Usage of Hydrogen as a Fuel in Spark Ignition Engine

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Abstract. Nowadays due to fast depletion of fossil fuels and their pollution problems demanding an urgent need of alternative fuels for accomplishing ecological energy demand with minimum environmental impact. This paper describes a widespread overview of hydrogen as a fuel for spark ignition engine. It includes the most significant advancement made on the technical adaptations in the spark ignition engine and some of the advantages and disadvantages of the integration of hydrogen as a fuel.

1. Introduction
Concerning to the current environmental issues and energy security has led to the investigation of alternative fuels for internal combustion engines. From various researches, Hydrogen is found to be better alternative fuel among the available options for use in IC engines which is abundantly available and gives near zero-emissions [1]-[4]. Hydrogen can be produced directly from all primary energy sources, more likely can be being produced from water using electrolysis. Alternatively, H₂ 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 and can also be produced by solid methane reforming process, thermal catalytic process and thermo-chemical process. The energy stored in hydrogen can be converted to useful energy through either fuel cells to directly produce electricity or combustion to produce power.

Hydrogen has a much simpler molecular structure than gasoline and therefore its specific-heat ratio is higher than that of conventional gasoline. Hydrogen can be used in engine as an additive in a hydrocarbon mixture, or as an only fuel, in the presence of air. Some of the physical properties of hydrogen fuel compared to other fuels are shown in Table I. Hydrogen has very low ignition energy. It sustains lower emissions and higher thermal efficiencies than gasoline engine due to wide range of flammability and high flame speed of hydrogen compared to other fuels. 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. A significant advantage of this is that hydrogen can run on a lean mixture and ensures prompt ignition. Generally,
## Table 1. Physical Properties of Hydrogen Fuel Compared to Other Fuels

| Property                                      | Hydrogen | Gasoline | Methane |
|-----------------------------------------------|----------|----------|---------|
| Chemical formula                              | H₂       | C₈H₁₈   | CH₄     |
| 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    |
| Flame velocity (m/s)                          | 2.65–3.25| 0.30–0.50| 0.4–0.6 |
| Quench distance at NTP (mm)                   | 0.64     | 2.0     | 2.03    |
| Density at 1 atm and 300 K (kg/m³)            | 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   |

fuel economy is greater and the combustion reaction is more complete when an internal combustion (IC) engine runs on a lean mixture. The energy density of hydrogen on a mass basis is higher than that of gasoline. The high laminar speed of hydrogen also improves the consistency in the cylinder mixture which helps the fuel to be completely burnt. 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. The use of hydrogen can provide carbon dioxide (CO₂), smoke, and hydrocarbon (HC) free combustion in SI engine.

### 2. Performance and emission characteristics of hydrogen fueled SI engine

#### 2.1. Performance Characteristics:

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. 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 [5]-[7].

Ford Motor Company, BMW, Nissan Motors, Sandia National Lab, IIT Delhi, Ghent University and some reputed research organizations, laboratories are exploring hydrogen as an alternative fuel for IC engines [8]-[11].

Ford Motor Company began development of a hydrogen fueled IC engine in 1997 which was a Ford Zetec engine. The pistons, cylinder head, ignition system, wrist pins, connecting rods, piston ring lands and fuel injectors were all modified to improve combustion. The experimental results showed that hydrogen as a fuel for an IC engine has unique properties such as high fuel economy and low carbon related emissions due to high octane number. Ford’s testing indicated that torque output reduced by 50% at high speed and 35% at low and mid speeds compared to gasoline. At stoichiometric ratio of 0.25, the best specific fuel consumption occurred and unburned exhaust emissions of hydrogen drastically increased. NOₓ concentration increases dramatically as stoichiometric ratio increases above 0.5. Hydrogen engine was operated with a supercharger, which results improvement in the performance [12].

Researchers of Nissan Motors and Musashi Institute of Technology found that the adding boost pressure to a hydrogen fueled engine will help achieve higher power, efficiency and lower NOₓ emissions. With aid of this, larger bore also increased thermal efficiency may lead to further development of work with larger displacement engines [13]. Sandia National Lab researchers demonstrated that a hydrogen fueled engine can provide the necessary power with a drive-cycle
efficiency approaching that of the fuel cell vehicle of the future. Lab test data shows that the engine obtained higher thermal efficiency and lower NOx emissions when running on hydrogen [14].

