RESEARCH ARTICLE OPEN ACCESS

Using Hydrogen As An I.C Fuel

Aaryan Singh

Introduction

The small number of vehicles using hydrogen combustion engines (HICE) makes it difficult to explain how they work. In this article we will study the hydrogen engine and its main components, its advantages, disadvantages and how the components can be modified or redesigned to reduce these disadvantages.

Getting an internal combustion engine to run on hydrogen is not difficult. However, getting the internal combustion engine running in a suitable condition is a bigger problem.

The first attempt to develop a hydrogen engine was reported by the Reverend W. Cecil in 1820. Cecil presented his work before the Cambridge Philosophical Society in a paper entitled "On the Application of Hydrogen Gas to the Production of Motive Power in Machines". The engine itself worked on a vacuum principle in which atmospheric pressure drives a piston back against the vacuum to produce power. The vacuum is created by burning a mixture of hydrogen and air, which is allowed to expand and then cool. Although the engine ran satisfactorily, vacuum engines never became practical.

Sixty years later, during his work with internal combustion engines in the 1860s and 1870s, Otto (the inventor of the Otto cycle) was said to have used synthetic generator gas as fuel, which probably had a hydrogen content of over 50%. Otto also experimented with gasoline, but found it dangerous to work with, prompting him to return to using gaseous fuels. But the development of the carburetor started a new era, in which it was possible to use gasoline practically and safely, and the interest in other fuels declined.

Since then, hydrogen has been used extensively in the space program because it has the best energy-to-weight ratio of any fuel. Liquid hydrogen is the preferred fuel for rocket engines and has been used in the upper stages of launch vehicles on many space missions, including the Apollo missions to the moon, Skylab, the Viking mission to Mars, and the Voyager mission to Saturn.

In recent years, interest in cleaner air, along with stricter air pollution regulations and a desire to reduce dependence on fossil fuels, has rekindled interest in hydrogen as an automotive fuel.

Main Information

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1999:2022
Sources (Journals, Books, etc)	23
Documents	28
Annual Growth Rate %	7.25
Document Average Age	4.64
Average citations per doc	19.61
References	1
DOCUMENT CONTENTS	

Keywords Plus (ID)	141
Author's Keywords (DE)	106
AUTHORS	
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Authors of single-authored docs	3
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Co-Authors per Doc	4.54
International co-authorships %	21.43
DOCUMENT TYPES	
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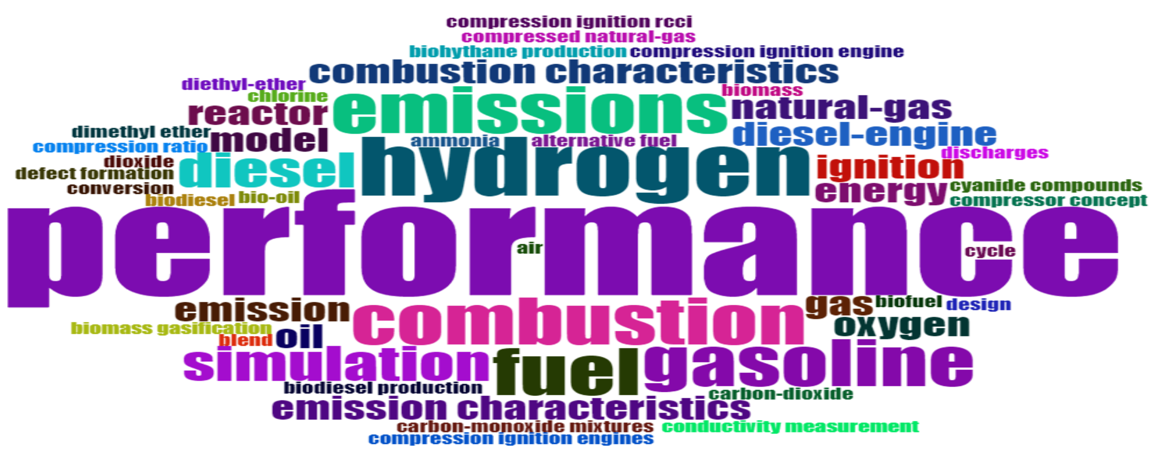
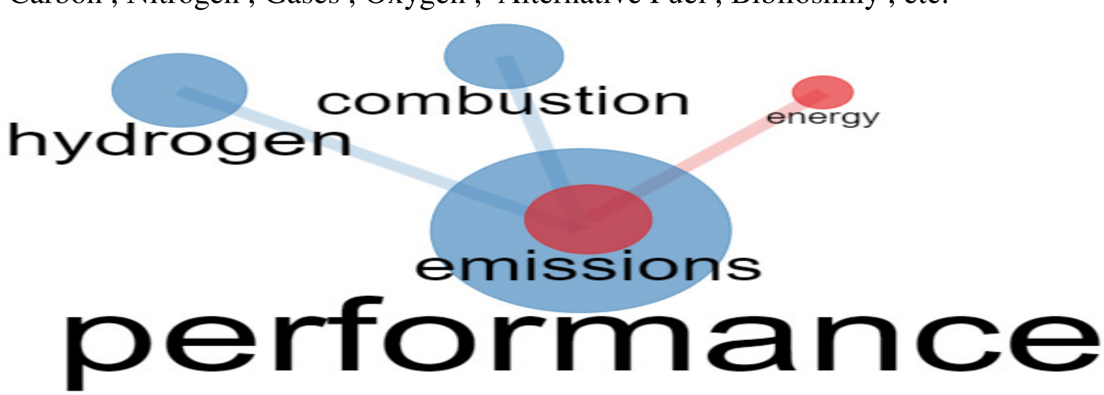
Keywords



Performance , Combustion , Hydrogen , Emission , Energy , Fuel , Gas, Ignition , Gasoline , Simulation , Exhaust , Carbon , Nitrogen , Gases , Oxygen , Alternative Fuel , Biblioshiny , etc.



