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The Use of Gaseous Hydrogen in Spark Ignition Engines

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Abstract: The world suffers from air pollution from burning fossil fuels to produce energy. Cars consume a large proportion of fuel, especially spark ignition engines. The pollutants produced by these engines can be reduced using new types of alternative fuels, including hydrogen gas. Hydrogen is characterized by its high speed and high resistance to knock, making it an acceptable option for use in spark ignition engines. Among the disadvantages that prevent the use of hydrogen is its ease of ignition, safety requirements, lack of energy on the volume basis. In this study, we are trying to review a number of new researches which have tested practically and theoretically the use of hydrogen in ignition engines.
Keywords: hydrogen, spark ignition engine, performance, pollutants, hydrocarbon fuels.

INTRODUCTION

The world faces many problems resulting from human intervention in the ecosystem. The burning of fossil fuels for energy purposes has resulted in numerous pollutants. The increasing concentrations of these pollutants cause imbalance of concentrations of air components, causing several phenomena including global warming, ozone hole, and acid rain.

Internal combustion engines are used to produce energy capable of moving cars, buses, ships, aircraft, and power generators. The pollutants produced by these engines is estimated to be about 40% of the emissions to air around the world and the bulk of these pollutants 24% of the engines emitted by the spark ignition engines [1, 2].

The researchers studied several options to reduce the exhaust gas emissions of spark ignition engines, including the use of alternatives to gasoline fuel. Researchers have used many types of fuel alternatives, including natural gas, liquefied petroleum gas, and hydrogen. Also, they used liquid alternatives such as ethanol and methanol. The researchers also studied mixing gasoline with these types of fuel to reduce emissions from the engine [3].

Hydrogen is the most abundant material in existence, but not its neat form, as hydrogen atoms tend to bind to other atoms. So, it is rare to find single hydrogen molecules. Hydrogen is found in water molecules, which cover more than 70% of the earth's surface and account for more than 80% of the living body's in the Earth. Many scientists and researchers are refusing to name hydrogen as fuel and prefer to use an energy-bearing term. Hydrogen is obtained from water either by electrolysis or by re-forming with natural gas [4]. When it burns, it produces heat energy and water mainly.

The combustion of hydrogen in the ignition engines by the spark gives less pollutants and cleaner exhaust, as it produces only water and a small amount of NOx. In this way, the work of the spark ignition engines by hydrogen will avoid the emission of hydrocarbon contaminants, most importantly CO_2, the main cause of global warming [5].

Hydrogen is stored as high pressure gas (3000 psi) or stored as cryogenic liquid at very low temperatures less than -200°C. Besides, it is stored as metal hydrates, or in hydrogen carriers such as methanol. Hydrogen is a non-toxic gas and is produced by electrolysis of water. Chemical industries use hydrogen gas in many industrial chemical processes, including ammonia (NH3) production. Hydrogen is produced and used in large quantities in the manufacture of compounds such as methane CH4 and methanol (CH3OH), which is used as antifreeze and other chemical industries. Hydrogen is also used in food industries for hydrogenation (adding hydrogen to liquid oils) [6]. Metallurgy engineers use hydrogen to separate pure metals from their oxides, such as the interaction of hydrogen with oxygen, remove the last copper oxides, leaving pure copper behind. Also, they use liquid hydrogen in laboratories to cool the instruments to very low degrees to study several material properties such as superconductivity, which is the material's conductivity for electricity without resistance as the materials become superconducting at very low temperatures [7].

Some recent studies have shown that hydrogen can be fitted to the car at an approximate cost of gasoline and is limited to $ 0.25/liter. For each fuel storage method in the vehicle, the gaseous hydrogen storage has a small volume of energy compared with the liquid fuel currently used, such as gasoline. For the same distance, the size of a compressed hydrogen fuel tank should be about 10 times the size of the gasoline tank, which requires bigger size of the hydrogen tank. The fluid volume is four times the size of the mineral hydrate tank is about eight times the normal tanks currently used. Recent studies of the emergence of alternative species or developments of storage technologies will provide practical solutions acceptable to the users [8].

