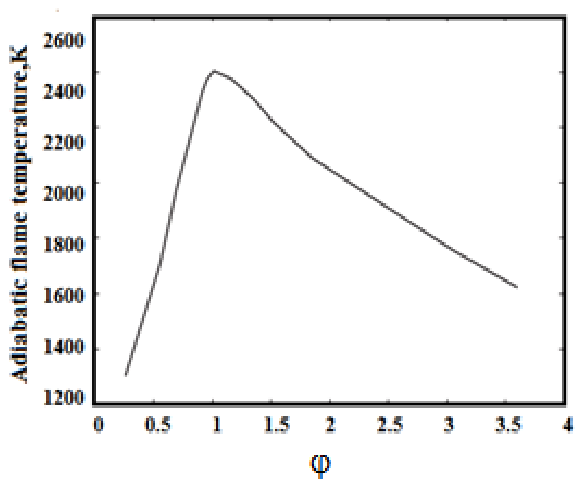

Fig. 1. Adiabatic flame temperature for hydrogen-air mixtures [5].

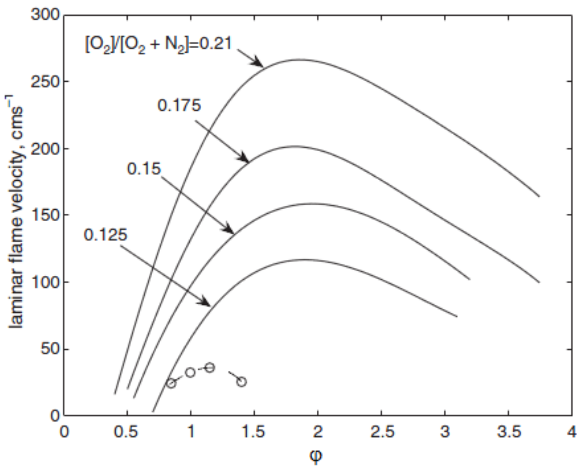

Fig.2. Laminar flame velocity for (—) hydrogen, oxygen and nitrogen mixtures and (◦, - -) gasoline and air mixtures [5].

1.1.4. 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 a hydrogen and air mix it is about an order of magnitude lower than that of a petrol-air mix 0.02 mJ as compared to 0.24 mJ for petrol - and is approximately constant over the range of flammability. This is illustrated in **Fig 3**. Unfortunately, the low ignition energy means that hot gases and hot spots on the cylinder can serve as sources of ignition, creating problems of premature ignition and flashback [4,17].

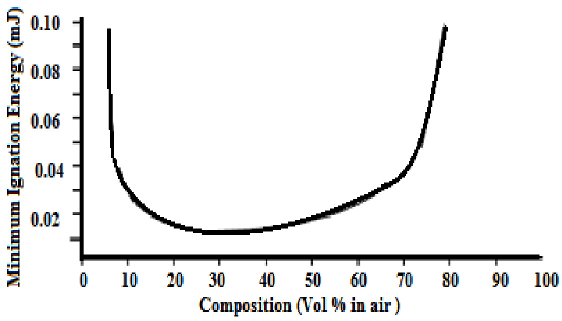

Fig. 3. Minimum ignition energy of hydrogen in air [4]

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.

1.1.5. High diffusivity

Hydrogen has very high diffusivity. This ability to disperse into 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 [6].

1.1.6. Low density

The most important implication of hydrogen's low density is that without significant compression or conversion of hydrogen to a liquid, a very large volume may be necessary to store enough hydrogen to provide an adequate driving range. Low density also implies that the fuel-air mixture has low energy density, which tends to reduce the power output of the engine. Thus when a hydrogen engine is run lean, issues with inadequate power may arise [3].

1.1.7. High auto-ignition temperature

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 585ºC. This makes it difficult of 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 the compression ratio [26].

