Performance Evaluation of Hydrogen Fuelled Spark Ignition Engine: A Review

Rushikesh Mahandule, Srikanth Karankoti, Sanjay Patil

Abstract—Fast depletion of fossil fuels fuels is demanding an urgent need of alternative fuels for meeting sustainable energy demand with minimum environmental impact. A lot of research is being carried throughout the world to evaluate the performance, exhaust emission and combustion characteristics of the existing engines using several alternative fuels such as hydrogen, compressed natural gas (CNG), alcohols, liquefied petroleum gas (LPG), biogas, producer gas, bio-diesels, and others. Expert studies indicate hydrogen as one of the most promising and advantageous energy carriers for the future due to its superior combustion qualities and availability. Hydrogen is the lightest and most abundant element on the earth. Hydrogen is always found in combined form in the nature. It has some unique properties which allow it to be used as a fuel. Hydrogen fuel burns completely with zero carbon emission and it is highly flammable. Hydrogen fuel can be implemented as a renewable energy medium with immense potential. When utilized properly, it has the potential to entirely replace fossil fuels. This paper provides a comprehensive overview of hydrogen as a fuel for Spark Ignition (SI) internal combustion engine. Paper aims to study introduction to hydrogen, its basic properties, flexibility of hydrogen as a fuel for SI engine, performance and emissions of hydrogen fuel operated SI engine.

Index Terms— Combustion Properties, Diffusivity, Emissions, Flammability, Ignition Energy, Performance Properties, Quenching Distance

1 Introduction

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

Direct combustion of conventional fossil fuels has been used for centuries and has been refined considerably in recent years due to increasingly stringent pollutant emissions limits and higher-efficiency requirements brought on by recent fuel shortages. As will be described in greater detail in the following sections, recent research indicates that while some technical challenges exist, H2 can be successfully burned in conventional combustion systems with minimal design changes. In particular, with regard to systems based on dilute premix combustion technology, the unique characteristics of H2 offer several advantages over conventional hydrocarbon fuels [1].

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2 Hydrogen As A Combustible Fuel

The use of hydrogen in IC engines may be part of an integrated solution to the problem of depletion of fossil fuels and pollution of the environment. Today, the infrastructure and technological advancement in engines can be useful in the insertion of hydrogen as a fuel.

Hydrogen has a high flammability range when compared with all other fuels. Because of this property, hydrogen can be combusted in an internal combustion engine over a wide range of fuel-air mixtures. Hydrogen has very low ignition energy. A benefit of this is that hydrogen can run on a lean mixture and ensures prompt ignition. Generally, fuel economy is greater and the combustion reaction is more complete when an IC engine runs on a lean mixture. But, the low ignition energy means that hot gases and hot spots in the cylinder can serve as sources of ignition, creating problems of premature ignition. Preventing this is one of the challenges associated with running an engine on hydrogen [2].

The high flame speed of hydrogen, hydrogen engine is much closer to the ideal constant volume combustion than a gasoline engine which produces the reduced exhaust losses and increased engine thermal efficiency [3]. Auto ignition temperature of hydrogen is very high. This means that hydrogen is most suitable as a fuel for spark ignition (SI) engines and it is very difficult to ignite hydrogen just by the compression process.

The high diffusion speed of hydrogen also improves the homogeneity in the cylinder mixture that helps the fuel be completely burnt [4]. Since the flame speed of hydrogen is about five times as large as that of gasoline, spark timing should be adopted for hydrogen engines to ensure its power output and prevent knock [5]. However, due to the high adiabatic flame temperature of hydrogen, at a specified excess air ratio, NOx emissions from hydrogen engines are generally much higher than those from gasoline engines, which limit the wide commercialization of the pure hydrogen-fueled engines to some extent [6]. Besides, the production and storage of hydrogen are still costly at present, which are also the barriers for the pure hydrogen engines to be commercialized in the near future.

The energy density of hydrogen on a mass basis is higher than that of gasoline. However, since hydrogen is very light, the energy density of hydrogen on a volume basis is only 10.8 MJ/m3, which may lead to a reduced power output for hydrogen engines at stoichiometry conditions, compared with gasoline engines [7].

3 Combustion Properties of Hydrogen

3.1 Wide Range of Flammability

It can be observed that the flammability limits are very wide for hydrogen (between 4-75 % hydrogen in the mixture) compared to gasoline (between 1-7.6 %). This means that the load of the engine can be controlled by the air to fuel ratio, as for diesel engines. Nearly all the time the engine can be run with a wide open throttle, resulting in a higher efficiency.

3.2 Low Ignition Energy

Hydrogen has very low ignition energy. The amount of energy needed to ignite hydrogen is about one order of magnitude less than that required for gasoline. This enables hydrogen engines to ignite lean mixtures and ensures prompt ignition.

3.3 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.

3.4 High Auto ignition Temperature

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.

3.5 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.

3.6 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 [8].

3.7 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 hydrogen air mixture, and hence the power output, is reduced.

