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A Review of the Use of Hydrogen Gas in Internal Combustion Engines

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Abstract. The demand for fossil fuels is expanding daily as a result of the globalization of industry, which has driven a rise in global energy consumption. To address the growing need for sustainable energy to lower harmful emissions and address the depletion of fossil fuel reserves, research into viable alternative fuels with reduced environmental effects is urgently needed. Alternative energy sources that are sustainable, cost-effective, easy, and safe are thus being investigated by a number of countries. Hydrogen is a clean-burning alternative fuel that offers excellent efficiency and use characteristics. Due to its carbon-free nature, broad flammability limitations, and rapid flame rates, hydrogen may be regarded as a possible alternative to most fossil fuels. Carbon monoxide (CO) and other toxic gases are also produced by hydrocarbon fuels, such that replacement by hydrogen in the near future would help to fulfil current rigorous emissions criteria. It is also anticipated that the use of hydrogen as a primary or additional fuel in engines would have a favorable influence on the environment. Hydrogen, despite being the most plentiful element in the universe, is not easily accessible in its molecular form, however, and it must be created via the use of other sources of energy. As a result, hydrogen acts mainly as a transporter of energy rather than an energy source. The difficult tasks of hydrogen production and delivery, as well as creating safe hydrogen storage for use in internal combustion engines, must be addressed before fully hydrogen-driven cars become economically feasible. Its uses as an additive for gasoline and diesel engines to increase engine performance and reduce exhaust emissions are thus discussed. Engine power and torque rise significantly in gasoline engines when hydrogen is added to the fuel system, whereas they decrease in diesel engines when hydrogen is introduced. In terms of chemical compounds, gasoline engines emit fewer dangerous exhaust gases, while some diesel engines emit more nitrogen oxides under the influence of hydrogen. Overall, this study contains a summary of the numerous advancements that have occurred in this sector in recent years.

Keywords: Hydrogen, energy, combustion, fuel, renewable.

INTRODUCTION

For a long time, fossil fuels such as gasoline and diesel were the main sources of energy for both transportation and power generation. As fossil fuels have a limited capacity and significant adverse environmental impacts, however, the worldwide community has become increasingly interested in developing alternative fuels that are better for the environment [1]. This century's most pressing concerns include the need to produce more energy, while mitigating the environmental problems of both pollution on a local level and global warming: however, in the year 2016, a target of limiting global warming to 2 °C was agreed upon by most nations when it was finally recognized that some warming was unavoidable given modern behaviors [2]. This is because currently, fossil fuels in liquid form provide about 65% of the world's energy requirements [3], as they are readily available and simple to utilize. However, even using current technology, approximately 25% of passenger cars and 20% of non-electric rail transport could be powered by hydrogen by 2050, according to the Hydrogen Council, a global hydrogen energy initiative composed of various energy and transportation companies, which would support a 20% reduction in daily oil consumption for transportation [4][5]. This may be optimistic, without further technological development, yet it must be considered, as the danger from fossil fuel use is both worrying and significant, while fossil fuel reserves themselves are limited. Figure 1 shows a graph of projected global natural oil reserves as a ratio of reserves to production (R/P) [6].

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Studies have been conducted to analyze the performance and emissions of conventional engines using various alternative fuels, with encouraging results. In particular, its unique qualities such as quick flame velocity, high calorific value, low ignition energy, and the ability to run in the ultra-lean range in internal combustion engines (IC) mean that hydrogen gas offers an attractive alternative fuel [7]. Hydrogen also has several advantages over traditional fossil fuels. It produces much less toxic exhaust when used in the internal combustion engines and fuel cells: when used in a fuel cell, it produces only water vapor, making it highly ecologically friendly [8]. In addition, hydrogen has a calorific value three times higher than petroleum [9].

