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Performance, Emission and Fuel Induction System of Hydrogen Fuel Operated Spark Ignition Engine - A Review

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ABSTRACT

Fast depletion of fossil fuels and their detrimental effect to the environment 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 is one of the most promising energy carriers for the future due to its superior combustion qualities and availability.

This paper provides a comprehensive overview of hydrogen as a fuel for Spark Ignition (SI) internal combustion engine. Discussed topics are introduction to hydrogen, its basic properties, flexibility of hydrogen as a fuel for SI engine, performance and emissions of hydrogen fuel operated SI engine. Also it includes the most significant advances and developments made on the technical adaptations in the SI engine which operate with hydrogen. Finally, it describes the best design of the fuel induction system for SI engines when they are fed with hydrogen.

***Keywords* – Autoignition, Combustion, Flammability, Knocking**

1. INTRODUCTION

Hydrogen shows considerable promise as a primary energy carrier in the future. First, it can be produced directly from all primary energy sources, enabling energy feedstock diversity for the transportation sector. These alternative energy resources include wind, solar power, and biomass (plant material), which are all renewable fuel sources. Electricity produced from nuclear fission, or fusion, has also been mentioned with increasing frequency as a possible source of hydrogen (H_2) production through electrolysis of water or thermo chemical cycles. A major benefit of increased H_2 usage for power generation and transportation is that all of these sources minimize our dependence on non-renewable fossil fuels and diversify our energy supply for utilization in end-use energy sectors. Alternatively, H_2 can be produced through coal gasification, or by “steam reforming” of natural gas (NG), both of which are non-renewable fossil fuels but are abundantly available throughout the world. Combining the latter technologies with carbon capture and storage (CCS) would provide a significant increase in sources same time eliminating green--house gas emissions. Second, since all conventional fossil fuels contain carbon atoms in addition to hydrogen atoms, carbon dioxide (CO_2) is a major product gas formed during the conversion of the fuel to energy. The release of stored chemical energy in H_2 of useful heat produces only water as a product, thus eliminating CO_2, a significant contributor to climate change as a significant greenhouse gas. The concept of H_2 as an energy carrier is often discussed. This concept can best be described in the context of H_2 produced directly from water using electrolysis. While this process is not economically attractive at current costs, if the electricity required to convert H_2O to H_2 is provided by wind or solar power, then the H_2 is produced without creating any CO_2. Given the intermittent nature of wind and solar power sources, the surplus energy produced during the very windy or bright sunny days could be used to produce H_2 that is stored for later use. Under these conditions the stored H_2 becomes an energy carrier that can be used later to produce power where it is needed, either in conjunction with a fuel cell to produce electricity or in a combustor to produce power (internal combustion engine (ICE) or turbine). It should be noted that there are many different ways to produce H_2 from a primary energy feedstock which are usually much more efficient than simple electrolysis, but this serves as a good example of how one might store energy in hydrogen as a carrier for use later. The energy stored in hydrogen can be converted to useful energy through either fuel cells to directly produce electricity or combustion to produce power. However, much more work is needed to improve fuel cells cost effectiveness for everyday use in the general population. For example, fuel cells were recently estimated to be ten times more expensive to produce than a power-comparable ICE.

Another energy conversion technology that is also well proven is combustion. 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, H_2 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 H_2

offer several advantages over conventional hydrocarbon fuels [1].

II. HYDROGEN AS A COMBUSTIBLE FUEL

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 advances in matters of engines can be useful in the insertion of hydrogen as a fuel.

Hydrogen has a wide flammability range in comparison with all other fuels. As a result, hydrogen can be combusted in an internal combustion engine over a wide range of fuel-air mixtures. Hydrogen has very low ignition energy. A significant advantage 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. Unfortunately, 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]. Autoignition 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 of in the cylinder mixture which helps the fuel be completely burnt [4]. Since the flame speed of hydrogen is about five times as large as that of gasoline, retarded spark timing should be adopted for hydrogen engines to ensure its power output and prevent knock [5]-[6]. However, due to the high adiabatic flame temperature of hydrogen, at a specified excess air ratio, NO_x 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 [7]-[8]. 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/m^3, which may lead to a reduced power output for hydrogen engines at stoichiometry conditions, compared with gasoline engines [9].