M.A. Escalante Soberanis and A.M. Fernandez [15] reported that the thermal efficiency of an engine increased with hydrogen fuel (38.9% with hydrogen and 25% with gasoline). Sierens, R and Verhelst [16] conducted experiments on a Volvo four cylinder sixteen valve gasoline engine with some modifications with the use of hydrogen fuel. They revealed that, the mechanical efficiency of the engine increases with the increment of torque. Shivaprasad KV et al. [17] experimentally found that the increase in hydrogen addition fraction distinctly raises the cylinder pressure. Addition of the hydrogen also results to bring the peak of the pressure rise gradually shifting towards the TDC. This indicates that combustion in the cylinder takes place relatively at high pressure and temperature, due to the high adiabatic flame temperature and high flame speed of hydrogen. These provide improvement in the combustion process with shorter combustion duration. They also found that the brake mean effective pressure (BMEP) rises as the hydrogen fraction in the fuel blend increases compared to pure gasoline operation. This is mainly due to hydrogen’s wider flammable range, faster flame propagation speed and a much higher adiabatic flame temperature than those of gasoline, which helps to accelerate the combustion of hydrogen–air mixtures.

Changwei and Wang [18]-[19] conducted experiments on a hydrogen fuelled spark ignition engine equipped with an electronically controlled port system for hydrogen injection. The investigational outcomes showed the increment in cylinder peak pressure and temperature while reduction in flame development and propagation durations with the increase of hydrogen addition. Subramanian et al. [20] reported in their technical paper that the addition of hydrogen distinctly raises the cylinder pressure. They also concluded that hydrogen addition results peak of the pressure rise gradually shifting towards the TDC. This indicates that combustion in the cylinder takes place relatively at high pressure and temperature which is mainly due to high adiabatic flame temperature and high flame speed of hydrogen. Wang et al. [21] and Kiyoshi et al. [22] also explored that the addition of hydrogen to conventional engines improves combustion efficiency due to shorter period of combustion and hence, extreme amount of heat release occur nearer to top dead centre (TDC) position and also availed easing of cyclic variations.

Andrea et al. [23] investigated the effect of various engine speeds and equivalence ratios on combustion of a hydrogen blended gasoline engine. Their experiment results showed that the combustion duration decreases and the nitrogen emission increases with the increase of hydrogen blending fraction. Rahaman et al. [24] focused on the effect of air fuel ratio and engine rotational speed on the performance of a single cylinder hydrogen fuelled spark ignited engine. The experiment shows the increase in brake mean effective pressure and brake thermal efficiency, but decrease at higher air fuel ratio and higher speed. This is because of low flammability of hydrogen and lower densities and air required for combustion is less. The volumetric efficiency of hydrogen fuelled is a serious problem and reduces the power of hydrogen per unit volume.

Fontana et al. [25] found that the engine thermal efficiency of the spark ignition engines can be improved significantly by running the engine at WOT condition. Mariani et al. [26] found that the addition of hydrogen in the fuel-air mixtures resulted in the 16% reduction of CO2 emission. Kahraman et al. [27] observed that HC and CO emissions from hydrogen-enriched gasoline engine were lower than the original gasoline engine.

Moreno et al. [28] conducted experiment on two cylinders SI Engine in order to find out the effect of hydrogen at different volume fractions on performance and emissions. It was observed that hydrogen enrichment of the gasoline fuel improves combustion for the ignition timing chosen. This improvement is more appreciable at low speeds, because at high speeds hydrogen effect is attenuated by the high turbulence. Especially at stoichiometric conditions, the high NOx emission was measured due to increment in the combustion temperature that hydrogen produces. Higher rate of heat release were observed for blend with more hydrogen content.
2.2. Emission Characteristics:

Since last few 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\textsubscript{x}), carbon monoxide (CO), and unburned hydrocarbons (UBHC). Combustion of hydrogen does not produce any of the major pollutants such as carbon monoxide (CO), hydrocarbon (HC), sulphur oxides (SO\textsubscript{x}) and smoke. An oxide of nitrogen (NO\textsubscript{x}) is the only pollutant which needs to be strictly monitored [29]-[30].