Table 1. Comparison of hydrogen with other fuels [26]

Fuel	LHV (MJ/kg)	HHV (MJ/kg)	Stoichiometric Air/FuelRatio (kg)	Combustible Range (%)	Flame Temp(°C)	Min. Ignition Energy (MJ)	Auto Ignitin Temp. (°C)
Methne	50.0	55.5	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	15.1	0.31	0.95-6	1980	0.26	415
Methanol	18.0	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

The temperature may not exceed hydrogen's auto ignition temperature without causing premature ignition. Thus, the absolute final temperature limits the compression ratio. The high auto ignition temperature of hydrogen allows larger compression ratios to be used in a hydrogen engine than in a hydrocarbon engine [6].

1.2.8. Stoichiometric air-fuel ratio and mixture energy content

The stoichiometric composition of fuel and air is that which provides the chemically precise amount of oxidant to completely burn all the fuel. For hydrogen and oxygen the stoichiometric combustion equation expressed per mole of fuel is expressing equation 3. The calculation of the volumetric composition and mass stoichiometric air-fuel ratio (σ), is given below. The actual mass ratio of air to fuel, m_a/m_f, can be expressed as where is called the air excess ratio - the relative amount of mass of air over that required for stoichiometric combustion.

$$(m_a/m_f)_{actual} = \lambda\ (m_a/m_f)_s = \lambda.\sigma \qquad (1)$$

Another commonly used term is the equivalence ratio, denoted φ:

$$\varphi=\lambda^{-1} \qquad (2)$$

The equivalence ratio is the relative amount of mass of fuel over that required for stoichiometric combustion;

$$(mf/ma)\ actual = \lambda\ (mf/ma)_s = \varphi.\ \sigma^{-1} \qquad (3)$$

Atmospheric air contains 20.95% O_2 and 79.05% atmospheric nitrogen N_2 by volume. On a molar 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 mole of O_2 in atmospheric air. Thus the stoichiometric combustion equation for hydrogen and atmospheric air is;

$$H_2 + \tfrac{1}{2}(O_2 + 3.773N_2 \rightarrow H_2O + 1.887N_2 \qquad (4)$$

Expressing Equation 2 in numbers of moles of each species;

$$1 + \tfrac{1}{2}(1 + 3.773 \rightarrow 1 + 1.887 \text{ or } 1 + 2.387 \rightarrow 1 + 1.887 \qquad (5)$$

Thus 2.387 moles of air per mole of H_2 are required to completely burn all the fuel. This corresponds to a stoichiometric volume percent of hydrogen in air of;

$100/3.387 = 29.52\%$

For the mass stoichiometric air-fuel ratio, φ, express the above equation in terms of relative mass, by multiplying by the molecular weight of the species - for atmospheric air, water and atmospheric nitrogen, the molecular weights, M, are 28.96, 18.02 and 28.16 kg/kmol respectively giving;

$$(1 \bullet 2.01) + (2.38 \bullet 28.96) \rightarrow (1 \bullet 18.02) + (1.88 \bullet 28.16)$$

Per kg of fuel divide through by 2.016

$$1 + 34.3 \rightarrow 8.94 + 26.35$$

The stoichiometric air-fuel ratio is thus φ_{H2} = 34.3 kg air per kg fuel. It can be similarly shown that for petrol, the stoichiometric volume percent of fuel in air is 1.76%, and σ_{petrol} = 14.6.

Comparison of the stoichiometric volume composition of hydrogen and petrol (29.52% and 1.76% respectively) leads to comparison of the energy content of the fuel-air mix. The density of hydrogen is just 0.09 kg/m^3 at normal temperature and pressure, so despite its lower heating value Q_{LHV} being 120 MJ/kg compared to petrol's 44 MJ/kg, its energy content on a volume basis is lower [4].

1.2. 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 [7]. When hydrogen is burned, hydrogen combustion does not produce toxic products such as hydrocarbons, carbon monoxide, and oxide of sulfur, organic acids or carbon dioxides shown in Eq. (6), except for the formation of NO_x [8].

$$2H_2 + O_2 = 2H_2O \tag{6}$$

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 [9]. 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 [10]. 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/m^3, 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 cm^2/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 [9]. 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 [11].