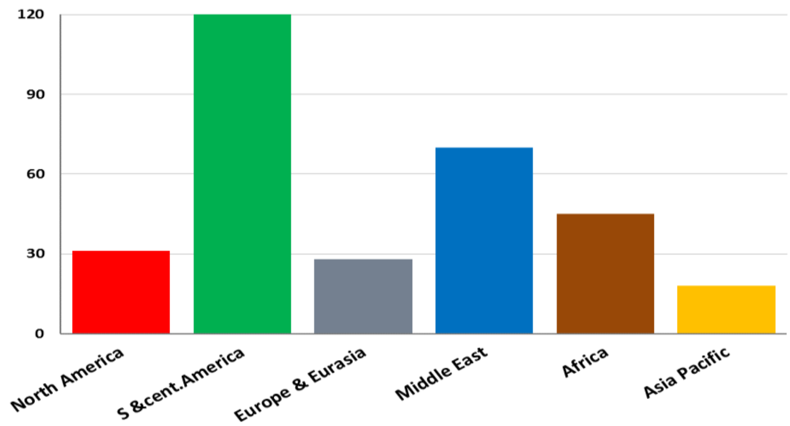


FIGURE 1. Forecasts for world reserves of natural oil

Previous research has found that engine efficiency and low operating limits are also increased on using hydrogen, suggesting that using hydrogen as a fuel has the potential to cut emissions and fuel consumption even further. Despite the benefits of utilizing hydrogen in IC engines, however, issues with hydrogen gas storage, costs, and manufacturing techniques remain significant, blocking roll-out of this technology. Using onboard-hydrogen manufacturing methods and adopting adequate control mechanisms to manage the fuel might help overcome these difficulties [10], supporting the use of hydrogen as an excellent carbon-free fuel with a calorific value three times higher than petroleum that also limits creation of pollutants [9]. As hydrogen used in a fuel cell creates H_2O, it is an ecologically beneficial fuel [8], and as compared directly with coal, gasoline and methane, hydrogen has a heating value 4, 2.8, and 2.4 times greater, respectively [11]. A more detailed comparison of the properties of hydrogen, gasoline, and diesel is shown in Table 1.

TABLE 1. Fuel characteristics

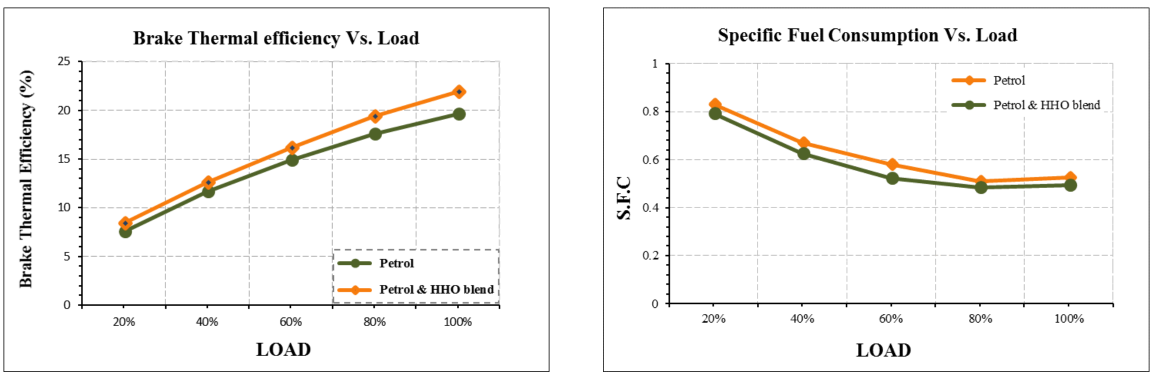
Properties	Hydrogen	Gasoline	Diesel
Content of carbohydrates (mass%)	0	84	86
Closing gap (cm)	0.06	0.2	-
Diffusion coefficient under stoichiometric conditions (cm^2/s)	0.61	0.05	-
Flame speed of 293 k (cm/s).	237	41.5	-
Limits of flammability (Vol % in air)	4.1–75	1.5–7.6	0.6_5.5
ratio of A/F stoichiometry	34.3	14.6	17
The molecular mass	2.015	110	170
The adiabatic flame's temperature (K)	2384	2270	2300
The calorific Its value is in kilograms (MJ/kg) is lower.	120	44	-
The ignition temperature (K)	858	530	-

Due to the obvious promise of hydrogen fuels in internal combustion engines as a renewable and eco-friendly fuel, further research into their effects on spark- and compression-ignition engines is ongoing. Spark- and compression-ignition engines using hydrogen fuels are compared to existing engines to see how such engines perform and emit when using various fuels. However, the challenges associated with hydrogen generation and consumption must also be considered, and the development of hydrogen for use in engines powering cars and other forms of transportation has also become a major research area. Hydrogen-powered transmission systems must thus be evaluated by considering all of the latest developments in the field, although the focus should be on internal combustion engines (ICE) and fuel cells (FCV).

EFFECTS OF HYDROGEN USE ON PETROL ENGINE

One emphasis in current research is on the examination of the effects of HHO gas added to IC engines in combination with gasoline. Experiments with two different kinds of electrolyte to improve the electrolysis process's efficiency [13]. showed that 6 g/L of potassium hydroxide (KOH) used as a catalyst provides superior efficiency at various speeds, while 4 g/L of NaOH provides superior thermal efficiency in comparison to concentrations. Further findings based on the usage of HHO gas in conventional engines include the fact that when HHO gas is added to an air/fuel combination, the thermal efficiency of the engine may be boosted by up to 10%, resulting in a reduction in fuel consumption of up to 34%. When HHO is added into the system, the concentrations of NOx, CO, and HC gases are also lowered, to averages of about 15%, 18%, and 14%, respectively. KOH, at a concentration of 6g/L, is the best available catalyst as tested.