Combustion Properties of Hydrogen

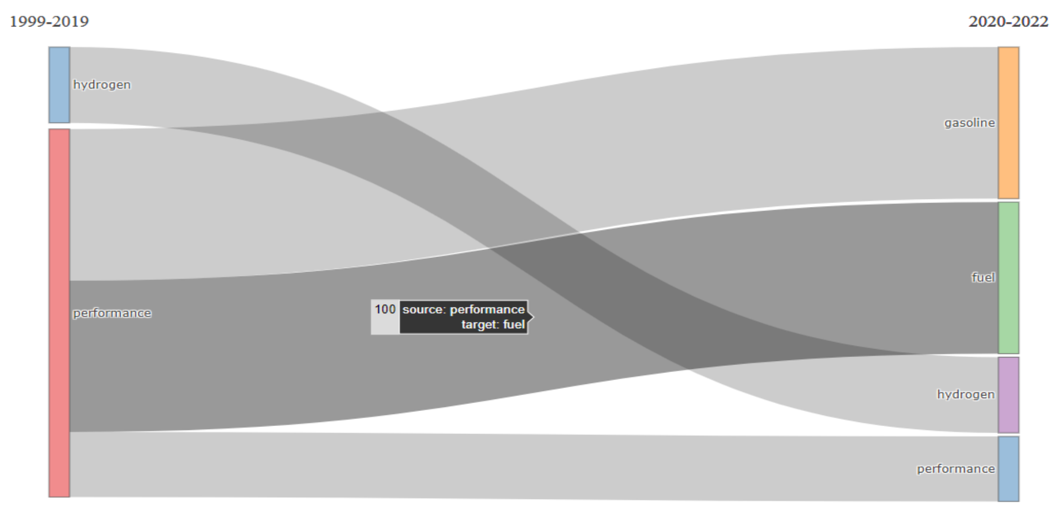
Properties that may affect the use of hydrogen as a combustible fuel:

- wide range of flammability
- low ignition energy
- small extinguishing distance
- high auto-ignition temperature
- high flame speed at stoichiometric ratios
- high diffusivity
- very low density

Wide Range of Flammability

Hydrogen has a wide range of flammability compared to all other fuels. As a result, hydrogen can be burned in an internal combustion engine in a wide variety of fuel-air mixtures. A significant advantage of this is that the hydrogen can run lean. A lean mixture is one in which the amount of fuel is less than the theoretical, stoichiometric, or chemically ideal amount required for combustion with a given amount of air. This is why it is relatively easy to start a hydrogen engine. So cold starts are very comparable to petrol or diesel.

In general, fuel consumption is higher and the combustion reaction is more complete when the vehicle is operated on a lean mixture. In addition, the final combustion temperature is generally lower, which reduces the amount of pollutants such as nitrogen oxides emitted in the exhaust. The lean rate of the engine is limited because lean operation can significantly reduce power output due to a reduction in the volumetric calorific value of the air/fuel mixture.



Low Ignition Energy

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

Unfortunately, the low ignition energy means that hot gases and hot spots on the cylinder can serve as sources of ignition, causing pre-ignition and flashback problems. Preventing this is one of the challenges of starting an engine. hydrogen. The wide range of hydrogen's flammability means that almost any mixture can be ignited by a hot spot.

Small Extinguishing Distance

Hydrogen has a small extinguishing distance, less than gasoline. As a result, hydrogen flames travel closer to the cylinder wall than other fuels before they die out. Thus, it is more difficult to extinguish a hydrogen flame than a gasoline flame. Shorter extinguishing distance can also increase the tendency to flashback, since a hydrogen-air mixture flame passes through a nearly closed intake valve more easily than a hydrocarbon-air flame.

High Auto-Ignition Temperature

Hydrogen has a relatively high auto-ignition temperature. This has important consequences when compressing a hydrogen-air mixture. The auto-ignition temperature is actually an important factor in determining what compression ratio an engine can use because the temperature rise during compression is related to the compression ratio. The temperature rise is represented by the equation:

$T_2=T_1 (V_1/V_2)$ ^$y-1$

where:

V_1/V_2 = compression ratio

T_1 = absolute initial temperature

T_2 = absolute final temperature

□ = ratio of specific temperatures

The temperature must not exceed the autoignition temperature of hydrogen without premature ignition. The absolute final temperature therefore limits the compression ratio. The high auto-ignition temperature of hydrogen allows higher compression ratios to be used in a hydrogen engine than in a hydrocarbon engine. This higher compression ratio is important because it is related to the thermal efficiency of the system, as discussed in Section 3.7. On the other hand, it is difficult to ignite hydrogen in a diesel or diesel ignition configuration because the temperatures required for these types of ignition are relatively high.

High Flame Speed

Hydrogen has a high flame speed at stoichiometric ratios. Under these conditions, the hydrogen flame speed is almost an order of magnitudehigher (faster) than gasoline. This means that hydrogen engines can come closer to the thermodynamically ideal engine cycle. For leaner mixtures, however, the flame speed drops significantly.