Table 2. Properties of hydrogen [10]

Properties	Diesel	Unleaded gasoline	Hydrogen
Formula	C*n*H1.8*n* C_8–C_{20}	C*n*H1.87*n* C_4–C_{12}	— H_2
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 valve (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	—

1.3. Hydrogen Use in International Combustion Engine

1.3.1. 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 [13]. 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 [14]. 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 [25].Hence hydrogen cannot CI engine without the assistance of a spark plug or glow plug. This makes hydrogen unsuitable for a diesel engine as a sole fuel. Because of this reason of the reported literature, activities on hydrogen fuelling of a diesel engine were based on dual-fuel mode. In a dual fuel engine the main fuel is inducted/carbureted or injected into the intake air while combustion is initiated by diesel fuel that acts as an ignition source. The pilot fuel quantity may be in the range of 10–30% while the rest of the energy is supplied by the main fuel. Hydrogen operated dual fuel engine has the characteristics to operate at leaner equivalence ratios at part loads, which results in NO_x reduction, and increase in thermal efficiency thereby reducing the fuel consumption. Oxides of nitrogen (NO_x) are the major problem in hydrogen operated dual fuel engine [14]. One method that has been used to successfully reduce NO_x emissions is exhaust gas recirculation (EGR). EGR is very effective in reducing NO_x emissions due to the dilution effect of, where the oxygen concentration of the intake charge is reduced. In addition, volumetric efficiency reductions with increasing EGR rates are significant (reductions of about 15% compared with hydrogen dual-fuel operation without EGR are recorded). At the same time, EGR addition to hydrogen dual-fuel operation can increase particulate emissions compared with hydrogen dual-fuel operation without EGR. As a result, hydrogen dual-fuel operation with EGR produces smoke levels similar to normal CI engine operation. In addition to reducing NO_x, increases in unburned HC, CO and CO_2 emissions with EGR addition are also recorded. Another method of is introducing liquid water into the combustion chamber. Water injection can also prevent knocking and pre-ignition during hydrogen combustion. Here water acts in a similar manner to diluents such as EGR, cooling the charge and reducing the combustion rate. However, water injected into the intake manifold reduces volumetric efficiency [15].

Conventional diesel engines can be converted to operate on hydrogen–diesel dual mode with up to about 38% of full-load energy substitution without any sacrifice on the performance parameters such as power and efficiency [16].

1.3.2. 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 H_2 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 [17-18-26].

Therefore, the extensive research pure H_2 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 H_2 as fuel. With an external mixture formation system, this engine has a power out about 170 kW and an engine torque of 340 Nm [17].

1.3.3. 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. [19]. 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 [27].

1.4. 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. Three different fuel induction mechanisms are observed in the literature [16].

1. Fuel Carburetion Method (CMI)
2. Inlet Manifold and Inlet Port Injection
3. Direct Cylinder Injection (DI)

The engine was operated using all these fuelling modes.

1.4.1. 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 is shown in **Figure 4.**

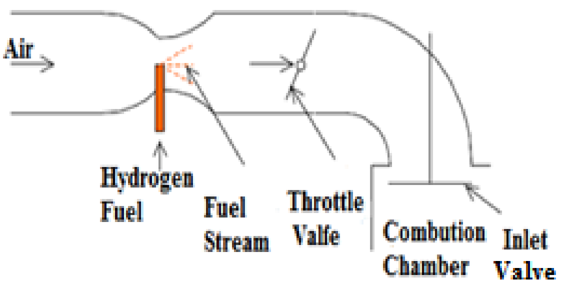

Fig.4. Fuel carburetion method [4]

1.4.2. Inlet manifold and inlet port injection

The port injection fuel delivery system injects fuel directly into the intake manifold at each intake port by using mechanically or electronically operated injector, rather than drawing fuel in at a central point. Typically, the hydrogen is injected into the manifold after the beginning of the intake stroke. Electronic injectors are robust in design with a greater control over the injection timing and injection duration with quicker response to operate under high speed conditions. 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 [14]. 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 [6]. A schematic diagram illustrating the operation of inlet port injection is shown in **Figure 5**.