Investigation of how the addition of hydroxyl gas affects a four-stroke, multi-cylinder gasoline engine was also performed by [14]. After testing, it was confirmed that engine braking performance improved by about 11.5% on average, while average engine-specific fuel consumption was reduced by 6.35% and average engine thermal efficiency increased about 10.26%. Engine exhaust gas temperature decreased by approximately 4%, and the improved fuel combustion reduced NO_X emissions, as shown in Fig. 2.



(a)

(b)

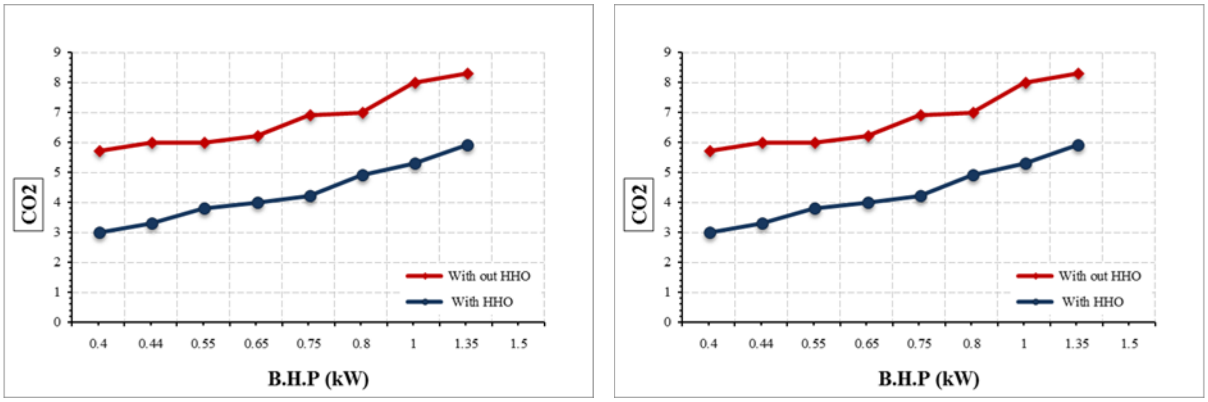
FIGURE 2. (a) Brake thermal efficiency, and (b) Specific fuel consumption vs load.

Experiments were conducted in [15] to determine the effects of adding HHO gas to the fuel mix on the emissions from a Honda G200 engine. HHO gas was mixed with fresh air just prior to this being fed into the carburetor, and the resulting exhaust gases were assessed using a gas analyzer, with all exhaust components identified and their concentrations determined. Nitrogen oxides and nitrogen monoxide (NOx) emissions were significantly reduced, by up to 50%, when a mixture of HHO, air, and fuel was used, and a reduction in fuel consumption of 20 to 30% was also observed.

Researchers in [16] focused on studying and evaluating the performance and emission characteristics of regular gasoline and HHO gas in an unmodified SI four-stroke single-cylinder engine with no storage tanks. The most notable result was an average 6.7% reduction in hydrocarbon emissions as compared to the use of pure gasoline. Thermal efficiency was also improved by the addition of hydroxyl gas, even when no load changes occurred: the SFC method suggests that the use of HHO gas results in an average increase of 16.3%.

The use of HHO gas in a gasoline engine was also examined in [17], which found that using hydrogen as a fuel in gasoline engines improves combustion efficiency and results in a 20% reduction in fuel consumption. The use of hydrogen in gasoline engines can also reduce the production of hazardous pollutants such as carbon monoxide and unburned hydrocarbons while improving power output by 5.7%. The thermal efficiency of gasoline engines is also improved by about 5% when hydrogen is used instead of gasoline.

The focus in [18] was on conducting an experiment with a four-stroke gasoline engine using HHO gas as a fuel additive. A number of interesting results were obtained, including the fact that the use of HHO in gasoline engines improved combustion efficiency and resulted in a 20% reduction in fuel consumption. The use of HHO in gasoline engines also reduced hazardous emissions such as carbon monoxide and unburned hydrocarbons while increasing engine power by about 5.7% and thermal efficiency by about 5%. The graphs in Fig. 3 illustrate the lowered levels of exhaust gas emissions on using HHO gas.