III. PERFORMANCE CHARACTERISTICS OF HYDROGEN FUELED 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 [10]-[11]-[12]. 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
Physical Properties of Hydrogen compared to Gasoline and Methane

Property	Hydrogen	Gasoline	Methane
Chemical farmula	H_2	C_8H_{18}	CH_4
Flammability limits (Φ)	0.1–7.1	0.7–4	0.4–1.6
Minimum ignition energy (mJ)	0.02	0.25	0.28
Laminar flame speed at NTP (m/s)	1.90	0.37–0.43	0.38
Adiabatic flame temp (K)	2318	2470	2190
Auto ignition temperature (K)	858	500–750	813
Quenching distance at NTP (mm)	0.64	2.0	2.03
Density at 1 atm and 300 K (kg/m^3)	0.082	730	0.651
Stoichiometric composition in air (% by volume)	29.53	1.65	9.48
Stoichiometric fuel/air mass ratio	0.029	0.0664	0.058
High heating value (MJ/kg)	141.7	48.29	52.68
Low heating value (MJ/kg)	119.7	44.79	46.72
Combustion energy per kg of stoich. mixt. (MJ)	3.37	2.79	2.56
Kinematic viscosity at 300 K (mm^2/s)	110	1.18	17.2
Diffusion coefficient into air at NTP (cm^2/s)	0.61	0.05	0.189

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, [13] were made a technical revision of the internal combustion engines operate 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 report the effect of variation in the concentration of the mixture hydrogen/air versus the emissions of NO_x.

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 [14].

Hariganesh R et al, In the Madras Institute of Technology, a comparison study between gasoline and hydrogen as fuels was made [15]. 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 UHC emissions showed that, using hydrogen as a fuel, the levels were near zero, while with gasoline it would maintain over the 2500 rpm, 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%.

S. Verhelst et al, conducted experiments on a Volvo four cylinder sixteen valve gasoline engine with a total swept volume of 1783 cc and a compression ratio of 10.3:1 with some modifications [16]. Their results are presented of the brake thermal efficiency of a bi-fuel hydrogen/gasoline engine, at several engine speeds and loads. They revealed that the efficiencies of both gasoline and hydrogen can be seen to increase as the delivered torque increases. As a result of the increasing torque, the mechanical efficiency increases strongly. For gasoline, the flow losses across the throttle valve increase because of the larger flow, although this is slightly compensated by a larger throttle position (TP). The increase in mechanical efficiency is clearly the dominating effect. In the case of hydrogen, the flow losses have decreased because of a smaller air flow since more air is displaced by hydrogen as a result of the rich mixture. This also leads to a decreased influence of the engine speed on the hydrogen break thermal efficiency (BTEs) too rich with backfire as a consequence. They investigated from their experiment that at low loads (torque outputs of 20Nm) the brake thermal efficiency of hydrogen is (much) higher than on gasoline, the hydrogen BTEs are 40–60% higher relative to the gasoline BTEs. This difference is due to the absence of throttling losses and the lean mixtures of hydrogen. The higher burning velocity of hydrogen is also a contributing factor, as this leads to a more isochoric combustion. The BTE on hydrogen at high speed about 4500 rpm (throttle position for gasoline and H_2TP = 50%, torque output 40 Nm) is about 18% higher relative to gasoline. This difference is not entirely down to a difference in burning velocity however as hydrogen displaces more air due to its low density, throttling losses are lower even though the throttle position is identical, as the lower air flow results in lower flow losses. The gasoline BTE can be seen to be relatively insensitive to the engine speed. For hydrogen, the BTE decreases with engine speed, although the decrease is less pronounced in the wide open throttle (WOT) case. Two effects explain this behavior: first, due to the lean burn operation and large throttle openings, the air flow is much higher in the hydrogen case than for gasoline. This leads to higher flow losses in the intake manifold. For the throttled case, the flow losses include pumping losses so in this case, the BTE is lower and decreases more strongly with engine speed.