In this study we examine the experiments, research and development processes in the use of hydrogen gas in spark ignition engines and the extent of the reduction of emissions of the engine pollutants. The operation of any engine with hydrogen fuel must precede the safety and safety settings due to the danger of leakage of the storage containers or expose these vessels to blows that may cause an explosion.

The performance of spark ignition engine fueled by hydrogen

Scientists and researchers have been interested in hydrogen since Ricardo conducted his first experiments in 1923. Hydrogen is a fuel of good quality. Many researchers are working to improve the performance of spark engines and reduce their emissions and fuel consumption by adding hydrogen to gasoline or using hydrogen as a neat fuel [8]. Many researchers are concerned about the safety of using hydrogen as fuel in internal combustion engines. The hydrogen heating value is 9.65 MJ/m^3 at atmospheric pressure and 25°C, so it has low energy content based on volume. The vapor heat for liquid hydrogen (452.2 kJ / kg) is high, which means the need for adding heating parts to the hydrogen inlet to evaporate the fuel when liquid hydrogen is used or injected into the combustion chamber, which require additional costs [9]. Pre-ignition and backfire are easily happened when hydrogen is used as a fuel, due to its low ignition power (10 mJ) [10].

There are two main reasons that make hydrogen an excellent alternative to gasoline. First, it is possible to analyze hydrogen from water so that hydrogen sources are not limited and can be both renewable and non-renewable. A potential advantage of hydrogen is that it can be produced and consumed continuously, using solar, water, wind and nuclear energy for electrolysis. The second reason is the clean burn of the hydrogen combustion as it burns without emitting HC, CO or CO_2, and emits a small amount of NOx [11].

In addition, hydrogen has many good features such as ease of mixing with air. It has a wide range of flammability limits from (Ø = 0.1) to (Ø = 2.5). It results in a high thermal efficiency. Hydrogen has a high ignition speed (265 to 325 cm / sec), causing rapid combustion near the ideal combustion required in the Otto cycle, which increases the thermal efficiency [12].

Ref. [13] studied the performance of a single cylinder, four-stroke engine Ricardo E6. This engine has variable compression ratio, spark timing, and equivalence ratio. The addition of hydrogen to gasoline has been tested. The study focused on the effect of several key variables in engine performance such as speed, sparks timing, equivalence ratio, and compression ratio. The results showed that the higher useful compression ratio for the mixture of the two fuels was (9:1), while for the gasoline it was 8: 1. The engine's brake power increased by increasing the compression ratio and this power was higher for gasoline than hydrogen. However, when the fuel is mixed, the brake power was increased to a certain extent (the proportion of hydrogen in the mixture is 70%).

The equivalence ratio at which the highest brake power was achieved located between (Ø = 1.0-1.1) when mixing the two fuels. The study results showed that the engine can work at very lean equivalence ratios by adding hydrogen. The thermal efficiency increased by this addition, also. The specific fuel consumption reduced by increasing the hydrogen volumetric fraction added.

Ref. [14] studied the use of hydrogen enriched gasoline mixture in a spark ignition engine as a favorable means to improve the process of burning gasoline, especially in the case of burning a lean mixture. Hydrogen injection directly into the combustion chamber forms a mixture with fire protection. The experimental investigation of the analysis of the properties of the low-grade combustion of hydrogen-enhanced gasoline engine and direct injection of hydrogen was done using five different parts of the added hydrogen (3.9%, 5.3%, 7.2%, 8.9% and 10.5%). Four different ratios of excess air (1. 0, 1.2, 1.5, 1.8) were used when the engine was working at a rotational speed of 1500 rpm. Hydrogen injection timing was advanced to form the stratified mixture. The results showed that the flame speed increased and the duration of combustion decreased after the addition of hydrogen. Engine performance and heat release rate improved with increased hydrogen and improved thermal efficiency.

