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Hydrogen Usage in I.C. Engines

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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 provides a pathway for energy diversity. It can store the energy from diverse domestic resources (including clean coal, nuclear, and intermittently available renewable sources) for use in mobile applications and more. 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 (C.O.), hydro carbon (H.C.) during combustion. In this paper contemporary research on the hydrogen-fueled internal combustion engine can be given.

Index Terms— Air-Fuel Ratio, Pre-Ignition, Back Fire, Auto-Ignition, Stoichiometric Ratio, Flammability, Fuel Injection, Combustion.

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1 Introduction

There have been a lot of researches for an alternative fuel because of environmental consequences as well as regulations. There are many number of alternative fuels such as liquefied petroleum gas (L.P.G.), compressed natural gas (C.N.G.), hydrogen, vegetable oils, bio gas, producer gas but hydrogen is a less-polluting, renewable fuel. When it is burnt in an internal combustion engine, the primary combustion product is water with no CO_2.

2 Reasons for Choosing Hydrogen

Hydrogen is the most abundant element present on earth. [8] The ever increasing demands for fossil fuels have left us with very miniscule reservoirs. Hydrogen has a very high calorific value compared hydrocarbons. It is not a pollutant and also does not contaminate the ground water.

3 Properities of Hydrogen

3.1 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.

3.2 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.

3.3 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.

3.4 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 0.02mJ as compared to 0.24mJ for petrol - and is approximately constant over the range of flammability. 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.

3.5 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

3.6) 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.

3.7 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.

4 Stoichiometric Air-Fuel Ratio and 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. The actual mass ratio of air to fuel, ma/mf, can be expressed as where is called the air excess ratio - the relative amount of mass of air over that required for stoihiometric combustion. Because air is used as the oxidizer instead oxygen, the nitrogen in the air needs to be included in the calculation:

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Moles of N_2 in air = 3.762 moles N_2

Number of moles of air = 4.762 moles of air

Weight of O_2 = 32 g

Weight of N_2 = 105.33 g

Weight of air = weight of O_2+ weight of N_2

= 137.33 g

Weight of H_2 = 4 g

Stoichiometric air/fuel (A/F) ratio for hydrogen and air is:

A/F based on mass = mass of air/mass of fuel

= 34.33:1

A/F based on volume = volume (moles) of air/volume (moles) of fuel

= 2.4:1

The percent of the combustion chamber occupied by hydrogen for a stoichiometric mixture:

% H_2 = volume (moles) of H_2/total volume

= volume H_2/ (volume air + volume of H_2)

= 2 / (4.762 + 2) = 29.6%

As these calculations show, the stoichiometric or chemically correct A/F ratio for the complete combustion of hydrogen in air is about 34:1 by mass. This means that for complete combustion, 34 pounds of air are required for every pound of hydrogen. This is much higher than the 14.7:1 A/F ratio required for gasoline.

5 Hydrogen as a Fuel

Hydrogen produces only water after combustion. It is a non-toxic, non-odorant gaseous matter and also can be burned completely. 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, except for the formation of NOx.

$$2H_2 + O_2 = 2H_2O$$

Hydrogen has some peculiar features compared to hydrocarbon fuels.

1. The burning velocity is so high that very rapid combustion can be achieved.
2. 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.
3. The minimum energy required for ignition of hydrogen–air mixture is 0.02mJ only.
4. The density of hydrogen is 0.0838 kg/m3, which is lighter than air that it can disperse into the atmosphere easily.
5. The diffusivity of hydrogen is 0.63 cm2/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.
6. Hydrogen has the highest energy to weight ratio of all fuels. The flame speed of hydrogen is 270 cm/s.

6 Hydrogen Use in Internal Combustion Engines

6.1 Hydrogen use in diesel engines

Here are several reasons for applying hydrogen as an additional fuel to accompany diesel fuel in the internal combustion (IC) compression ignition (CI) engine.

1. Firstly, it increases the H/C ratio of the entire fuel.
2. 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.

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. Oxides of nitrogen (NOx) are the major problem in hydrogen operated dual fuel engine. One method that has been used to successfully reduce NOx emissions is exhaust gas recirculation (EGR). Another method of is introduing liquid water into the combustion chamber. Water injection can also prevent knocking and pre-ignition during hydrogen combustion.

6.2 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. 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 NOx emission.

7 Hydrogen Internal Combustion Engines Fuel Induction Techniques

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)

7.1 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%.