Intake-air pressure-boosting (supercharging or turbo charging) is an effective and proven strategy for increasing peak engine power in conventional petroleum-fueled IC engines. For hydrogen engines, pressure-boosting is likely necessary to achieve power densities comparable to petroleum- fueled IC engines. Early work testing boosted hydrogen engine has been carried out by many researchers such as Nagalingam et al [17], Furuhama, Fukuma [18] and Lynch [19]. Nagalingam et al, worked with a single-cylinder research engine and simulated turbocharged operation by pressurizing inlet air to 2.6 bar. In early tests of turbocharged hydrogen engines in commercial vehicles, Lynch converted gasoline and diesel engines to spark-ignited hydrogen operation at maximum inlet pressures of 1.5 bar. Berckmuller et al [20] have reported results from a single-cylinder engine supercharged to 1.8 bar that achieves a 30% increase in specific power output compared to a naturally aspirated gasoline engine. Boosting pressure increases the charge pressure and temperature, the problems of preignition, knock and NO_x control are heightened during boosted operation.

Swain et al, [21] designed an intake manifold to take advantage of the characteristics of hydrogen. The important feature is the use of large passageways with low-pressure drop, which is possible with hydrogen fueling since high intake velocities required for fuel atomization at low engine speeds are not necessary. With the use of a large diameter manifold, Swain et al. reported a 2.6% increase in peak power output compared to that for a small diameter manifold. However, the improvement was lower than the estimated 10% that was expected. One possible explanation for the less than expected performance improvement was that the intake flow dynamics with hydrogen fueling are more complex than for gasoline-fueled engines. In this context, Sierens and Verhelst [16] found that the start and duration of injection influences the volumetric efficiency due to the interaction between the injected hydrogen and the intake pressure waves.

In a technical center of the company Toyota, in Belgium, an experimental research about the combustion characteristics and a spark ignition engine performance, with a four stroke single cylinder, was made [22]. Hydrogen Injection during the intake stroke (300^0 crank angle (CA) before top dead centre (BTDC)) inhibits backfire, but thermal efficiency and power output are limited by knocking and decrease of volumetric efficiency. Hydrogen injection during the compression stroke (130^0 CA BTDC) prevents knocking, increases thermal efficiency and maximizes the power output. However, it was observed that, retarding injection timing during the compression stroke, can lead to a thermal efficiency of about 38.9%, reducing at the same time emissions of nitric oxides.

Changwei Ji, Wang S F [23] carried out the experiments on a modified four-cylinder hybrid hydrogen gasoline engine equipped with an electronically controlled hydrogen port injection system and a hybrid electronic control unit applied to govern the spark timings, injection timings and durations of hydrogen and gasoline. For given hydrogen blending fraction and excess air ratio, the engine load, which was represented by the intake manifolds absolute pressure (MAP), was increased by increasing the opening of the throttle valve. The experimental results demonstrated that the engine brake mean effective pressure (Bmep) was increased after hydrogen addition only at low load conditions. However, at high engine loads, the hybrid hydrogen gasoline engine (HHGE) produced smaller Bmep than the original engine. The engine brake thermal efficiency was distinctly raised with the increase of MAP for both the original engine and the HHGE. The coefficient of variation in indicated mean effective pressure (COVimep) for the HHGE was reduced with the increase of engine load. The addition of hydrogen was effective in improving gasoline engine operating instability at low load and lean conditions. HC and CO emissions were decreased and NO_x emissions were increased with the increase of engine load. The influence of engine load on CO_2 emission was insignificant. All in all, the effect of hydrogen addition to improving engine combustion and emissions performance was more pronounced at lower loads than at high loads.