Ref. [15] studied practically the use of several fuels (gasoline, liquefied natural gas, natural gas, and hydrogen) to operate a single-cylinder engine. The results showed that the higher useful compression ratio (HUCR) for gasoline was 8: 1, the liquid petroleum gas was 10.5: 1, the natural gas was 13: 1, and for hydrogen it was 11: 1. The results also showed that the optimum spark timing of the fuel spray was advanced when natural gas was used compared to other types of fuel because of the slow flame propagation of natural gas. The optimum spark timing was delayed when using hydrogen compared to other types of fuel because of its high flame propagation. The power of the three alternatives is reduced when the engine was operating at compression ratio of 8: 1 compared to gasoline, but the brake powers of the LPG and natural gas converged when the engine was running at the HUCR of each fuel. Hydrogen brake power remained the lowest because of its low heating value based on volume.

Ref. [16] demonstrated the potential for thermodynamically and chemically reforming fuels inside the cylinders to improve engine performance. At the same time, this procedure operated the engine at higher compression ratios, increasing the overall pressure in the cylinder and positively reflecting the engine performance improvement. Two compression ratios were selected, namely 11:1 and 13:1. Thermal brake efficiency has increased and fuel consumption has decreased rapidly with increases in the equivalence ratio of reformed gas. Thermal efficiency was maximized, while consumption was reduced to a minimum at equivalence ratio of 1.25, where large amounts of H_2 and CO were generated from the reformed gas.

Ref. [17] modified the single-cylinder diesel engine to operate with compressed natural gas and turned the engine into spark ignition engine. The engine was tested at 1500 rpm under wide open throttle conditions and variable compression ratios with different equivalence ratios. The HUCR for natural gas was 12.5:1. In other experiments, part of the natural gas was replaced with hydrogen by 5% and 10% on the energy basis to study and compare performance and combustion behavior. The wide ignition limits of hydrogen caused the combustion of super-lean mixtures and thus the lean limit of the process extends to an equivalence ratio of 0.42 with the addition of 10% hydrogen compared to 0.50 with the process of compressed natural gas alone.

Ref. [18] has checked the ability to burn a weak mixture in spark ignition engines using biofuel and use the cycle simulator and the sampling of Latin Hepercop. The variables studied were increased pressure, spark timing, air-to-fuel relative ratio, and H_2 content. H2 was added in small increments to enhance the brake power and to burn a lean mixture. The addition of H_2 enhanced the fuel combustion completely and caused the spark timing to be delayed.

Ref. [19] investigated practically the weak operating limits when using gasoline, liquefied petroleum gas, natural gas and hydrogen. The researcher considered that the first appearance of fire extinguishing is the limits of the engine poor limit. The author studied the effect of several variables such as the effect of compression ratio, engine speed, and timing of sparks on the engine's lean misfire limits. The performance and engine contaminants were also examined in detail when the engine worked at this limit.

The results showed that the increase in the compression ratio causes the expansion of the weak and more visible primers, which is apparent when hydrogen is used that has a wide range of equivalence ratios. For the hydrocarbon fuels used in the research, the effect was limited. Moving from a slow speed to a medium speed increased the weak limits of all studied fuels, while moving from medium to high speed reduced the engine's misfire limits.

Ref. [20] reviewed a set of recent researches on the addition of hydrogen to compressed natural gas (CNG). The study concluded that the spark ignition engines fed by natural gas and hydrogen have a useful performance compared to traditional gasoline engines in terms of fuel efficiency and emissions taking into consideration the wide availability of natural gas.

Ref. [21] studied the effect of changing the spark timing on the performance of a rotary engine powered by hydrogen-gasoline fuel. The engine has been modified and equipped with a dual fuel injection system with an electronic control unit (ECU) to control the fuel injection, excess air ratio, and volume fracture of hydrogen. Hydrogen is added in volume fractions of 0%, 3% and 6%, while adjusting the amount of gasoline to keep the mixture at the optimum equivalent ratio. The brake thermal efficiency was increased by advancing the spark timing for a specific number of crank degrees, but as the advancing continued, the brake power decreased. The advanced spark timing increased the period of flame development, low flame duration, and reduced the exhaust temperature.