High Diffusivity

Hydrogen has a very high diffusivity. This ability to disperse in the air is considerably greater than that of gasoline and is advantageous for two main reasons. First, it facilitates the creation of a uniform mixture of fuel and air. Second, if there is a hydrogen leak, the hydrogen dissipates quickly. In this way, dangerous conditions can either be avoided or minimized.

Low Density

Hydrogen has a very low density. This results in two problems when used in an internal combustion engine. First, a very large volume is necessary to store enough hydrogen to give the vehicle enough range. Second, the energy density of the hydrogen-air mixture

Air/fuel ratio

The theoretical or stoichiometric combustion of hydrogen and oxygen is given as:

$2H_2 + O_2 = 2H_2O$

Moles of H_2 for complete combustion = 2 moles

Moles of O_2 for complete combustion = 1 mole

Since air is used as an oxidizer instead of oxygen, the nitrogen in the air must also be included in the calculation:

Moles of N_2 in air = Moles of O_2 x (79% N_2 in air / 21% O_2 in air)

= 1 mol O_2 x (79% N_2 in air / 21% O_2 in air)

= 3.762 mol N_2

Number of moles of air = moles of O_2 + moles of N_2

= 1 + 3.762

= 4.762 moles of air

Mass of O_2 = 1 mol O_2 x 32 g/mol

= 32 g

Mass of N_2 = 3.762 mol N_2 x 28 g/mol

= 105.33 g

Air mass = O_2 mass + N mass (1)

= 32 g + 105.33 g

= 137.33 g

Mass of H_2 = 2 moles of H_2 x 2 g/mol

= 4 g

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

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

= 137.33 g / 4 g

= 34.33:1

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

= 4.762 / 2

= 2.4:1

Percentage of combustion chamber occupied by hydrogen for stoichiometric mixture:

% H_2 = volume (mol) of H_2/total volume (2)

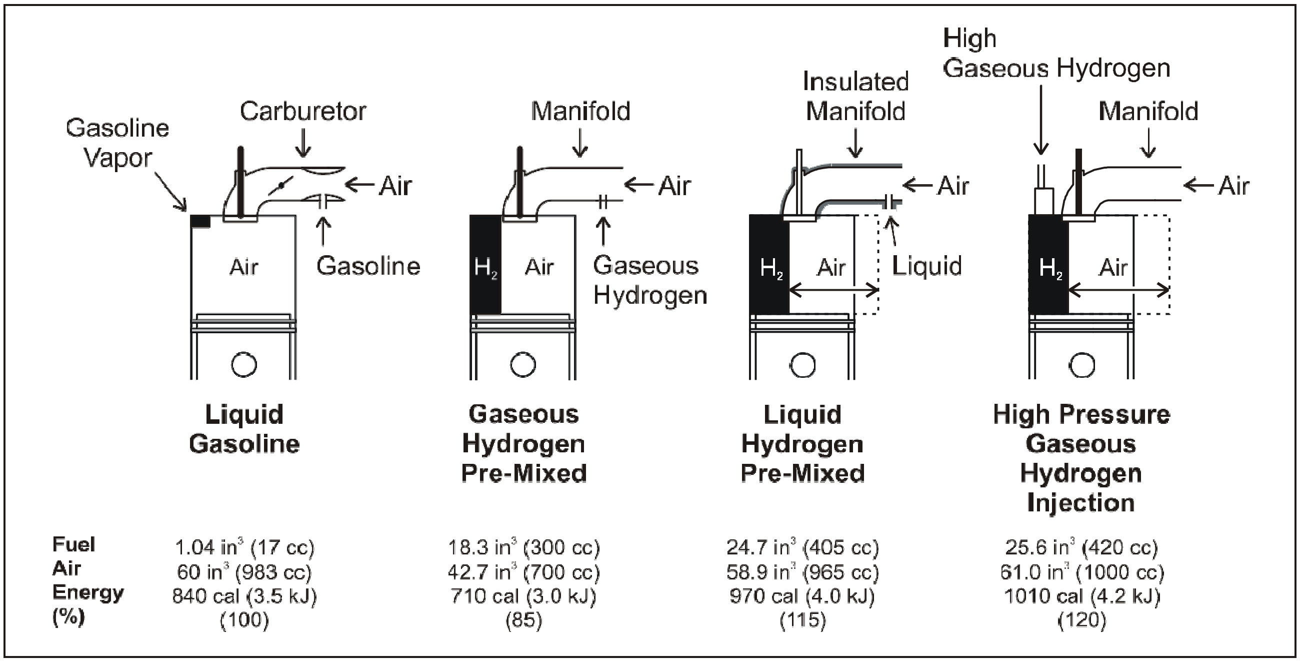
= volume of H_2/(volume of air + volume of H_2)

= 2 / (4.762 + 2)

= 29.6%

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

Since hydrogen is a gaseous fuel under ambient conditions, it displaces more of the combustion chamber than a liquid fuel. As a result, the air can occupy a smaller part of the combustion chamber. Under stoichiometric conditions, hydrogen displaces about 30% of the combustion chamber, compared to about 1 to 2% for gasoline.



Depending on the method used to dose the hydrogen to the engine, the output can be anywhere from 85% (intake manifold injection) to 120% (high pressure injection) compared to a gasoline engine.
Due to the wide range of hydrogen's flammability, hydrogen engines can run at A/F ratios from 34:1 (stoichiometric) to 180:1. The A/F ratio can also be expressed as an equivalence ratio, referred to as phi (□). Phi is equal to the stoichiometric A/F ratio divided by the actual A/F ratio. For a stoichiometric mixture, the actual A/F ratio is equal to the stoichiometric A/F ratio, and thus phi is equal to unity (one). For lean A/F ratios, the phi value will be less than one. For example, a phi value of 0.5 means that there is only enough fuel available in the mixture to oxidize with half the available air. Another way of saying this is that there is twice as much air available for combustion as is theoretically needed.