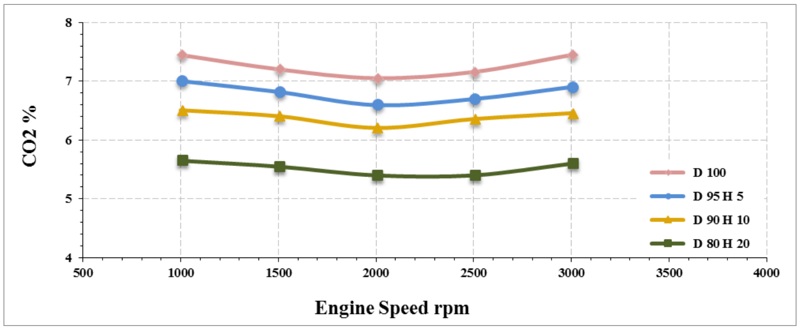
(a) (b)

FIGURE 3. (a) Unburned hydrocarbons emissions, and (b) Carbon dioxide emissions, vs Brake Horse Power.

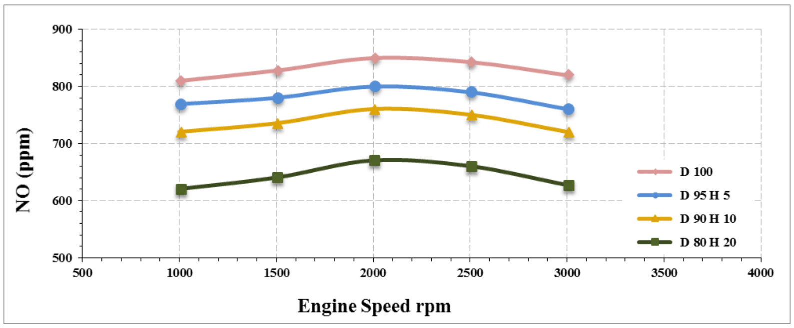
Adding HHO gas to a TVS Victor 109cc engine produced results that showed that the engine was quieter and cleaner, with increased economy, increased horsepower, and reduced pollutants. The theoretical calculations used to determine HHO emissions were the main focus of [19], however, and according to the estimates produced, the electrolysis of water produces 0.25 L of hydrogen and 0.063 L of oxygen when 4.5 A of current is applied over a time period of 216.5 seconds.

EFFECTS OF USING HYDROGEN ON DIESEL ENGINES

The researchers in [20] focused on investigating and evaluating engine performance, exhaust gas characteristics, and the combustion process in a hydrogen diesel engine as compared to a pure diesel engine. The use of hydrogen as a fuel additive to diesel fuel improved engine performance and exhaust emissions, with both nitrogen oxide and carbon dioxide emissions reduced, as shown in Fig. 4.



(a)



(b)

FIGURE 4. (a) Carbon dioxide emissions, and (b) Nitrogen oxides emission vs engine speed

An experiment in which HHO gas was injected through an air filter into the intake manifold of a four-stroke diesel engine was undertaken in [21], which examined and compared fuel consumption under typical operating conditions. The diesel and HHO gas mix reduced gasoline consumption by 12.08%, while in one of the tests, braking performance decreased. Carbon deposits in the cylinder were reduced and oil life was extended.

The researchers in [22] investigated whether injecting HHO gas into the intake air of a direct-injection diesel engine affects performance. The experiment was performed at steady speed with variable loads, and the HHO was generated using electrolysis of water. HHO was found to lower the maximum power output of the engine, potentially due to the fact that the cylinder contains less additional air while the sheer volume of oxygen-hydrogen in the intake mixture reduces the volumetric efficiency, thereby reducing the incoming air flow. At low loads of up to 20%, the specific fuel consumption decreased, while at higher loads, the specific fuel consumption remained steady, however. According to this experience, oxy hydrogen can increase engine performance only at low loads.

Other experiments have shown that adding HHO gas to a diesel engine makes it run better, however. Consumption of fuel and brake thermal efficiency, as well as volumetric efficiency, and load were monitored during testing in [23], with results that demonstrated that the specific fuel consumption was reduced. The tests showed that, at a maximum load of 8kg, approximately 10g less fuel is needed to produce the same amount of energy per hour: as a larger volume of the mixture goes into the combustion chamber with this fuel mixture, the volumetric efficiency also goes up. An increase in braking force similarly occurs due to the hydrogen gas present in the air, while the resulting water vapor in the combustion chamber decreases the temperature inside, which helps to keep the cylinder walls from developing carbon deposits.