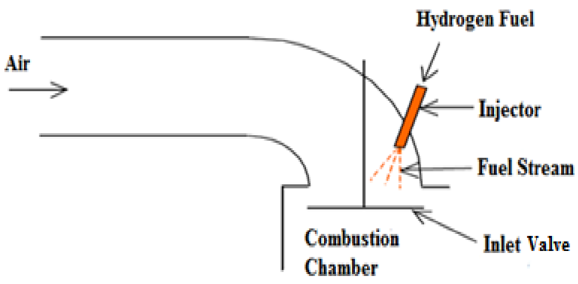

Fig.5. Inlet manifold and inlet port injection [4]

Inlet manifold or port injection methods of fuel induction, the inducted volume of air per cycle is kept constant and the power output can be controlled by the amount of fuel injected into the air stream, thus allowing lean operation. The fuel can either be metered by varying the injection pressure of the hydrogen, or by changing the injection duration by controlling the signal pulse to the injector [4].

1.4.3. 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. The problem of drop in power output in manifold induction/injection can be completely eliminated by in-cylinder ignition. 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 [12]. 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 [20]. A schematic diagram illustrating the operation of direct injection is shown in **Figure 6**.

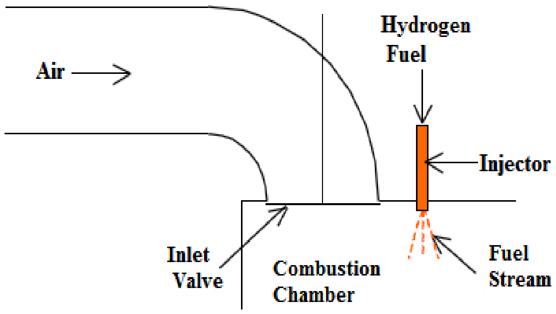

Fig.6. Direct injection system [4]

1.4.4. Injector specifications

A fuel injection system performs two basic functions: fuel pressurization and fuel metering. When dealing with gaseous fuels, only the metering function is required to be carried out by the injection system as the pressurization is performed separately [12]. Many different types of injector have been used in both inlet manifold and direct cylinder injection hydrogen internal combustion engines. As has already been indicated, the design of inlet manifold or inlet port injectors is less challenging as lower injection pressures are required. For direct cylinder injectors, not only must the design accommodate for higher injection pressure against the cylinder pressure, but the equipment must also be capable of withstanding the hostile environment of the combustion chamber [4]. Lubrication between the injector moving parts also makes the design of direct injector more complicated. Typical injector construction is illustrated in **Figure 7.**

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 [14].

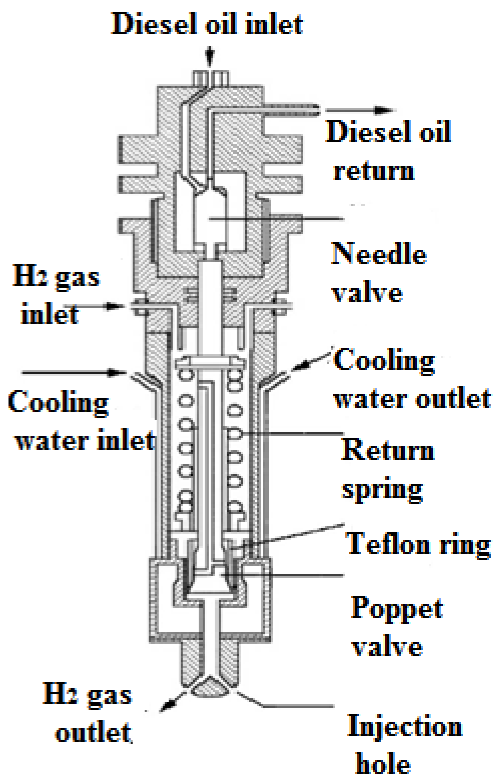

Fig.7. Hydrogen injector [21]

1.5. Abnormal combustion

The same properties that make hydrogen such a desirable fuel for internal combustion engines also bear responsibility for abnormal combustion events associated with hydrogen. In particular, the wide flammability limits, low required ignition energy and high flame speeds can result in undesired combustion phenomena generally summarized as combustion anomalies.