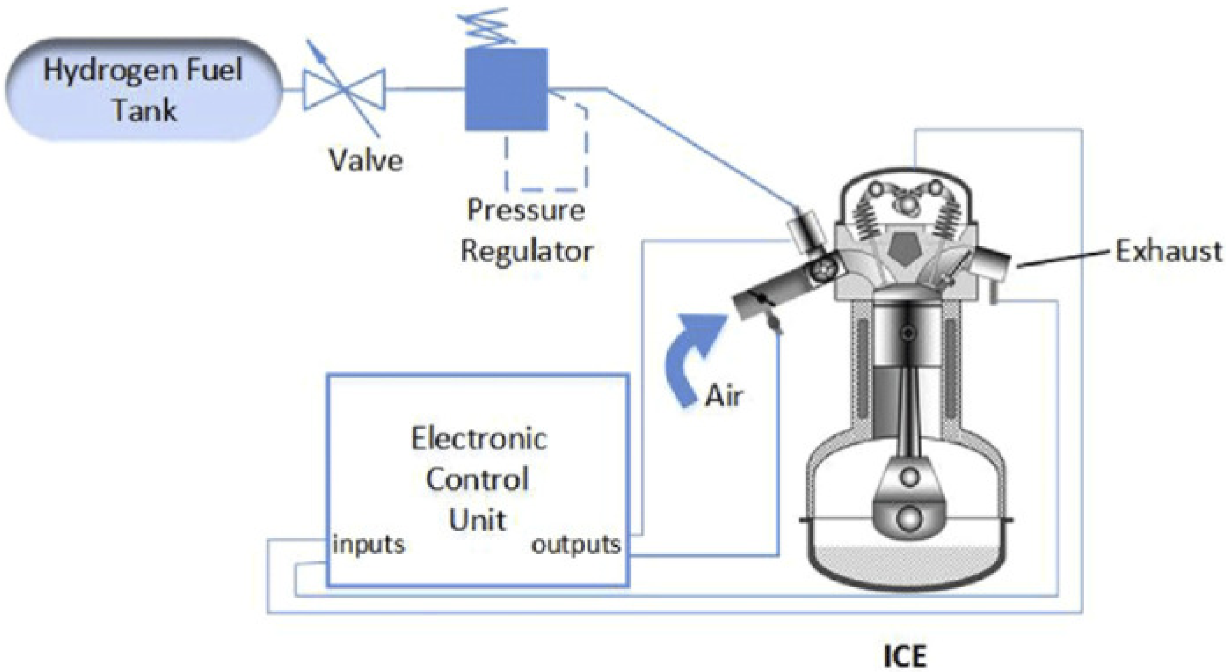
Pre-ignition Problems and their Solutions

The primary problem encountered in the development of functional hydrogen engines is pre-ignition. Pre-ignition is a much greater problem with hydrogen engines than with other internal combustion engines because hydrogen has a lower ignition energy, a wider range of flammability and a shorter extinguishing distance.
Pre-ignition occurs when the fuel mixture in the combustion chamber ignites before being ignited by the spark plug, resulting in an inefficient, rough engine run. Back-ignition conditions can also develop if pre-ignition occurs near the fuel intake valve and the resulting flame travels back into the intake system.
A number of studies have been focused on determining the cause of the advance in hydrogen engines. Some results indicate that pre-ignition is caused by hot spots in the combustion chamber, such as on the spark plug or exhaust valve, or by carbon deposits. Other research has shown that flashback can occur when there is an overlap between the opening of the intake and exhaust valves.

It is also believed that pyrolysis (chemical decomposition caused by heat) of oil suspended in the combustion chamber or in the crevices just above the upper piston ring may contribute to pre-ignition. This paralyzed oil can enter the combustion chamber by blow-by from the crankcase (i.e. around the piston rings), seepage around the valve train seals, and/or from the crankcase positive vent system (i.e. through the intake manifold).

Fuel Delivery Systems

Adapting or redesigning the fuel delivery system can be effective in reducing or eliminating pre-ignition.
The hydrogen fuel supply system can be divided into three main types: central injection (or "carbureted"), port injection, and direct injection.
Central and port fuel injection creates a mixture of fuel and air during the intake stroke. In the case of central injection or carburettor, the injection is at the inlet of the air intake manifold. In the case of port injection, it is injected at the inlet port.
Direct cylinder injection is technologically more sophisticated and consists in creating a mixture of fuel and air inside the combustion cylinder after closing the air intake valve.