HYDROGEN PRODUCTION METHODS

In recent years, hydrogen has become recognized as potentially one of the most useful alternatives to fossil fuels due to its unique properties such as a wide range of flammability, a short cooling distance, low energy of the ignition source, high diffusion, and low density. The form of hydrogen used for this does not exist in nature in its pure form, however, and it must thus be produced from hydrogen containing molecules, such as fossil fuels or hydrogen supplied, or from biomass and water. Hydrogen must also be isolated from the other items in the products of such processes

[24]. The processes that can be used to produce hydrogen include methane steam reforming and coal gasification, which are the current industry standards due to being less expensive (under \$2/kg of H_2) than other alternatives [25].

Hydrogen Production from Fossil Fuels

Steam Methane Reforming.

The steam methane reforming method accounts for approximately 90% of the hydrogen produced worldwide [26]. It is both a common and cost-effective method of producing hydrogen gas in which impurities are removed from natural gas before it is mixed with steam and passed through a heated external reactor to produce hydrogen (H_2) and carbon monoxide (CO). A catalytic water gas conversion reaction then converts the carbon monoxide (CO) and water into hydrogen gas and carbon dioxide (CO_2), allowing the hydrogen to then be purified [27].

The chemical reaction between steam and methane [28] is that:

$$\text{Heat} + H_2O + CH_4 \rightarrow CO + 3H_2 \tag{1}$$

The water-gas reaction **[**28**]** is then:

$$H_2O + CO \rightarrow \text{Heat (few amount)} + H_2 + CO_2 \tag{2}$$

Coal Gasification.

The main components of coal are carbonate (the decaying remains of ancient plants) and metallic materials (originating from the earth from which coal is mined). After metal removal, the carbon-based substance thus consists of five basic components: carbon, hydrogen, oxygen, nitrogen, and Sulphur [29]. In coal gasification, steam and oxygen are used to partially oxidize coal at high pressure in a high temperature reactor. Carbon dioxide and hydrogen gas, along with steam, are the end products (syngas), with the carbon dioxide produced acting as a gasifier. Syngas can undergo a conversion process to improve hydrogen generation; however, as carbon dioxide emissions from coal are greater than those from other feedstock types, the high carbon content of coal is the primary problem in coal gasification. Carbon capture and storage technologies are thus being investigated to address this issue.

Hydrogen Production from Nuclear Energy

The thermochemical splitting of water.

In the energy industry, sustainable development is critical to the adoption of zero-carbon alternative fuels. It is possible to manufacture hydrogen from both renewable and non-renewable sources, converting it into electricity, or extract it directly from the power grid [27][30]. Long-term hydrogen generation using fossil fuels is unreliable, however, and the development and dissemination of H_2 generation methods based on sustainable energy sources, such as nuclear or renewable energy, are required in order to manufacture hydrogen in a safe and sustainable manner [4]. One sustainable approach to hydrogen production is water separation, and, depending on the type of energy driving the process, hydrogen can be formed from water in several ways [4]. Thermochemical Water Splitting Cycles (TWSCs) offer one of the most well-known hydrogen production methods, using a series of well-known chemical processes that split water into hydrogen and oxygen using the energy provided by a heat source [31]. High temperatures and sufficient building materials are required for one-step water splitting, which occurs at temperatures above 2000 °C [32]. Such thermochemical cycles thus require special reactors that use inert chemicals capable of withstanding high temperatures. Developing these special materials in an economically feasible manner is thus a further challenge for thermochemical cycle use. However, this approach has shown promising results in laboratory settings [33], thus raising hopes for potential methods for hydrogen production in the future.

High temperature electrolysis.

The High Temperature Electrolysis (HTE) reaction is carried out in an electrolytic cell, which consists of a cathode and anode that split water into hydrogen and oxygen. In the HTE reaction, water is heated using an external source before entering the electrolysis cell in the form of steam. The steam is then fed to the cathode of the electrolysis cell, which splits it into hydrogen and oxygen ions. Both thermal and electrical energy are thus required, commonly derived from nuclear sources [34].

Production of Hydrogen Using Renewable Energy Sources

Electrolysis.

The electrolyze, a system of cells with a positive and a negative electrode in each, forms the nucleus of the well-known electrolysis procedure. Electrodes are submerged in water rendered electrically conductive by the addition of hydrogen or hydroxyl ions, often in the form of alkaline potassium hydroxide (KOH). The rate of hydrogen production is then correlated with the current density, which is calculated as current flow divided by electrode area [A/m^2]. The source voltage requirements and energy cost per unit of hydrogen thus increase with increase in current density. Currently, electrolysis are up to 80% efficient, as well as relatively dependable. Using renewable energy to produce hydrogen thus offers a practical alternative to other methods, although power prices are currently excessively high [35].

Solar energy.