Changwei Ji and Shuofeng Wang, [24] investigated the idle performance of a spark ignited gasoline engine with hydrogen addition. The research results show that, with the increasing of hydrogen enrichment levels, the engine idle speed remains approximately at its original target. The hydrogen-enriched SI engine gains a higher indicated thermal efficiency and a lower energy flow rate than the pure gasoline SI engine at idle and stoichiometric conditions. The flame development, propagation durations and COVimep are reduced with the increasing hydrogen fraction. Since hydrogen has a wide flammability and fast burning velocity, the CO and HC emissions are reduced with the hydrogen enrichment at idle and lean conditions. Due to the lower peak cylinder temperature, the NO_x emissions are also reduced for the hybrid hydrogen gasoline engine at idle and lean conditions.

Erol Kahraman et al [25] 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. NO_x 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 of using hydrogen across a wider operating range.

Fanhua Maa, Yituan He, Jiao Deng Long Jiang et al [26] experimentally investigated the effect of the equivalence ratio (Φ) and ignition advance angle (θ) on idle characteristics of a turbocharged hydrogen fueled SI engine. The experimental data as conducted under various operating conditions including different Φ and θ. It is found that, the ignition advance angle at maximum braking torque (MBT) point decreases gradually with the equivalence ratio increasing from 0.4 to 0.9. Indicated thermal efficiency decreases as Φ increases. Emissions of NO_x increase as Φ increases. When Φ is kept constant, the stated emissions increase as θ increases. During idle conditions of hydrogen fueled engine, a lean mixture with a Φ less than 0.4 is suitable, and the θ should be increased appropriately. The maximum cylinder pressure rises with an increase of Φ and θ. The trend of the maximum rate of pressure rise is similar at different Φ. Only under the conditions of $\Phi = 4$ and $\theta < 10^0$ CA the maximum pressure rise rate remains almost unchanged.

From several practical considerations, hydrogen is safer compared to conventional petroleum fuels. Hydrogen is a low density fuel thus leaking hydrogen rises up very rapidly through the air, thus creating an explosion possibility only to the space immediately above the leak. The ignition energy required to ignite an air fuel mixture depends very much on the equivalence ratio. Hydrogen has an extremely low ignition energy compared to gasoline. Based on the lower flammability limit, hydrogen seems to be superior to gasoline. As far as the quenching distance is concerned, hydrogen combustion which can be initiated with a low energy spark becomes difficult to quench. It can be suggested that appropriate changes in the combustion chamber together with a better cooling mechanism would increase the possibility of using hydrogen across a wider operating range. The hydrogen engine combustion and emissions performance were more evident at lower loads than at high loads.

IV. EMISSION CHARACTERISTICS OF HYDROGEN FUELED 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 (NO_x), 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 (SO_x), leads or other toxic metals, sulfuric acid deposition, ozone and other oxidants, benzene and other carcinogenic compounds, carbon dioxide (CO_2), formaldehyde and other greenhouse gases. The only undesirable emission is nitric oxide (NO) and nitrogen dioxide (NO_2), which are oxides of nitrogen (NO_x) which can collect and avoid their emission to the atmosphere.

H_2ICE emissions and control techniques have been thoroughly reviewed by many researchers. Das [27] revealed that ultra-lean combustion (i.e., Φ=0:5), which is sufficiently identical with low temperature combustion, is an effective means for minimizing NO_x emissions in ICEs. He compiled data from various sources for tailpipe emissions with exhaust after-treatment. These data show that NO_x emissions at Φ > 0:95 are near zero with the use of a three-way catalyst) three-way catalyst (TWC).