Hydrogen is an odorless, colorless gas with molecular weight of 2.016 and it is the lightest element. Its density is about 14 times less than air (0.08376 kg/m3 at standard temperature and pressure). Hydrogen is liquid at temperatures below 20.3 K (at atmospheric pressure). Hydrogen has the highest energy content per unit mass of all fuels – higher heating value is 141.9 MJ/kg, almost three times higher than gasoline [9].

4 Performance Characteristics of Hydrogen Fuelled SI Engine

The properties of hydrogen, in particular its wide flammability limits, make it an ideal fuel to combine with other fuels and thereby improve their combustion properties. There are different ways to use hydrogen as a fuel; it can be used as an additive in a hydrocarbon mixture, or as an only fuel, in the presence of air.

The use of the hydrogen as a fuel in the engines has been studied by different authors in the last decade with several degrees of success. However, these reports are not necessarily consistent among several researchers. The tendency in this type of reports is focused on the results obtained for specific engines under very narrow operation conditions, and also made emphasis on the emissions and considerations of efficiency. It should be taken into account what has been achieved in this field, focused on the attractive features as in the limitations associated with the disadvantages that are needed to overcome the hydrogen broadly acceptable as a fuel for engines.

TABLE 1
Properties of Hydrogen Compared With Methane And Iso-Octane. Data Given At 300K And 1 Atm. [7]

Property	Hydrogen	Methane	Iso-octane
Molecular weight (g/mol)	2.016	16.043	114.236
Density(kg/m3)	0.08	0.65	692
Mass diffusivity in air(cm2/s)	0.61	0.16	~0.07
Minimum ignition energy(mJ)	0.02	0.28	0.28
Minimum quenching distance(mm)	0.64	2.03	3.5
Flammability limit	4.75	5-15	1.1-6

in air (vol %)			
Flammability limit(λ)	10-0.14	2-0.6	1.51-0.26
Flammability limit(ψ)	0.1-7.1	0.5-1.67	0.66-3.85
Lower heating value(MJ/Kg)	120	50	44.3
Auto-ignition temperature in air(K)	858	723	550
Flame velocity(m/s)	1.85	0.38	0.37-0.43
Higher heating value(MJ/Kg)	142	55.5	47.8
Stoichiometric air-to-fuel ratio(kg/kg)	34.2	17.1	15
Stoichiometric air-to-fuel ratio(kmol/kmol)	2.387	9.547	59.666

TABLE 2
MIXTURE PROPERTIES OF HYDROGEN-AIR, METHANE AIR AND ISOOCTANE-AIR

DATA GIVEN AT 300 K AND 1 ATM (WITH THE EXCEPTION OF THE LAMINAR BURNING VELOCITY, GIVEN AT 360 K AND 1 ATM) [10]

Property	H2-Air	CH4-Air	C8H18-Air
Volume fraction fuel (%)	29.5	9.5	1.65
Mixture density(kg/m3)	0.85	1.123	1.229
Kinematic Viscosity(mm2/s)	21.6	16	15.2
Auto ignition temperature(K)	858	813	690
Adiabatic Flame Temperature(K)	2390	2226	2276
Thermal Diffusivity(mm2/s)	42.1	20.1	18.3
Thermal conductivity (W/mK)	4.97	2.42	2.36
Ration of specific heat	1.401	1.354	1.389
Speed of sound(m/s)	408.6	353.9	334
Air to fuel ratio(kg/kg)	34.2	17.1	15.1
Mole ratio before and after combustion	0.86	1.01	1.07
Laminar burning velocity,~360K (cm/s)	290	48	45
Gravimetric energy content(KJ/kg)	3758	3028	3013
Volumetric energy content(KJ/m3)	3189	3041	3704

It is also necessary to indicate the practical steps to incorporate the different experimental condition in the existent commercial engines to operate with hydrogen gas. White et al, [11] were made a technical revision of the internal combustion engines operated with hydrogen; their work was an emphasis in the use of hydrogen/gas mixtures with light and heavy load in order to reduce the bad combustion engines. Also, they reported the effect of variation in the concentration of the mixture hydrogen/air versus the emissions of NOx.

M.A Escalante Soberanis, A.M Fernandez also carried out a technical revision on internal combustion engine run with hydrogen fuel. They reported the thermal efficiency of an engine fueled with hydrogen can overcome to that achieved with a gasoline engine (38.9% with hydrogen and 25% with gasoline). The power output of an engine fueled with hydrogen has reached, in laboratory tests, an 80% of that reached by a gasoline engine [12].