Solar power can be used to electrolyze water to make hydrogen. Proton exchange membrane electrolysis (PEM), solid oxide electrolysis cells (SOEC), and alkaline electrolysis of water (AEW) are the main technologies used thus far in this approach. The AEW and PEM technologies are the most promising for H2 generation on the market right now, especially PEM, which has the benefit of being able to be paired with renewable energy sources [36][37].

Wind.

Existing electricity and water infrastructure is often used in electrolysis. Hydrogen can be produced by the electrolysis of water in an electrolyze using energy generated by wind turbines; however, the high costs of the necessary electrolysis and wind turbines pose a problem for this technology. Another issue is the need to create an electrical storage system for turbine energy: hydrogen production by wind turbines is thus currently more expensive than that from fossil fuels [38].

Combustion of biomass.

Hydrogen can be produced from renewable feedstock's by means of thermochemical conversion procedures such as pyrolysis, gasification, steam gasification, steam reforming of bio-oils, and supercritical water biomass gasification. Renewable hydrogen manufacture uses biomass resources to run clean and highly efficient technologies for large-scale hydrogen production that do not rely on potentially dangerous fossil fuels [39].

VARIOUS METHODS OF UTILISING HYDROGEN IN ENGINES

Hydrogen as a Direct Fuel Source

Hydrogen can be directly used as a fuel in an internal combustion engine roughly equivalent to a spark-ignition gasoline engine. Hydrogen is an excellent candidate for use in spark-ignition engines due to its low ignition energy and a very high flame propagation speed. The resulting ultra-light combustion leads to lower flame temperatures and thus to less heat transfer to the engine walls, increasing engine efficiency and lowering NOx emissions. For this reason, extensive research on pure H_2 as a fuel has been undertaken, leading to the successful development and commercialization of hydrogen engines [40].

Hydrogen as a Secondary Fuel Source

In an internal combustion (IC) compression ignition engine (CI), hydrogen can usefully be added as a supplemental fuel source alongside diesel fuel. The H/C ratio of the total fuel is thus improved, while spray heterogeneity in a diesel engine is reduced by injecting tiny quantities of hydrogen, which has a high diffusivity, making the combustible mixture more homogeneous and more adequately premixed with air [41]. The resulting combustion process thus does not natively produce any hydrocarbons, carbon monoxide, or carbon dioxide, though a small quantity of these compounds may be produced if lubricating oil is partially burned in the combustion chamber [42]. However, hydrogen cannot be utilized as the only fuel in a compression ignition (CI) engine in the absence of a spark plug or glow plug. owing to its high self-ignition temperature [43]. As a result, hydrogen is inappropriate for use as a singular fuel for diesel engines.

METHODS OF PROVIDING HYDROGEN TO INTERNAL COMBUSTION ENGINES (IC ENGINES)

Hydrogen engines may be built that resemble conventional internal combustion engines; however, the fuel distribution and combustion systems must be modified to address multiple difficulties, including NOx emissions, power output irregularity, and erratic burning [25]. There must be a 1:34 air/fuel mass ratio for hydrogen to completely burn, and, under stoichiometric conditions, hydrogen takes up around 30% of the combustion chamber [7]. Three different fuel delivery systems have thus been tested to determine whether they can be used to power fuel cells.

- Fuel carburization method (CMI).
- Inlet manifold and inlet port injection.
- Direct cylinder injection (DI).

Fuel Carburization Techniques

The use of a gas carburetor, which is one of the oldest and more successful systems in IC engines, offers several advantages for hydrogen engines. In particular, as most gasoline engines use carburetors, hydrogen gasification can be used to easily convert petrol engines into hydrogen engines. The air-hydrogen mixture enters the intake manifold, and a valve controls the amount of hydrogenated air used to start the engine. Some engines require water, and steam and hydrogenated air are then mixed to increase engine power at high engine speeds, depending on the amount of gasoline injected. However, engine power is reduced by 15% due to volumetric efficiency and system losses, and, as the ratio remains constant, pre-ignition, backfiring and knocking may occur with this method [44]. Figure 5 shows the fuel carburetion process.