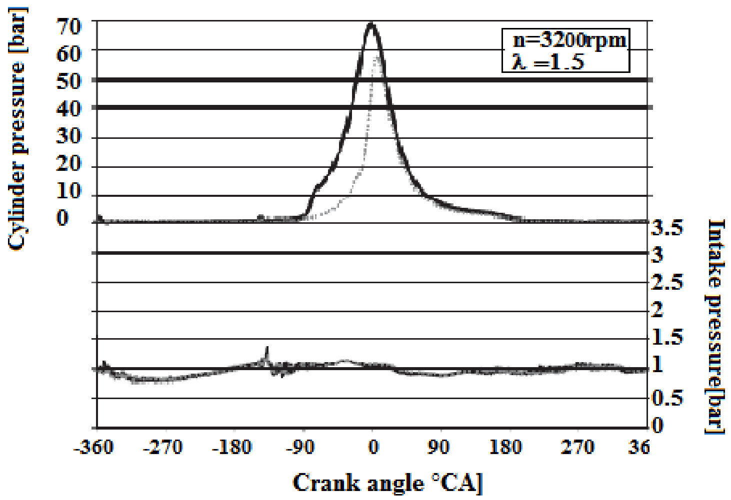

Fig.8. Typical cylinder and intake manifold pressure traces with pre-ignition (solid lines), compared to regular pressure traces (dotted lines) [22]

These anomalies include surface ignition and backfiring as well as auto ignition [22].The suppression of abnormal combustion in hydrogen has proven to be quite a challenge and measures taken to avoid abnormal combustion have important implications for engine design, mixture formation, and load control. For SI engines, three regimes of abnormal combustion exist: knock (auto-ignition of the end gas region), pre-ignition (uncontrolled ignition induced by a hot spot, premature back flash, flashback, and induction ignition; this is a premature ignition during the intake stroke, which could be seen as an early form of pre-ignition) and backfire. [23].

1.5.1. Pre-ignition

Pre-ignition is often encountered hydrogen engines because of the low ignition energy and wide flammability limits of hydrogen. As a premature ignition causes the mixture to burn mostly during the compression stroke, the temperature in the combustion chamber rises, which causes the hot spot that led to the pre-ignition to increase in temperature, resulting in another earlier pre-ignition in the next cycle [23]. This advancement of the pre-ignition continues until it occurs during the intake stroke and causes backfire. Due to the dependence of minimum ignition energy on the equivalence ratio, pre-ignition is more pronounced when the hydrogen–air mixtures approach stoichiometric levels. Also, operating conditions at increased engine speed and engine load are more prone to the occurrence of pre-ignition due to higher gas and component temperatures

Fig.8 shows the in-cylinder pressure trace as well as the crank angle resolved intake manifold pressure for a combustion cycle in which pre-ignition occurred. A regular combustion event is shown for comparison. The data were taken on an automotive-size single cylinder hydrogen research engine at an engine speed of 3200 RPM and an IMEP of 7 bars for the regular combustion case (dotted line). It is interesting to note that the peak pressure for the pre-ignition case is higher than the regular combustion cycle. However, due to the early pressure rise that starts around 80 °CA BTDC, the indicated mean effective pressure for the pre-ignition case is around 0 bars. The intake pressure trace for the pre-ignition case does not show any significant difference from the regular trace, because the pre-ignition occurred after the intake valves closed [22].