Ref. [22] conducted experimental tests on a single-cylinder spark ignition engine running at 3000 rpm using hydrogen gas as fuel. The study was carried out at compression ratios of 4.5:1, and 6.5:1 (base) and 7.2:1. The spark timing was fixed at 20°CA BTDC with exhaust gas recycling (EGR) up to 25% by volume. The engine operation at a higher compression ratio caused an increase in the brake thermal efficiency and reduced back-fire of hydrogen. The most important point derived by the researchers from the study is that when using hydrogen in the spark ignition engine the spark timing must be delayed.

Ref. [23] tested the impact of spark timing on combustion and emission characteristics when injecting hydrogen directly into a spark ignition engine operated at 1500 rpm and excess air ratio of 1.2. The study showed that when increasing the volume of hydrogen from 0% to 10%, and the hydrogen injection timing at 110°CA BTDC, the optimum spark timing is from 4 to 16°CA BTDC. The brake thermal efficiency raised and then dropped rapidly when the spark timing was advanced. Increasing the volumetric hydrogen fraction caused the spark timing to delay and increased cylinder peak pressure and maximum high pressure rate.

Ref. [24] used the Ricardo E6 single-cylinder engine and studied its performance when adding variable hydrogen volumetric fraction to liquefied petroleum gas (LPG). The results showed that the increase in the brake power increased with increasing the engine's compression ratio, especially when mixing the two fuels up to hydrogen volumetric fraction of 70%. After this fraction, the engine's brake power dropped sharply. The engine started to work at very lean equivalence ratios when hydrogen is added; the specific fuel consumption reduced, also.

Ref. [25] studied the performance of a spark ignition engine by adding hydrogen gas to LPG. The results showed that the HUCR of the mixture of two gases was (10.5: 1). The brake power using LPG is higher than that produced when hydrogen is used. The study also showed that the equivalence ratio obtained at the HUCR of a mixture of the two fuels lies between (Ø = 1-1.1).

Ref. [26] investigated the impact of the hydrogen addition to gasoline in the spark ignition engine using semi-dimensional simulations. The effect of this addition on the cycle to cycle variation was studied too. The study showed that the change from one cycle to another is significant in these engines, especially under operating conditions at a lean equivalence ratio. The reduction of these periodic differences will ultimately improve performance records with lower consumption and emissions. As for the lean mixture, the amplitude of the oscillations decreases with the increase in the hydrogen volumetric fraction in the mixture.

Ref. [27] modified a single-cylinder spark ignition engine to operate by hydrogen gas with the aid of electronic control unit to regulate fuel injection in a timely manner. Performance and combustion specifications were examined at maximum brake torque and wide open throttle. Experiments were carried out at a speed range of 1100 to 1800 rpm. The results showed that hydrogen engine operated at 19.6% brake power, and thermal efficiency increased to a peak of 31.16%. The heat release rate was 1.36 times higher when hydrogen was used than gasoline at 1400 rpm.

Ref. [28] used the solid biomass gasification (industrial gas) as a good fuel for internal combustion engines in the transition period from carbon-based fuels to zero-emission fuels. This kind of fuel suffers from a problem that it has a low heating value about a third of the heating value of the compressed natural gas. This heating value can be improved by adding rich hydrogen ratios to the industrial gas and mixing it with percentages of methane. The experimental results showed that the direct injection spark ignition motor fueled by adding 20% methane to 50% hydrogen-rich industrial gases a significant improvement in engine performance.

Ref. [29] added hydrogen to gasoline in a rotary engine operated at idle conditions and lean mixture. The engine is equipped with an electronic management unit to control spark and fuel injections. The performance of the engine was compared with the hydrogen added at 0% and 3%, respectively. The results indicated that engine fluctuations and fuel flow rate both decreased after the addition of hydrogen. The combustion duration reduced and the point at which the central heat released by adding hydrogen was reduced, too.

Hydrogen engine contaminants

Ref. [31] studied the CO and NOx pollutants when the hydrogen was added to liquefied petroleum gas (LPG) at variable volumetric fractions in a single-cylinder motor. The study results indicated that the exhaust gas contaminants are mainly based on the equivalence ratio variation. It was observed that the retarding of the spark timing significantly reduced NOx concentrations, but has no effect on CO concentrations. NOx concentrations were higher at medium velocities and these concentrations decreased at low and high velocities. CO levels increased with speed. Increasing the hydrogen fraction in the mixture increased NOx levels, while CO concentrations decreased with this increase.