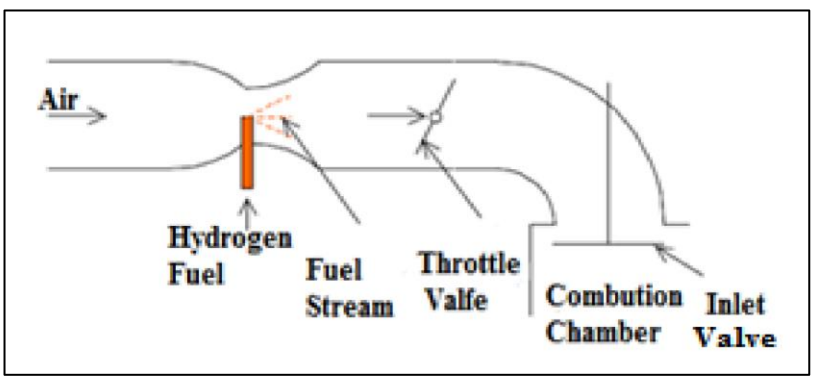


FIGURE 5. Fuel carburetion method

Injection Techniques for Inlet Manifolds and Inlet Ports

Figure 6 illustrates the intake port injection technique. Mechanical or electrical injectors may be used to provide hydrogen to the cylinder, which is mixed with the air flowing in via the manifold intake. The manifold intake is thus a critical component to avoid premature aging, shrinkage, and shock generation caused by the carburizing process [45].

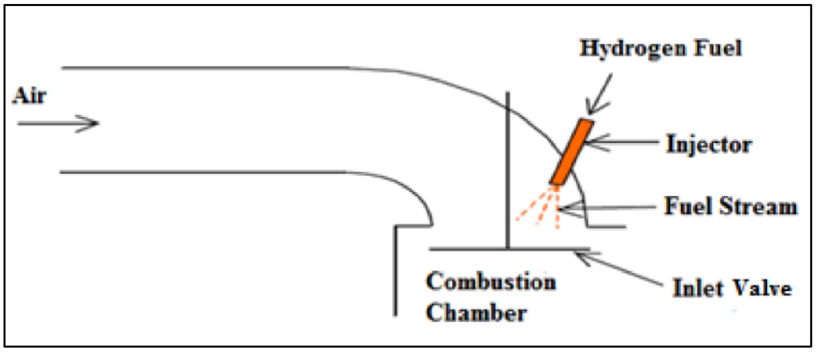


FIGURE 6. Injection Techniques for Inlet Manifolds and Inlet Ports

Direct-Injection Techniques (DI Techniques)

After the intake valve is closed, the combustion cylinder produces an air-fuel mixture, creating a more advanced system. After compression, the hydrogen can then be injected directly into the combustion chamber, where the rapid diffusion of hydrogen can be used to ignite a "spark plug" [46]. The direct injection method is shown in the diagram in Fig. 7.

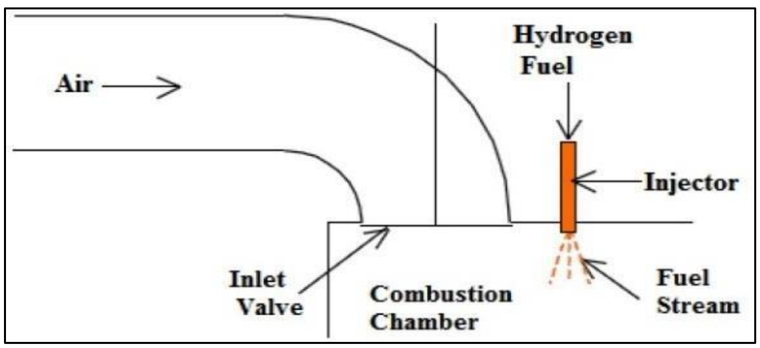


FIGURE 7. Direct Injection System.

CHALLENGES IN HYDROGEN-POWERED VEHICLES

Hydrogen is expected to become a significant energy source in the coming decades, yet to achieve this, the correct infrastructure must be established and developed. Hydrogen production, storage, transportation, and recharging all require further development to form a comprehensive network, and overcoming obstacles such as financial constraints, government regulations, and public opinion all add to the challenge of achieving this. This is necessary, however, to reduce the world's reliance on oil and other fossil fuels.

Safety of Hydrogen Vehicles

High specific heat and high diffusion coefficients are better indicators of safety than low density. For a given heat input, temperature mitigations can be created by a greater specific heat [47], while broader ignition limits and lower ignition temperatures reduce a fuel's safety by increasing the range of conditions under which a fire might develop. There is little danger of combustion or explosion with hydrogen, as it is relatively light (6.9% of the density of air), four times as diffusive as NG, and 12 times as diffusive as gasoline [48]. H2O is also an excellent choice for fire safety, as it burns with low heat radiation; thus, only items very close to it are likely to catch fire [49].