Hydrogen fueled SI engine emissions and control techniques have been thoroughly reviewed by many researchers. Das [31] 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\textsubscript{x} emissions in ICES. He compiled data from various sources for tailpipe emissions with exhaust after-treatment. These data show that NO\textsubscript{x} emissions at Φ > 0.95 are near zero with the use of a 3-way catalytic converter.

Soberanis and Fernandez [32] reported in their technical paper that the emissions of air-hydrogen mixtures consist mainly of nitric oxides. In the case of NO\textsubscript{x}, higher levels of emissions can be observed, due to higher flame velocity and temperature of hydrogen fuel. Emissions of unburned UBHC are the product of lubricant oil heating and the use of oil derivatives for engine cooling. Hydrogen combustion at light load, reducing injection time and delaying the spark, can reduce emissions of NO\textsubscript{x} and avoid abnormal phenomena of combustion.

In University of California Riverside, Heffel [33] conducted the experiments on hydrogen fueled spark ignition engine to ascertain the effect of exhaust gas recirculation (EGR) and a standard 3-way catalytic converter on NO\textsubscript{x} emissions and engine performance. All the experiments were conducted at a constant engine speed of 3000 rpm and each experiment used a different fuel flow rate, ranging from 1.63 to 2.72 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. A standard 3-way catalytic converter was installed at the exhaust manifold collector and EGR line was connected from the exhaust pipe to the inlet of the air intake manifold. The results showed that if the NO\textsubscript{x} emission is not taken into considerations then lean burn strategy can produce more torque than EGR strategy. However, if low NO\textsubscript{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\textsubscript{x} emissions to near to 1 ppm.

In addition, Kumaret al. [34] reported measurements on a single-cylinder hydrogen engine equipped with a supercharger and an exhaust gas recirculation system. The results showing NO\textsubscript{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 shows significantly increase in the power output while limiting tailpipe emissions of NO\textsubscript{x}. Stebar et al. [35] used hydrogen-supplemented fuel as a means of extending the lean limit of operation in a gasoline engine in order to control NO\textsubscript{x}. A single-cylinder engine was tested while adding 10% hydrogen by mass of fuel. The lean limit was extended from 0.89 to 0.55 reducing NO\textsubscript{x} emissions to near minimal levels. However, as a consequence of running on lean mixtures, the HC emissions increased.

Lucas and Richards [36] performed an investigation on an engine which was fueled by hydrogen only while idling and then was run with a constant hydrogen flow rate to which gasoline was added as the load increased. This dual fuelling mode reduced fuel consumption by up to 30%. As a result of lean operation, CO emissions were reduced due to completeness of combustion.

The effect of hydrogen addition on the combustion processes was also examined by Apostolescu and Chiriac [37] on gasoline fueled single cylinder passenger car engine at mid and light load operation. The test results revealed that NO\textsubscript{x} emissions were increased and HC emissions were decreased with the hydrogen gasoline engine operation.

Changwei Ji et al. [38] converted a four cylinder gasoline engine into a hybrid hydrogen gasoline engine (HHGE). The experimental results indicated that the HHGE was started successfully with the pure hydrogen, which produced 99.5% and 94.7% reductions in CO and HC emissions compared to
original gasoline engine. Moreover HC, CO and NO\textsubscript{x} emissions were effectively reduced for the HHGE due to eased engine cyclic variation and shortened combustion duration.

3. Hydrogen fuel induction techniques for SI engine

The fuel induction technique has been found to be playing a very dominant and complex role in determining the characteristics of an IC 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 fuelled engine is not very different from that of a traditional internal combustion engine but if a gasoline engine without any modification were fuelled by hydrogen, some problems such as small power output, abnormal combustion and high NO\textsubscript{x} emission would occur. So its fuel supply system and combustion system need suitable modification.