Ref. [32] empirically measured the particulate matters (PM) emitted from a hydrogen-fueled engine ignited using laser systems. The experiments were performed at a fixed engine speed, and the engine was modified to function properly with gaseous fuel and using both laser primers and ignition primers. The results showed that the lasers of the fuel caused a relatively higher concentration of particulate matters as well as particle mass compared to a spark ignition engine. PM levels increased with engine load increase in both ignition systems, but the rate of increase was relatively higher in the laser system.

Ref. [33] compared between methane and methane/hydrogen mixture in a single cylinder, direct injection spark ignition engine run in stable conditions in terms of engine exhaust emissions. The results showed that fuel consumption was less efficient during the front flame spread and the greater amount of carbon dioxide and methane resulted in the exhaust gas.

Ref. [34] measured CO and NOx pollutants from a four-stroke single-cylinder engine when hydrogen was added to gasoline at variable volumetric ratios. The results of the study showed that the maximum value of NOx levels was in the lean side near the stoichiometric equivalence ratio and these concentrations decreased by moving away from that ratio in both sides of the mixture (lean or rich). CO concentrations are low on the lean side, slightly affected by the equivalence ratio. CO levels increased in the rich side and are heavily influenced by the equivalent in this range. Retarding the spark timing reduced NOx concentrations significantly and had little effect on CO levels. NOx concentrations are increased by increasing the hydrogen fraction in the mixture, while CO levels decreased with this increase.

Ref. [35] studied the combustion properties of spark ignition engine with a heavy compression ratio that uses liquefied methane and hydrogen at a low engine speed. The hydrogen was injected using the fuel injection port in the ignition mode. The results showed that nitrogen oxides emissions increased significantly with increased load and injected hydrogen. HC and CO_2 levels decreased by increasing hydrogen, and CO concentrations remained low in all loads.

Ref. [36] investigated the cold start operation characteristics and the cold start emissions using four-cylinder engine run with natural gas and multiple-point hydrogen gas injection and exhaust gas recycling. The results showed that HC contaminants remained stable with the addition of hydrogen in the cold phase. Carbon dioxide emissions can be reduced for all different conditions using this method.

Ref. [37] studied the effect of using different types of liquefied petroleum fuels such as benzene, hexane, iso-octane and toluene, and gaseous fuels such as propane, methane, and hydrogen. The results manifested that the toluene produces maximum brake power, hexane produces maximum thermal efficiency, and hydrogen gives minimum performance and NO values. Low NO emission can be achieved by low temperature inside mixture, input pressure, cylinder wall temperature; increase in percentage of residual gas part of cylinder.

Ref. [38] used liquefied petroleum gas, natural gas and hydrogen to operate a spark ignition engine and to study the NOx emission from it, and compare it with the engine operation with gasoline. The results showed that the maximum level of NOx was located on the lean side. These concentrations decreased by moving away from that ratio for both sides of the mixture for all types of fuel studied. NOx levels were high when the engine was fueled by hydrogen at compression ratio of 8:1 and was close to the rest of the three fuels when the engine was operated HUCR of each fuel. However, the hydrogen engine emits the highest NOx values.

Ref. [39] focused on the effect of the use of several gases, namely liquefied petroleum gas, natural gas, and hydrogen on the CO concentrations emitted from the engine and compared those levels with the engine run by gasoline. The study was done at the HUCR for gasoline 8:1 and then when the engine at the HUCR for each fuel separately. CO levels were low in the lean side of all fuels used and were very limited by the change in the equivalence ratio. These concentrations increased in the rich side and are significantly affected by the equivalence ratio variation. The CO concentrations emitted from the gasoline engine are always higher than those of other fuels. CO concentrations when using hydrogen are virtually non-existent and the quantities measured were resulted from the burning of residual oil in the combustion chamber.

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