1.5.2. Backfire

Backfire is a violent consequence of the pre-ignition phenomena. Should pre-ignition occur at a point when the inlet valve is open, the enflamed charge can travel past the valve and into the inlet manifold, resulting in backfire. This problem is particularly dangerous in pre-mixed fuel inducted engines where there is the possibility that an ignitable fuel-air mix is present in the inlet manifold [4]. The main difference between backfiring and pre-ignition is the timing at which the anomaly occurs. Pre-ignition takes place during the compression stroke with the intake valves already closed whereas backfiring occurs with the intake valves open. This result in combustion and pressure rise in the intake manifold, which is not only clearly audible but can also damage or destroy the intake system. Due to the lower ignition energy, the occurrence of backfiring is more likely when mixtures approach stoichiometric. Because most operation strategies with hydrogen DI start injection after the intake valves close, the occurrence of backfiring is generally limited to external mixture formation concepts.

Limited information available on combustion anomalies also indicates that pre-ignition and backfiring are closely related with pre-ignition as the predecessor for the occurrence of backfiring. Pre-ignition thereby heats up the combustion chamber, which ultimately leads to backfiring in a consecutive cycle. Consequently, any measures that help avoid pre-ignition also reduce the risk of backfiring. Another work has been done on optimizing the intake design and injection strategy to avoid backfiring. Although trends identified on hydrogen research engines indicated that combustion anomalies significantly limit the operation regime, optimization of the fuel-injection strategy in combination with variable valve timing for both intake and exhaust valves [24].

3.4.3. 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 [24].

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. This is illustrated in **Figure 9.**

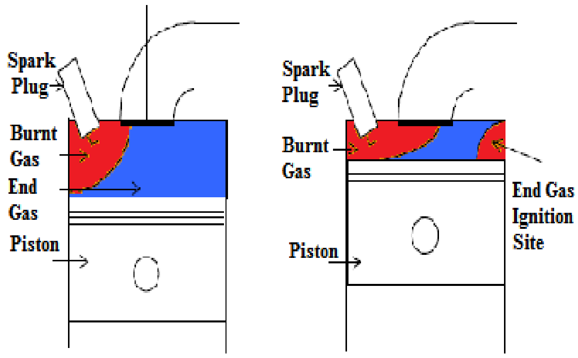

Fig.9. Knock - end gas ignition [24].

3.5. Emissions

The combustion of hydrogen with oxygen produces water as its only product:

$$2H_2 + O_2 = 2H_2O$$

The combustion of hydrogen with air however can also pro-duce oxides of nitrogen (NO_x):

$$2H_2 + O_2 + N_2 \rightarrow H_2O + N_2 + NO_x \qquad (7)$$

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 NO_x, traces of carbon monoxide and carbon dioxide can be present in the exhaust gas, due to fast 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.

Figure 10 illustrates a typically NO_x curve relative to phi (φ) for a hydrogen engine. A similar graph including other emissions is shown in **Figure 11** for gasoline.

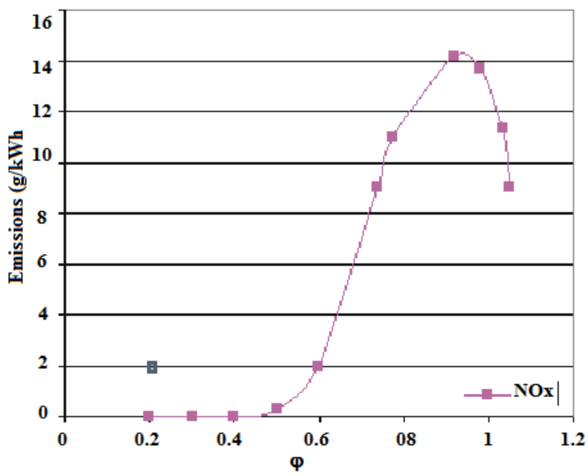

Fig.10. Emissions for a hydrogen engine [6].