Type of Fuel Delivery Systems that can be Used

Central Injection or Carburetor Systems

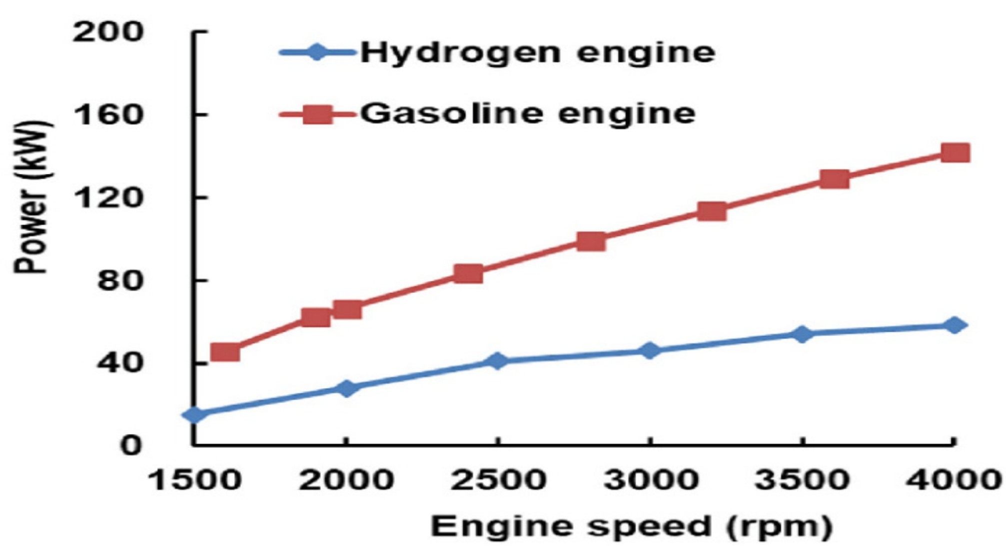
The simplest way to supply fuel to a hydrogen engine is through a carburetor or central injection system. This system has advantages for a hydrogen engine. First, central injection does not require the hydrogen supply pressure to be as high as other methods. Second, central injection or carburetors are used in gasoline engines, making it easy to convert a standard gasoline engine into a hydrogen or gasoline/hydrogen engine.
The disadvantage of central injection is that it is more prone to irregular combustion due to pre-ignition and flashback. A larger amount of hydrogen/air mixture in the intake manifold amplifies the effects of advance.

Port Injection Systems

A fuel injection system injects fuel directly into the intake manifold in each intake port, rather than drawing in fuel at a central point. Typically, hydrogen is injected into the manifold after the start of the intake stroke. At this point, conditions are much less severe and the likelihood of premature ignition is reduced.
In port injection, air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool any hot spots. Since there is less gas (hydrogen or air) in the manifold at any one time, any pre-ignition is less severe. The inlet inlet pressure for port injection tends to be higher than that of carbureted or central injection systems, but lower than that of direct injection systems.
The constant volume injection (CVI) system uses a cam-operated mechanical device to time the injection of hydrogen into each cylinder. The CVI block is shown on the far right of the photo with four fuel lines coming out of the left side of the block (one fuel line for each cylinder).
An electronic fuel injection (EFI) system doses hydrogen into each cylinder. This system uses separate electronic fuel injectors (solenoid valves) for each cylinder and are connected to a common fuel rail located in the center of the intake manifold. While the CVI system uses constant injection timing and variable fuel rail pressure, the EFI system uses variable injection timing and constant fuel rail pressure.

Direct injection systems

More sophisticated hydrogen engines use direct injection into the combustion cylinder during the compression stroke. In direct injection, the intake valve is closed during fuel injection, completely preventing premature ignition during the intake stroke. As a result, the engine cannot return to the intake manifold.
The output of the direct injection hydrogen engine is 20% higher than that of a gasoline engine and 42% higher than that of a carbureted hydrogen engine.
While direct injection solves the problem of advance in the intake manifold, it does not necessarily prevent pre-ignition in the combustion chamber. Additionally, due to the shortened air-fuel mixing time in a direct injection engine, the air-fuel mixture can be inhomogeneous. Studies suggest that this can lead to higher NOx emissions than indirect injection systems. Direct injection systems require higher fuel rail pressure than other methods.



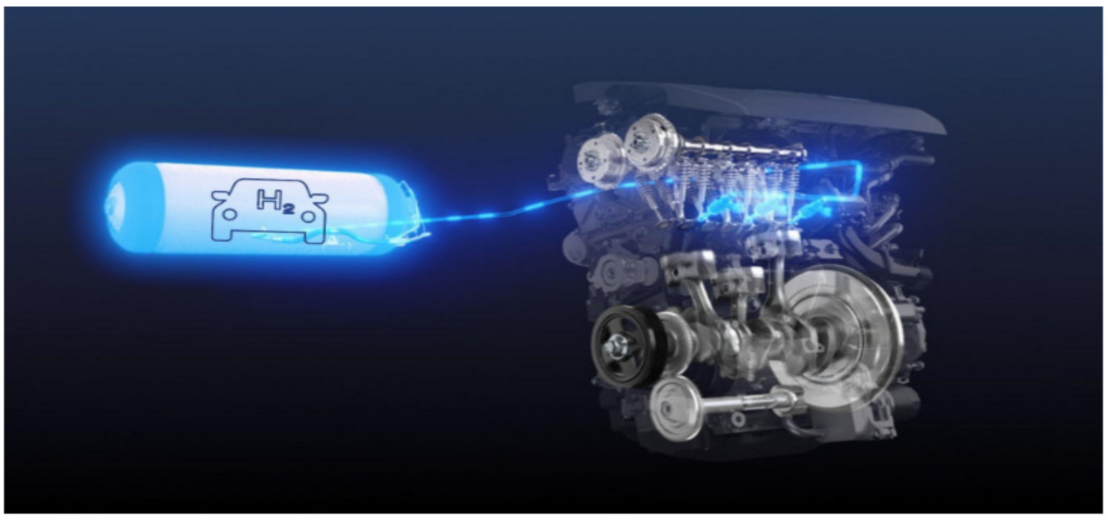
Thermal Dilution

Pre-ignition conditions can be reduced using thermal dilution techniques such as exhaust gas recirculation (EGR) or water injection.