Figure 1. Fuel Carburetion Method

Figure 2. Inlet Manifold/Inlet Port Injection

Figure 3. Direct Injection System

The fuel induction technique for an IC engine can be classified into three categories such as carburetion, inlet port injection / inlet manifold injection and direct cylinder injection system. Carburetion technique is the oldest technique where the carburetion is done by the use of a gas carburettor which is shown in figure 1. This system is also called as central injection system. The main advantage of this system is that it does not require high supply pressure as for other methods and enabling it to convert a standard gasoline engine to operate on pure hydrogen or a gasoline-hydrogen engine. The disadvantage of this technique is that the volume occupied by the fuel is about 1.7% of the mixture and hence results in 15-20% power loss. As shown in figure 2, 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. 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 pre-ignition 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. As shown in figure 3, direct cylinder injection of hydrogen into the combustion chamber does have all the benefits of the late injection as characterised by manifold injection. In addition, the system permits for fuel delivery after the closing of the intake valve and thus, intrinsically prohibits the possibility of backfire. An intensive research effort has been carried out by BMW since 1979 on port fuel injection of hydrogen engines. At stoichiometric air-fuel ratio operation, BMW found that with external mixture formation, hydrogen displaces approximately 30% of the aspirated air. BMW suggests that a direct supply of hydrogen at injection timing of 40 deg. to 60 deg. CA bTDC to the combustion chamber will allow the engine to have the best power density and indicated mean effective pressure greater than gasoline. Based on these studies, direct injection of hydrogen into the combustion chamber may provide a means to increase engine efficiency and decrease emissions while maintaining an optimal level of power output [39].

Das [1], [8] revealed from his experiments that the carburetion is not at all suitable for hydrogen engine, because it gives rise to uncontrolled combustion in the engine cycle. The symptoms of backfire were experienced at unscheduled points in the engine cycle with continuous manifold injection operation. Moreover, tests with timed manifold injection showed that the engine was able to run smoother when compared to continuous manifold injection over a wider operating range of speed and
equivalence ratio. As far as the direct cylinder injection is concerned, it intrinsically precludes backfire. However, limited tests with direct injection indicated that, it is very tough for the injector to survive in the severe thermal environment of the combustion chamber over a prolonged engine operation. The other problem which is characteristic of cylinder injection is that the time allowed for mixing of hydrogen and air after injection is very brief. This often results in incomplete combustion. Thus, after exhaustive tests on the research engine with various fuel induction techniques, timed manifold injection was observed to be the most pragmatic mode of hydrogen fuelling.

Alberto Boretti [40] 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. Ali Mohammadi et al. [41] 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\textsubscript{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 in 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 great reduction in NO\textsubscript{x} emission due to the lean operation.

4. Limitations associated with hydrogen engine applications

Much of the information reported in the open literature about the performance of engines on hydrogen as a fuel tends to highlight the positive features of hydrogen while de-emphasizing or even ignoring the many limitations associated with such fields of application.

4.1. Abnormal Combustion:

The main disadvantage of using hydrogen as a fuel in internal combustion engine is to control the undesired combustion phenomena due to low ignition energy, wide flammability range and rapid combustion speed of hydrogen. In this section the main abnormal combustion in hydrogen engine which are pre-ignition, backfire, and knock in terms of cause and method to avoid are discussed.

4.1.1. Pre ignition:

Pre-ignition is one of the undesired combustion that needs to be avoided in hydrogen engine [42]. During engine compression stroke, these pre-ignition occur inside the combustion chamber, with actual start of combustion prior to spark timing. Pre-ignition event will advance the start of combustion and produce an increased chemical heat-release rate. In turn, the increased heat-release rate results in a rapid pressure rise, higher peak cylinder pressure, acoustic oscillations and higher heat rejection that leads to rise in-cylinder surface temperature [4, 43]. The performance of hydrogen powered vehicle decrease as pre-ignition limit will border on the peak power output of hydrogen engine in comparison to its gasoline equivalent. At increased engine speed and load, operating conditions will also be prone to occurrence of pre-ignition due to higher gas and components temperature [32].

Sources of pre-ignition are;

- Hot exhaust valves or other hot spots in the combustion chamber.
- Hot spark plugs or spark plug electrodes.
- Residual gas or remaining hot oil particles from previous combustion events.
- Combustion in crevice volumes [7].