M A Escalante Soberanis, A M Fernandez [14] also carried out a technical revision on internal combustion engine run with hydrogen fuel. They reported the emissions of air/hydrogen mixtures consist mainly of carbon dioxide and nitric oxides. In the case of NO_x, higher levels of emissions can be observed, due to the higher temperature and flame velocity of hydrogen compared with other fuels, like gasoline. Emissions of UBHC are the product of lubricant oil heating and the use of oil derivatives for engine cooling. Moreover, in Riverside, University of California, a research about exhaust gas recirculation technique in a hydrogen engine at different fuel flows was carried out [28]. For this purpose, a four cylinder Ford engine was adapted, connecting a line which concludes exhaust gases back to the intake air manifold. Fuel flows from 0.78 to 1.63 kg/h, i.e., Φ from 0.35 to 1.02, and introducing exhaust gases in a phased manner, substituting air. These tests were carried out at an engine speed of 1500 rpm. This technique was shown as an effective method to reduce emissions of nitric oxides to less than 10 ppm, getting a better power output than that with lean mixtures ($\Phi< 0.45$, i.e., 14% Vol. of hydrogen), with thermodynamic efficiencies near 31%.

Erol Kahraman [29] 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 NO_x, CO, CO_2, HC, and O_2 versus engine speed are compared for a carbureted SI engine operating on gasoline and hydrogen. He found that NO_x emission of hydrogen fueled engine is about 10 times lower than gasoline fueled engines.

James W Heffel [30] conducted the experiments on hydrogen fueled spark ignition engine to ascertain the effect of exhaust gas recirculation and a standard 3-way catalytic converter had on NO_x emissions and engine performance. All the experiments were conducted at a constant engine speed of 1500 rpm and each experiment used a different fuel flow rate, ranging from 0.78 to 1.63 kg/h. The tests are conducted on a 4-cylinder, 2-liter Ford ZETEC engine specifically designed to run on pure hydrogen using a lean-burn fuel metering strategy. It has a compression ratio of 12:1 and uses a sequential port fuel injection system. From experiments conducted, it can be concluded that if the NO_x emission is not taken into considerations then lean burn strategy can produce more torque than EGR strategy. However, if low NO_x emissions (<10 ppm) are a requirement, the EGR strategy can produce almost 30% more torque than the lean-burn strategy. The results of these experiments demonstrated that using EGR is an effective means to lowering NO_x emissions to less than 1 ppm while also increasing engine output torque.

In addition, Nagalingam [17] reported measurements on a single-cylinder hydrogen engine equipped with a supercharger and an exhaust gas recirculation (EGR) system. The results showing NO_x 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 (NO_x).

V. HYDROGEN FUEL INDUCTION TECHNIQUES FOR SI ENGINE

The fuel induction technique has been found to be playing a very dominant and sensitive role in determining the characteristics of an IC engine. A unit volume of the stoichiometric hydrogen air mixture has only 85% of the calorific value of the gasoline air mixture. This means that the hydrogen pre mixture spark ignition engine has a smaller maximum power output than the gasoline engine. Therefore the methods to supply hydrogen into an engine and the corresponding design of a hydrogen supply system become one of the key problems to be solved in the research on a hydrogen engine.

The structure of a hydrogen fueled engine is not very different from that of a traditional internal combustion engine but if a gasoline engine without any modification were fueled by hydrogen some problems such as small power output, abnormal combustion (e.g. backfire, pre ignition, high pressure rise rate and even knock) and high NO_x emission would occur. So its fuel supply system and combustion system need suitable modification.

The fuel induction technique for an internal combustion engine can be classified into four categories such as carburetion, inlet port injection, inlet manifold injection, and direct cylinder injection.

Carburetion technique is the oldest technique where the carburetion is done by the use of a gas carburetor.

In an intake port injection system both air and fuel enter the combustion chamber during the intake stroke, but are not premixed in the intake manifold.