As the name suggests, the EGR system recalculates some of the exhaust gases back into the intake manifold. The introduction of exhaust gases helps reduce the temperature of hot spots and reduces the possibility of pre-ignition. In addition, the exhaust gas recalculation lowers the peak combustion temperature, which reduces NOx emissions. Typically, 25 to 30% exhaust gas recirculation is effective in eliminating backburn.

On the other hand, using EGR will reduce engine power. The presence of exhaust gases reduces the amount of fuel mixture that can be drawn into the combustion chamber.

Another technique for thermal dilution of the fuel mixture is water injection. Injecting water into the hydrogen stream before mixing with air produced better results than injecting it into the hydrogen/air mixture in the intake manifold. A potential problem with this type of system is that water can mix with the oil, so care must be taken not to leak the seals.



A hydrogen internal combustion engine can be produced by simply making a set of modifications to existing petrol and diesel engines. Image: Toyota

Engine Construction

The most effective means of controlling advance and knocking is to redesign the engine for hydrogen, specifically the combustion chamber and cooling system The most effective means of controlling advance and knocking is to redesign the engine for hydrogen use, specifically the combustion chamber and cooling system. A disc-shaped combustion chamber (with a flat piston and a chamber ceiling) can be used to reduce turbulence inside the chamber. The shape of the disk helps to create low radial and tangential velocity components and does not amplify the input vortex during compression.

Since unburned hydrocarbons are not a problem with hydrogen engines, a large bore to stroke ratio can be used with this engine. Two spark plugs are required to accommodate the wider range of flame speeds that occur over a larger range of equivalence ratios. The cooling system must be designed to provide an even flow to all areas that need cooling.

Additional measures to reduce the likelihood of advance are the use of two small exhaust valves as opposed to one large one and the development of an efficient scavenging system, a means of displacing the exhaust gases from the combustion chamber with fresh air.

Ignition systems

Due to the low ignition energy limit of hydrogen, ignition of hydrogen is easy and gasoline ignition systems can be used. At very lean air/fuel ratios (130:1 to 180:1) the flame speed is greatly reduced and the use of a twin spark plug system is preferred.

Hydrogen engines should not use ignition systems that use a waste spark system. These systems activate the spark every time the piston is at top dead center, whether the piston is on the compression stroke or the exhaust stroke. For gasoline engines, waste spark systems work well and are less expensive than other systems. In hydrogen engines, waste sparks are a source of pre-ignition.

Spark plugs for a hydrogen engine should be cold and have non-platinum tips. A cold spark plug is one that transfers heat from the spark plug tip to the cylinder head faster than a high performance spark plug. This means that the likelihood of the spark plug tip igniting the air/fuel charge is reduced. Hot spark plugs are designed to retain a certain amount of heat to prevent carbon deposits from building up. Since hydrogen does not contain carbon, high output spark plugs do not serve a useful function.

Platinum spark plugs should also not be used because platinum is a catalyst that causes hydrogen to oxidize in the air.

Crankcase Ventilation

Crankcase ventilation is even more important for hydrogen engines than for gasoline engines.

As with gasoline engines, unburnt fuel can seep through the piston rings and into the crankcase. Since hydrogen has a lower flash point than gasoline, any unburnt hydrogen entering the crankcase has a better chance of igniting. Hydrogen accumulation must be prevented by ventilation.

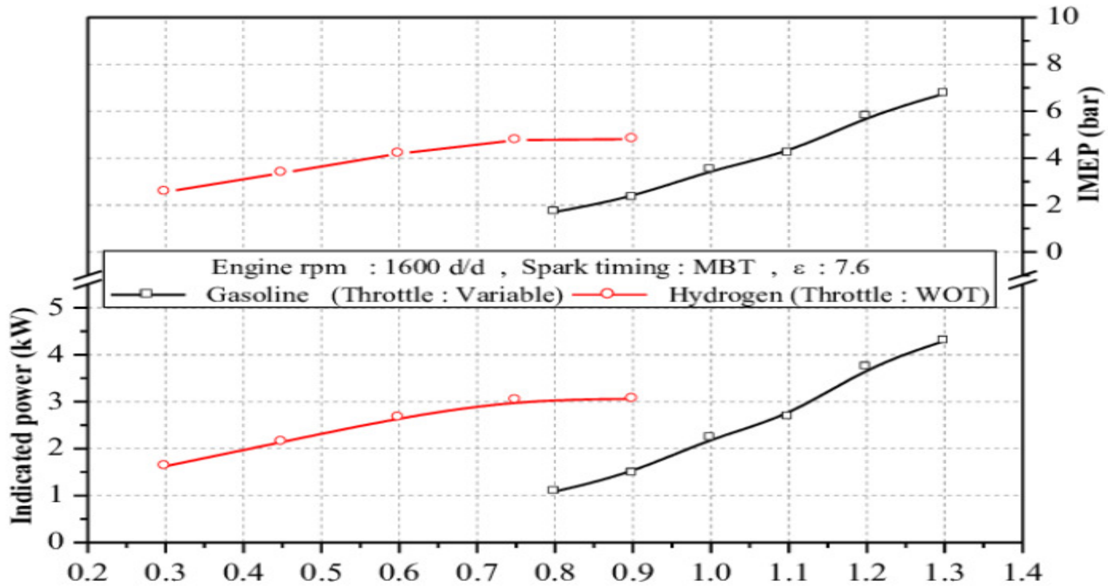
Ignition in the crankcase can be just a screeching sound or it can cause an engine fire. When hydrogen ignites in the crankcase, there is a sudden increase in pressure. A relief valve must be installed on the valve cover to relieve this pressure.