Several steps have been taken to minimize the source of pre-ignition which are:

- Proper design of spark plug.
- Specific design of crankcase ventilation.
- Ignition system design with low residual charge.
- Optimized design of the engine cooling passage to avoid hot spot.
With the use of hydrogen direct injection systems [44].

4.1.2. Backfire:
Backfire is one of the main problems to run a hydrogen fueled engine. Backfire or flashback is the uncontrolled combustion of fresh hydrogen–air mixture during the intake stroke in the combustion chamber and/or the intake manifold [43]. The fresh hydrogen–air mixture is aspirated into the combustion chamber with the opening of the intake valves. Backfiring is caused when combustion chamber hot spots, hot residue gas or remaining charge in the ignition system ignite the fresh charge as hydrogen has low ignition temperature. In pre-ignition, the uncontrolled combustion happens during end of compression stroke before spark plug fires in cylinder while backfire occurs during suction stroke [44]. Backfire initiates from the pre-ignition during the compression stroke, and then proceeds to the ignition of the intake mixture. Effect of backfire resulting in combustion and pressure rise in the intake manifold, is clearly audible as well as can also damage or destroy the intake system. When mixture approaches stoichiometry, the occurrence of backfire is more likely due to the low ignition energy. In port fuel injection, the hydrogen is injected before the intake valve opens, to mix with air in the intake manifold before entering combustion chamber which results backfire. While in direct injection, the occurrence of backfire can be neglected as hydrogen injection starts after the intake valve closes difference with external mixture formation concept [45].

Recently, many works have been carried out on optimizing the intake design and injection strategies to avoid backfiring. Consequently, the measures those help in avoiding pre-ignition also reduce the risk of backfiring. Some of the strategies that are used to avoid backfiring:

- Injection strategies that allow pure air to flow into the combustion chamber to cool potential hot spots before aspirating the fuel-air mixture.
- Optimization of the fuel-injection strategy in combination with variable valve timing for both intake and exhaust valves allow operation of a port injected hydrogen engine at stoichiometric mixtures over the entire speed range [46].

4.1.3. Knock:
Knock is defined as auto-ignition of the hydrogen–air end-gas ahead of the flame front that has originates from the spark. This follows a rapid release of the remaining energy generating high-amplitude pressure waves, mostly referred to as engine knock [47]. Engine damage can be caused by the amplitude of the pressure waves of heavy engine knock due to increased mechanical and thermal stress. The knocking tendency of an engine is dependent on the engine design along with the fuel-air mixture properties [7]. Knock is less likely for hydrogen in comparison with gasoline due to its high auto-ignition temperature, finite ignition delay and the high flame velocity properties.

Following are the effects of knock to engine operation:

- Undesirable engine performance and the potential damage to engine components.
- Increased heat transfer to the cylinder wall.
- Extremely high cylinder pressure and temperature levels and increased emissions.

4.2 Avoiding Abnormal Combustion:
It is an effective measure to limit maximum fuel-to-air equivalence ratio to avoid abnormal combustion in hydrogen operation. By operation, employing a lean-burn strategy, the excess air in lean operation acts as an inert gas and reduces combustion temperature effectively and components temperatures consequently. Although lean operation is very effective, it does limit the power output of hydrogen engine.

Using thermal dilution technique such as exhaust gas recirculation or water injection, pre-ignition conditions can be limited. A portion of the exhaust gases is re-circulated back into the intake manifold by EGR system. It helps to reduce the temperature of hot spots by introducing the exhaust gases, hence reducing the possibility of pre-ignition. Additionally, peak combustion temperature is reduced
by recirculation of exhaust gases, which also reduces NOx emissions. Typically, 25% to 30% recirculation of exhaust gases is effective in elimination of back fire [48]. Injection of water is the other technique for thermally diluting the fuel mixture. Injecting water into the hydrogen stream prior to mixing with air has produced better results than injecting it into the hydrogen–air mixture within the intake manifold [2]. A potential problem of mixing of water with oil exists with this type of system, so care must be taken ensuring that seals do not leak.

5. 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, varying operating parameters, multi-mode operating strategies, and advancements in engine design and materials.

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