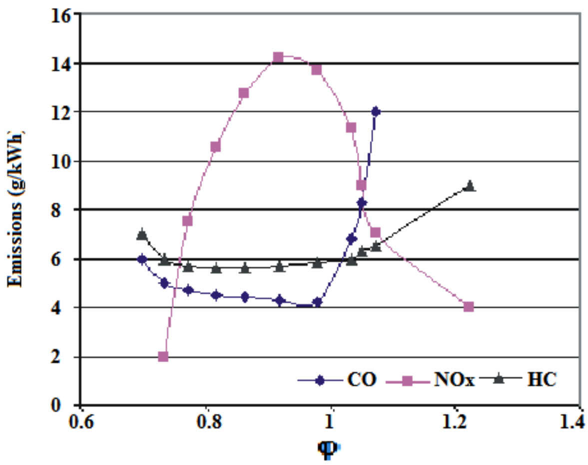

Fig.11. Emissions for a gasoline engine [6].

As Figure 10 shows, the NO_x for a gasoline engine is reduced as phi(φ) 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.

3.6. Power Output

The theoretical maximum power of a hydrogen engine depends on the air/fuel ratio and fuel injection method**.** Stoichiometric air/fuel ratio for hydrogen is 34:1. At this air/fuel ratio, hydrogen will displace 29% of the combustion chamber leaving only 71% for the air. As a result, the energy content of this mixture will be less than it would be if the fuel were gasoline (since gasoline is a liquid, it only occupies a very small volume of the combustion chamber, and thus allows more air to enter)

Since both the carbureted and port injection methods mix the fuel and air prior to it entering the combustion chamber, these systems limit the maximum theoretical power obtain-able to approximately 85% of that of gasoline engines. For direct injection systems, which mix the fuel with the air after the intake valve has closed (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 dangerous pollutant. Since one of the reasons for using hydrogen is low exhaust emissions, hydrogen engines are not normally designed to run at a stoichiometric air/fuel ratio [6].

3.7. 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.

- Internal combustion engine powered vehicles can possibly operate with both petroleum products and dual-fuels with hydrogen.
- 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.
- Direct injection solves the problem of pre-ignition in the intake manifold; it does not necessarily prevent pre-ignition within the combustion chamber.
- 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.
- 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.
- Optimizing the injection timings can also control the onset of knock during high hydrogen flow.
- Hydrogen engine may achieve lean-combustion in its actual cycles.

References

1. Antunes Gomes M J., Mikalsen R., Roskilly A.P., An investigation of hydrogen-fuelled HCCI engine performance and operation, International Journal of Hydrogen Energy, Volume 33, Pages 5823–5828, 2008.

2. Saravanan N., Nagarajan G., Sanjay G., Dhanasekaran C., Kalaiselvan M. K., Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode, Fuel, Volume 87, Pages 3591-3599,2008

3. Gillingham K., Hydrogen Internal Combustion Engine Vehicles: A Prudent Intermediate Step or a Step in the Wrong Direction?, Department of Management Science & Engineering Global Climate and Energy Project, *Precourt Institute for Energy Efficiency*, Stanford University, Pages 1-28, 2007

4. Overend E., Hydrogen Combustion Engines, The Unıversıty Of Edınburgh, *School of Mechanical Engineering*,Pages 1-77,1999

5. White M. C., Steeper R.R., Lutz E. A., The hydrogen-fueled internal combustion engine: a technical review, International Journal of Hydrogen Energy Volume 31, Pages 1292-1305, 2006.
6. COD (College of the Desert), Hydrogen fuel cell engines and related technologies course manual, Module 3: Hydrogen use in internal combustion engines, Pages 1-29, 2001.
7. Saravanan N., Nagarajan G., Sanjay G., Dhanasekaran C., Kalaiselvan K.M., An experimental investigation on hydrogen as a dual fuel for diesel engine system with exhaust gas recirculation technique, Renewable Energy,Volume 33, Pages 422-427, 2008,
8. Bose Kumar Probir, Maji Dines, An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation, International Journal of Hydrogen Energy, Volume 34, Pages 4847-4854, 2009,
9. Saravanan N., Nagarajan G., Performance and emission study in manifold hydrogen injection with diesel as an ignition source for different start of injection, Renewable Energy, Volume 34, Pages 328-334, 2009.