Exhaust gases can also enter the crankcase through the piston. Since hydrogen exhaust gases are water vapor, water may condense in the crankcase if proper ventilation is not provided. Mixing water into the crankcase can reduce the lubricity of the oil, resulting in high or elevated engine temperatures or high engine wear

Thermal Efficiency

The theoretical thermodynamic efficiency of an Otto cycle engine is based on the compression ratio of the engine and the ratio of the specific heat of the fuel as shown in the equation:

$$\eta_{th} = 1 - \frac{1}{\left(\frac{V_1}{V_2}\right)^{\gamma-1}}$$



Emissions

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

$2H_2 + O_2 = 2H_2O$

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

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

The oxides of nitrogen are created due to the high tempera- tures generated within the combustion chamber during combustion. This high temperature causes some of the ni- trogen in the air to combine with the oxygen in the air. The amount of NOx formed depends on:

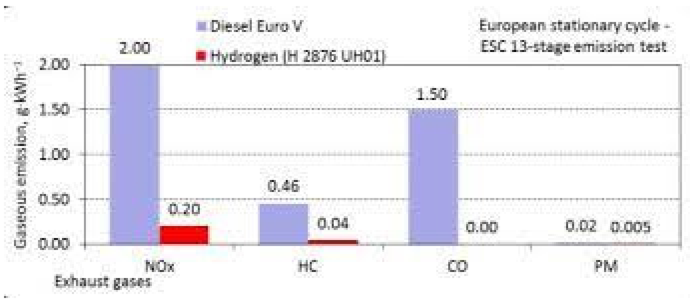
- the air/fuel ratio
- the engine compression ratio
- the engine speed
- the ignition timing
- whether thermal dilution is utilized

In addition to 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.

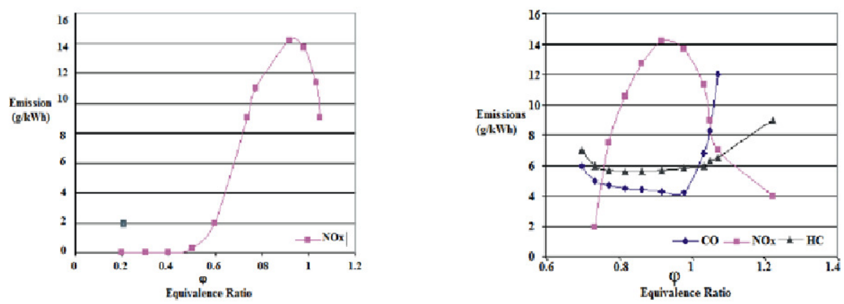
Depending on the condition of the engine (burning of oil) and the operating strategy used (a rich versus lean air/fuel ratio), a hydrogen engine can produce from almost zero emissions (as low as a few ppm) to high NOx and significant carbon monoxide emissions.

illustrates a typically NOx curve relative to phi for a hydrogen engine. A similar graph including other emissions is shown

Emission Graphs



Hydrogen vs. Diesel graph (Fig.1)



Hydrogen vs. Gasoline Graph (fig 2)

Power Output

The theoretical maximum power output from a hydrogen en- gine depends on the air/fuel ratio and fuel injection method used.

The stoichiometric air/fuel ratio for hydrogen is 34:1. At this air/fuel ratio, hydrogen will displace 29% of the combustion chamber leaving only 71% for the air. As a result, the energy content of this mixture will be less than it would be if the fuel were gasoline (since gasoline is a liquid, it only occupies a very small volume of the com- bustion chamber, and thus allows more air to enter).

Since both the carbureted and port injection methods mix the fuel and air prior to it entering the combustion chamber, these systems limit the maximum theoretical power obtain- able to approximately 85% of that of gasoline engines. For direct injection systems, which mix the fuel with the air after the intake valve has closed (and thus the combustion chamber has 100% air), the maximum output of the engine can be approximately 15% higher than that for gasoline engines.