Inlet manifold injection is another fuel induction technique where the hydrogen injected into the inlet manifold. This method uses the typical properties of hydrogen fuel to a point of advantage. In this technique, the system is so designed that the intake manifold does not contain any combustible mixture thereby avoiding undesirable combustion phenomena and the air being inducted prior to fuel delivery. It provides a precooling effect and thus avoids preignition sources that could be present on the surface. And also helps to quench or at least to dilute any hot residual combustion products that could be present in the compression space near TDC.

Direct cylinder injection of hydrogen into the combustion chamber does have all the benefits of the late injection as charecterised by manifold injection. In addition, the system permits for fuel delivery after the closing of the intake valve and thus, intrinsically precludes the possibility of backfire.

L M Das [31] concluded in his review paper that late fuel injection is a very promising fuel induction technique which avoids the possibility of backfire which can be effected for both two strokes as well as 4 stroke engines. An appropriate TMI system could be considered for a hydrogen engine in order to ensure smooth operation without any undesirable combustion phenomenon.

LS Guo [32] modified four cylinder hydrogen fueled internal combustion engine for a hydrogen injection with fast response solenoid valves, and its electronic control system. A four cylinder four stroke water cooled gasoline engine with spark ignition is refitted to an in-cylinder injection spark ignition hydrogen fueled engine. Their study to be focused mainly on modification of its hydrogen supply system and combustion system to solve such problems as small power output and abnormal combustion in a hydrogen fueled engine. This study shows that the abnormal combustion such as a backfire, preignition, high pressure rise rate and knock did not occur and performance of the engine could be improved by means of the hydrogen injection system with fast response solenoid valves. The fast response solenoid valve and its electronic control system possess good switch characteristics and very fast response, thus it could satisfy the working requirements of the injection system. The Intel 7987 chip microprocessor could be applied to control ignition and injection timing optimally so as to improve engine performance. In the hydrogen supply system, the hydrogen injector was always not under a high pressure, so preignition caused by the injector leakage at initial stage of starting the engine was avoided.

Alberto Boretti [33] reported direct injection and jet ignition coupled to the port water injection are used to avoid the occurrence of all abnormal combustion phenomena as well as to control the temperature of gases to turbine in a turbocharged stoichiometric hydrogen engine. Port water injection coupled with direct injection and jet ignition may permit the stoichiometric operation of hydrogen engines. This brings the advantages of high power densities, even if at the expenses of reduced peak fuel conversion efficiencies. High pressure and high flow rate direct injection performed close to the ignition top dead center eliminates the occurrence of backfire and contribute to reduce the probability of knock reducing the time in between an ignitable mixture is made available within the cylinder and the time the mixture is fully burned. Top dead center jet ignition produces very fast combustion rates, for an almost isochoric combustion process, with multiple jet of hot reacting gases igniting the mixture in the bulk in multiple locations thus permitting better conversion efficiencies and reduced likeliness of knock occurrence for the reduce time to complete combustion. Port water injection further reduces the likeliness of knock occurrence strongly reducing the charge temperature through vaporization.

Ali Mohammadi et al [22] developed a direct-injection spark ignition hydrogen engine and attention was paid on the effects of injection timing on the engine performance, combustion characteristics and NO_x emission under a wide range of engine loads. From this research it can be revealed that In-cylinder injection of hydrogen during the intake stroke as well as compression stroke prevents backfire and knock respectively. The experiments results suggested that Hydrogen injection at later stage of compression stroke can achieve the thermal efficiency higher than 38.9% and the brake mean effective pressure 0.95MPa and also under high engine output conditions, late injection of hydrogen offers a great reduction in NO_x emission due to the lean operation.

As indicated in the previous researches, employing direct-injection technology in a hydrogen engine is very effective to control the abnormal combustion of hydrogen and achieve high thermal efficiency and output power. Although late injection results in lower NO_x emissions, utilization of other techniques such as exhaust gas recirculation and after treatment methods are required to bring the NO_x emission to acceptable levels.

VI. 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 advances in matters of 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.

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