7.2 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. 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.

7.3 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. 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.

8 Pre-Ignition Problems and Solutions

8.1 Pre-Ignition

Premature ignition is a much greater problem in hydrogen fueled engines than in other IC engines, because of hydrogen's lower ignition energy, wider flammability range and shorter quenching distance. Premature ignition occurs when the fuel mixture in the combustion chamber becomes ignited before ignition by the spark plug, and results in an inefficient, rough running engine.

8.2 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. 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.

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.

9 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. Knocking combustion is a common problem found in hydrogen-fuelled engines. 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.

10 Acessories that Complete the Design

10.1 Crankcase Ventilation

Crankcase ventilation is even more important for hydrogen engines than for gasoline engines. As with gasoline engines, unburnt fuel can seep by the piston rings and enter the crankcase. Since hydrogen has a lower energy ignition limit than gasoline, any unburnt hydrogen entering the crankcase has a greater chance of igniting. Hydrogen should be prevented from accumulating through ventilation.

10.2 Storage

Hydrogen has a very low volumetric energy density at ambient conditions. Even when the fuel is stored as a liquid in a cryogenic tank or in a compressed hydrogen storage tank, the volumetric energy is small relative to that of gasoline. Hydrogen has a three times higher calorific value compared to gasoline (143 MJ/kg versus 46.9 MJ/kg).

11 Type of Fuel Delivery System

11.1 Port Injection System

The port injection fuel delivery system injects fuel directly into the intake manifold at each intake port, rather than drawing fuel in at a central point. Typically, the hydrogen is injected into the manifold after the beginning of the intake stroke. At this point conditions are much less severe and the probability for premature ignition is reduced. The two types of port injection system are constant volume injector and electronic fuel injector.

11.2 Direct Injection System

In direct injection, the intake valve is closed when the fuel is injected, completely avoiding premature ignition during the intake stroke. Consequently the engine cannot backfire into the intake manifold. The power output of a direct injected hydrogen engine is 20% more than for a gasoline engine and 42% more than a hydrogen engine using a carburetor.

11.3 Central Injection System

The simplest method of delivering fuel to a hydrogen engine is by way of a carburetor or central injection system. 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.

11.4 Ignition System

Due to hydrogen's low ignition energy limit, igniting hydrogen is easy and gasoline ignition systems can be used. At very lean air/fuel ratios (130:1 to 180:1) the flame velocity is reduced considerably and the use of a dual spark plug system is preferred. Ignition systems that use a waste spark system should not be used for hydrogen engines. These systems energize the spark each time the piston is at top dead centre whether or not the piston is on the compression stroke or on its exhaust stroke. For gasoline engines, waste spark systems work well and are less expensive than other systems. For hydrogen engines, the waste sparks are a source of pre-ignition.

12 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 produce oxides of nitrogen (NOx):

$$H_2 + O_2 + N_2 = H_2O + N_2 + NO_x$$

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 NOx formed depends on:

1. The air/fuel ratio
2. The engine compression ratio
3. The engine speed
4. The ignition timing
5. Whether thermal dilution is utilized

In addition to oxides of nitrogen, traces of carbon monoxide and carbon dioxide can be present in the exhaust gas, due to seeped 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 NOx and significant carbon monoxide emissions.

13 Power Output

The theoretical maximum power output from a hydrogen engine depends on the air/fuel ratio and fuel injection method used. At this air/fuel ratio, hydrogen will dis-place 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 cham-ber has 100% air), the maximum output of the engine can be approximately 15% higher than that for gasoline engines. Typically hydrogen engines are designed to use about twice as much air as theoretically required for complete combustion. At this air/fuel ratio, the formation of NOx is reduced to near zero. Unfortunately, this also reduces the power out-put to about half that of a similarly sized gasoline engine. To make up for the power loss, hydrogen engines are usually larger than gasoline engines, and/or are equipped with turbochargers or superchargers.

14 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.

1. Internal combustion engine powered vehicles can possibly operate with both petroleum products and dual-fuels with hydrogen.

2. 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.
3. Direct injection solves the problem of pre-ignition in the intake manifold; it does not necessarily prevent pre-ignition within the combustion chamber.
4. 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.
5. 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.
6. Optimizing the injection timings can also control the onset of knock during high hydrogen flow.
7. Hydrogen engine may achieve lean-combustion in its actual cycles.

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