10. Saravanan N., Nagarajan G., Sanjay G., Dhanasekaran C., Kalaiselvan K.M., Experimental investigation of hydrogen port fuel injection in DI diesel engine, International Journal of Hydrogen Energy Volume 32, Pages 4071-4080, 2007.
11. Bose Kumar Probir, Maji Dines, An experimental investigation on engine performance and emissions of a single cylinder diesel engine using hydrogen as inducted fuel and diesel as injected fuel with exhaust gas recirculation, International Journal of Hydrogen Energy, Volume 34, Pages 4847-4854, 2009
12. Antunes Gomes. M.J ., Mikalsen R., Roskilly A.P, An experimental study of a direct injection compression ignition hydrogen engine, International Journal Of Hydrogen Energy, Volume 34, Issue 15, Pages 6516-6522, 2009.
13. Szwaja S, Grab-Rogalinski K., Hydrogen combustion in a compression ignition diesel engine, International Journal of Hydrogen Energy, Volume 34, Pages 4413-4421,2009
14. Saravanan N., Nagarajan G., 2010, Performance and emission studies on port injection of hydrogen with varied flow rates with Diesel as an ignition source, Applied Energy Volume 87,Pages 2218-2229
15. Korakianitis T., Namasivayam M A., Crookes J. R., Hydrogen dual-fuelling of compression ignition engines with emulsified biodiesel as pilot fuel, International Journal Of Hydrogen Energy, Volume 35, Pages 13329-13344
16. Das M. L., Hydrogen engine: research and development (R&D) programmers in Indian Institute of Technology (IIT), Delhi, International Journal of Hydrogen Energy, Volume 27, Pages 953-965, 2002
17. Wahab Abd Bın Aswad M., Addition of hydrogen to gasoline-fuelled 4 stroke SI engine using 1-dımensıonal analysis, *Faculty of Mechanical Engineering University* Malaysia Pahang, Pages 1-68, 2009
18. Abdelghaffar A. W., Spark Ignition Engine Fueled by Hydrogen: Comparative Analysis, European Journal of Scientific Research, Volume 44, Pages 13-28, 2010
19. Huang Z., Wang J., Liu B., Zeng K., Yu J., Jiang D., Combustion Characteristics of a Direct-Injection Engine Fueled with Natural Gas-Hydrogen Mixtures, Energy & Fuels Volume 20, Pages 540-546, 2006.
20. Masood M., Ishrat M.M, Reddy S. A., Computational combustion and emission analysis of hydrogen–diesel blends with experimental verification, International Journal of Hydrogen Energy Volume 32, Pages 2539- 2547, 2007
21. Kim Y.Y., Lee T J., Choi H. G., An investigation on the causes of cycle variation in direct injection hydrogen fueled engines, International Journal of Hydrogen Energy Volume 30, Pages 69-76, 2005.
22. Verhelst S., Wallner T., Hydrogen-fueled internal combustion engines, Progress in Energy and Combustion Science, Volume 35,Pages 490-527, 2009.
23. Verhelst S., Verstraeten S., Sierens R., A comprehensive overview of hydrogen engine design features, J. Automobile Volume 221,Pages 911-920, 2005.
24. Verhelst S., Wallner T., Hydrogen-fueled internal combustion engines, Department of Flow, Heat and Combustion Mechanics, Ghent University, Sint-Pietersnieuwstraat, Belgium,Pages 1-80, 2009.
25. Saravanan N., Nagarajan G., Sanjay G., Dhanasekaran C., Kalaiselvan M. K., Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode, Fuel, Volume 87, Pages 3591-3599, 2008.
26. Gupta B. R, Hydrogen fuel production, transport and storage, CRC Press, ISBN 978-1-4200-4575-8, Pages 1-603.2008

27. Fanhua M., Nashay N., Mingyue W. Long J., Renzhe C. and Shuli Z., Hydrogen-enriched compressed natural gas as a fuel for engines, Natural Gas, ISBN 978-953-307-112-1, Pages 307-332, 2010