Hydrogen Storage Tanks

Developing a hydrogen economy requires many layers of hydrogen storage, from production facilities and filling stations, through onboard tanks and national strategic reserves. Hydrogen storage may thus be the most challenging hurdle for the development of the hydrogen economy [50]. In particular, before a hydrogen transport economy can be established, a suitable storage system for hydrogen-powered cars must be developed. Due to the incredibly low density of hydrogen, a huge on board tank would be required to transport it, though to achieve a range of 400 kilometers, comparable to that of a conventional car, only 8 kg of hydrogen is needed for an ICE and 4 kg for a FC [51].The challenge is thus to find a storage solution that meets three criteria: high hydrogen density, fast release/charge kinetics with low energy barriers, and reversibility of the release/charge cycle at moderate temperatures (70 to 100 °C). In addition, it must facilitate the formation of strong chemical bonds and the mobilization of atoms, as in the absence of atomic packing, diffusion of gaseous hydrogen through the surfaces is slowed. The thermal conductivity of the material used must also be sufficient to avoid collapse due to the heat of hydration [48].

Hydrogen Delivery and Transport

Appropriate infrastructure is required to move hydrogen from production plants to refueling stations in any effective hydrogen-based transportation system [52]. Smaller quantities can be transported by vehicle, while larger amounts may be transported through pipelines across longer distances; however, it is inefficient to ship liquid hydrogen or compressed hydrogen due to hydrogen's low density [53]. Transporting liquid hydrogen by ship, railcar, or truck is thus only theoretically feasible, as the power required for liquefaction (approximately 30 to 60 % of total liquefaction expenses) would have a large carbon imprint. Pipelines have high construction costs but lower operating costs, notably focused on compressor power. However, distance is an issue for hydrogen delivery systems, and hydrogen's unique physical and chemical properties mean that high-quality pipelines must be built [54].

CONCLUSION

In the future, energy must become greener and more efficient. Hydrogen currently outperforms all other alternative fuels in terms of reducing or eliminating hazardous vehicle emissions and environmental impacts, as hydrogen is one of the many elements already present in the atmosphere; this also means that there are several ways to produce it. Steam reforming of methane is currently the most widely used technology for hydrogen production. In this paper, multiple previous studies were reviewed for the purpose of studying the effects of adding hydrogen to other fuels used in engines: based on the results obtained, hydrogen fuel is most suitable for use in a gasoline engines, as by adding hydrogen to gasoline in certain proportions, the compression ratio can be increased, improving both efficiency and engine performance. In diesel engines, variable results are observed, however, depending on the amount of hydrogen added to the fuel and the engine speed. While the values of torque and power in some engines thus increase with the use of hydrogen, they decrease in others at increasing speeds due to the high ignition temperature of hydrogen. The investigation of the performance and exhaust emissions of SI and CI engines using hydrogen as fuel led to the following conclusions:

- Adding hydrogen to spark or pressure ignition engines affects volumetric efficiency due to hydrogen's higher calorific value (LHV) of 120 MJ/kg as compared to diesel’s 43.6 mega joules per kilogram) and gasoline’s 43.4 MJ/kg.
- When using hydrogen as a fuel in the internal combustion engine, the average H/C rises, which reduces combustion time and improves combustion efficiency. The use of hydrogen fuel also reduces emissions of secondary oxide carbon.
- In all cases, there was a significant improvement in brake efficiency. The HHO, which has greater calorific values than fossil fuels, may be used as a starting point for further calculations due to the presence of hydrogen.
- Adding hydrogen to internal combustion engines has a number of benefits, including a reduction in engine net fuel consumption.
- The addition of HHO to gasoline improves the fuel's ability to burn, based on the combined effects of hydrogen and additional oxygen, which allow full combustion to happen.
- Hydrogen may be added to minimize emissions of carbon monoxide (CO) from internal combustion engines of CI and SI types. Increasing the mass% of hydrogen in a hydrocarbon fuel will slow down hydrocarbon

synthesis due to hydrogen molecules' lack of carbon. Intense hydrogen flames thus enhance cylinder pressure and improve combustion efficiency, while using hydrogen before combustion results in a more homogenous and flammable mixture, as well as an increase in the amount of oxygen available. CO emissions and non-combusted hydrocarbons (UHC) emissions from internal combustion engines are also decreased as a consequence of these variables.

- Hydrogen is an ideal fuel for combustion due to its high temperature, low ignition energy, and rapid flame speed. Increases in working fluid temperature and nitrogen oxide emissions may thus be attributed to these characteristics.
- The reduction in harmful exhaust emissions and the improvement in engine efficiency that comes from using hydrogen in most internal combustion engines makes hydrogen an environmentally and economically beneficial energy source.
- In terms of emissions of nitrogen oxides, in many instances, these were found to increase with added hydrogen; however, in other cases, these were decreased.
- Vehicles with internal combustion engines can run on both petroleum and hydrogen, as well as on a mix of both types of fuel: one super-catalyst that can produce HHO at an average concentration of 6 g/L has also already emerged.

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