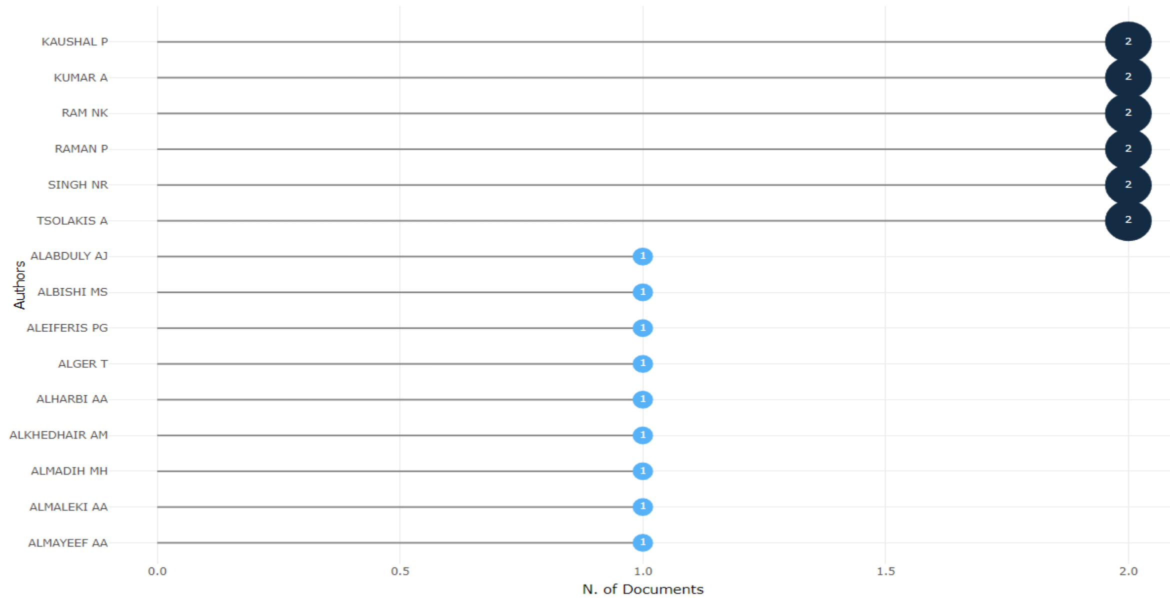
Therefore, depending on how the fuel is metered, the maxi- mum output for a hydrogen engine can be either 15% higher or 15% less than that of gasoline if a stoichiometric air/fuel ratio is used. However, at a stoichiometric air/fuel ratio, the combustion temperature is very high and as a result it will form a large amount of nitrogen oxides (NOx), which is a cri- teria pollutant. Since one of the reasons for using hydrogen is low exhaust emissions, hydrogen engines are not normally designed to run at a stoichiometric air/fuel ratio.

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.

Hydrogen Gas Mixtures

Hydrogen can be used advantageously in internal combustion engines as an additive to a hydrocarbon fuel.
Hydrogen is most commonly mixed with high pressure natural gas for this purpose since both gases can be stored in the same tank. If hydrogen is blended with other fuels, it usually has to be stored separately and mixed in the gaseous state immediately before ignition. In general, it is impractical to use hydrogen in conjunction with other fuels that also re- quire bulky storage systems, such as propane.
Gaseous hydrogen cannot be stored in the same vessel as a liquid fuel. Hydrogen's low density will cause it to remain on top of the liquid and not mix. Furthermore, liquid fuels are stored at relatively low pressures so that very little hydrogen could be added to the vessel.
Liquid hydrogen cannot be stored in the same vessel as other fuels. Hydrogen's low boiling point will freeze other fuels resulting in fuel "ice"!
Hydrogen can be used in conjunction with compact liquid fuels such as gasoline, alcohol or diesel provided each are stored separately. In these applications, the fuel tanks can be formed to fit into unused spaces on the vehicle. Existing vehicles of this type tend to operate using one fuel or the other but not both at the same time. One advantage of this strategy is that the vehicle can continue to operate if hydro- gen is unavailable.
Hydrogen cannot be used directly in a diesel (or "compression ignition") engine since hydrogen's auto ignition temperature is too high (this is also true of natural gas). Thus, diesel engines must be outfitted with spark plugs or use a small amount of diesel fuel to ignite the gas (known as pilot ignition). Although pilot ignition techniques have been developed for use with natural gas, no one is currently doing this with hydrogen.
One commercially available gas mixture known as Hyphened contains 20% hydrogen and 80% natural gas. At this ratio, no modifications are required to a natural gas engine, and studies have shown that emissions are reduced by more than 20%. Mixtures of more than 20% hydrogen with natural gas can reduce emissions further but some engine modifications are required.

Most Relevant Authors



Authors	Articles	Articles Fractionalized
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KUMAR A	2	0.40
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RAMAN P	2	0.40
SINGH NR	2	0.40
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BANKE K	1	0.17

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Abstract

The adverse environmental impact of fossil fuel combustion in engines has motivated research towards using alternative low-carbon fuels. In recent years, there has been an increased interest in studying the combustion of fuel mixtures consisting mainly of hydrogen and carbon monoxide, referred to as syngas, which can be considered as a promising fuel toward cleaner combustion technologies for power generation. This paper provides an extensive review of syngas production and application in internal combustion (IC) engines as the primary or secondary fuel. (Alharbi et al., 2022; Banke et al., 2019; First, a brief overview of syngas as a fuel is given, an introduction to the various methods of its production, with a focus on its historical use, and a summary of the advantages and disadvantages of using syngas as a fuel. Its physicochemical properties relevant to internal combustion engines are then reviewed, emphasizing studies of fundamental combustion characteristics such as ignition delay and laminar and turbulent flame speeds. The main part of the contribution is devoted to an overview of the influence of syngas utilization on the performance and emission characteristics of spark ignition (SI), compression ignition (CI), homogeneous charge compression ignition (HCCI) and advanced dual-fuel engines, such as reactivity - controlled compression ignition engines (RCCI). Finally, various on-board fuel reforming techniques for syngas production and use in vehicles are reviewed as a potential route to further increase the efficiency and reduce emissions of internal combustion engines. These are then related to research on the behavior of syngas and its mixtures in IC engines. The choice of syngas production method, choice of base fuel for reforming, its physicochemical properties, combustion strategy and engine combustion system, and operating conditions were found to play a critical role in determining the potential benefits of using syngas in IC engines. The discussion of this review article provides valuable insights for future research on synthesis gas as a possible fuel for IC engines for transportation.

Reference

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Chitragar et al., 2016; Dimitriou&Tsujimura, 2019;

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Nonomura, 2005;

Paykani et al., 2022;

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Sher & Sher, 2011;

Shukla et al., 2022;

Steinberg, 1999;

Wang et al., 2015; Yuan et al., 2012)