Hariganesh R. et al, in the Madras Institute of Technology, a comparison study between gasoline and hydrogen as fuels was made [13]. For this purpose, a single cylinder spark ignition engine was adapted to be fueled with hydrogen by injection in the intake manifold. The results of unburnt hydrocarbons emissions showed that, using hydrogen as a fuel, the levels were near zero, while with gasoline emissions wee very high, at different requirements of power output. The specific fuel consumption, working with hydrogen, is less than the half than that of gasoline, due to the low energy density of hydrogen. For the case of nitric oxides emissions, it was reported higher levels in hydrogen combustion. The emissions of the first mixture were about 8000 ppm at an equivalence ratio of 0.85, while for gasoline it was reported 2000 ppm at an equivalence ratio of 1.03, approximately. The minimum ignition energy and the wide range of flammability of hydrogen allow the presence of combustion at lower equivalence ratios than those with gasoline, and it can obtain a higher power at specific equivalence ratios. The high power output of the engine, running with hydrogen, was about 80% of the power reached with gasoline. Hydrogen engine recorded higher volumetric efficiency, compared with that of gasoline, with a power output between 2 and 7 kW, was observed. In the case of thermal efficiency, it reached a maximum of about 27%, at different speeds, over that with gasoline which is about 25%.

Erol Kahraman et al [14] experimentally investigated a conventional four cylinder spark ignition engine operated on hydrogen and gasoline. The compressed hydrogen at 20 MPa has been introduced to the engine adopted to operate on gaseous hydrogen by external mixing. In order to prevent backfire, they were installed the mixer between the carburetor body and inlet manifold at an engine speed above 2600 rpm. Specific features of the use of hydrogen as an engine fuel have been analyzed. The test results have been demonstrated that power loss occurs at low speed hydrogen operation whereas high speed characteristics compete well with the gasoline operation. But, fast burning characteristics of hydrogen permit high speed engine operation. This allows an increase in power output and efficiencies, relatively. NOx emission of hydrogen fueled engine is about 10 times lower than gasoline fueled engine. The slight traces of CO and HC emissions presented at hydrogen fueled engine are due to the evaporating and burning of lubricating oil film on the cylinder walls. Short time of combustion produces a lower exhaust gas temperature for hydrogen. They also suggested that appropriate changes in the combustion chamber together with a better cooling mechanism would increase the possibility.

5 Emission Characteristics of Hydrogen Fuelled SI Engine

In recent years, the internal combustion engine powered vehicles have been criticized for their role in environmental pollution through exhaust emissions of mainly the oxides of nitrogen (NOx), carbon monoxide (CO), and unburned hydrocarbons (UBHC). Hydrogen is considered to be clean and efficient alternative fuel among the available. Like electricity, hydrogen is an energy carrier not an energy source. Many scientists have worked both experimentally and analytically with internal combustion engine with hydrogen as fuel. Some of those literatures related to hydrogen are discussed with respect to hydrogen fueled spark ignition engine.

A primary advantage of hydrogen over other fuels is that its only major oxidation product is water vapor. The hydrogen is the most abundant material in the universe and during its combustion with air does not produce significant amounts of carbon monoxide (CO), hydrocarbon (HC), smoke, oxides of sulfur (SOx), leads or other toxic metals, sulfuric acid deposition, ozone and other oxidants, benzene and other carcinogenic compounds, carbon dioxide (CO2), formaldehyde and other greenhouse gases. The only undesirable emission is nitric oxide (NO) and nitrogen dioxide (NO2), which are oxides of nitrogen (NOx) which can collect and avoid their emission to the atmosphere.

Erol Kahraman [14] studied the performance and emission characteristics of hydrogen fueled spark ignition engine. The compressed hydrogen at 20 MPa has been introduced to the engine adopted to operate on gaseous hydrogen by external mixing. Two regulators have been used to drop the pressure first to 300 kPa, then to atmospheric pressure. The experiments were carried out on a four-cylinder, four stroke spark ignition engine with carburetor as the fuel induction mechanism. The variations of torque, power, brake thermal efficiency, brake mean effective pressure, exhaust gas temperature, and emissions of NOx, CO, CO2, HC, and O2 versus engine speed are compared for a carbureted SI engine operating on gasoline and hydrogen. He found that NOx emission of hydrogen fueled engine is about 10 times lower than gasoline fueled engines.

Additionally, Nagalingam [15] reported measurements on a single-cylinder hydrogen engine equipped with a supercharger and an exhaust gas recirculation (EGR) system. The results showing NOx levels below 100 ppm for equivalence ratios less than 0.4 when operating at supercharged intake pressures of 2.6 bar. Using EGR combined with supercharging and a three-way catalyst (TWC) is shown to significantly increase the power output while limiting tailpipe emissions of oxides of nitrogen (NOx).

6 Conclusion

The use of hydrogen in internal combustion engines may be part of an integrated solution to the problem of depletion of fossil fuels and pollution of the environment. Today, the infrastructure and technological advancement in engines can be useful in the insertion of hydrogen as a fuel. There are good prospects for increased efficiencies, high power density, and reduced emissions with hybridization, multi-mode operating strategies, and advancements in ICE design and materials.

The hydrogen infrastructure at the time is not in place to supply hydrogen demands, but with more development using hydrogen as a fuel will motivate the development of the infrastructure.

Acknowledgment

It gives immense pleasure to present research paper on "Performance Characteristics of a Hydrogen Fueled Spark Ignition Engine: A Review". It becomes our duty to express gratitude towards Dr. Sanjay Patil for being a constant source of help and guidance. His timely suggestions made it possible for us to complete satisfactory work on time.

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