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A brief review on hydrogen as a potential fuel for internal combustion engines

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ABSTRACT

The internal combustion engine has played an important role in the transport industry with outstanding advantages in power generation, although the increasing pressures of fuel use and environmental pollution from the these engines are big problem. Moreover, increasingly stringent emissions targets and the rapid depletion of oil resources have prompted researchers to study the use of alternative fuels for diesel engines. Hydrogen is one of the best alternatives to traditional fuels. Hydrogen has its benefits and limitations in its use as an alternative fuel in transportation engines. Hydrogen is the most abundant element in the universe and exists mainly as a compound with other elements. Hydrogen has long been viewed as a desirable fuel for internal combustion engines. Unlike fossil fuels, these are non-polluting fuels, renewable and can be produced from endless water. On the other hand, one of the most effective ways to improve combustion efficiency on existing engines without much change in engine structure is to add a small amount of hydrogen gas or hydrogen-rich gas to the engine. This paper briefly presents the outstanding properties of hydrogen fuels that affirm their applicability in internal combustion engines. Furthermore, the evaluation of hydrogen fuel using solutions on SI and CI engines is also presented to clarify the engine characteristics and emissions when using this fuel.

KEYWORDS

Hydrogen fuel, internal combustion engines, hydrogen engines, engine performance, emission characteristics.

INTRODUCTION

Along with the economic and technical development of each country, the internal combustion engine always has played a very important role in the social economy [1,2]. It is present in all sectors such as agriculture, industry, transportation, defence and others. The growth of the internal combustion engine is indispensable in the historical development of an economy [3,4]. Currently, the rapid increase in the number of internal combustion engines is causing the consumption of traditional fossil fuels to soar. Along with the growth in the number of transport vehicles is an increase in environmental pollution caused by toxic emissions from engines. This pollution source has a great impact on the health and life of people, especially in big cities [5, 6]. Therefore, urgent solutions are needed to overcome this problem. The research and development of alternative fuel sources with low emissions and efficient use of available fuels will be the fundamental solution with global influence [7,8]. That can be the solution to ensure the energy security of nations and sustainable development for humanity. However, a clean fuel source has not been developed yet, which has the potential to completely replace traditional fuels on internal combustion engines. Therefore, the research to optimize and improve the combustion efficiency of the engine to save fuel and reduce harmful emissions has always been the top concern [9,10].

The human environment is increasingly heavily polluted by wastes from human activities, one of which is the exhaust of motor vehicles. During operation, vehicles emit a large number of fumes and toxic gases such as CO, CO2, hydrocarbons (HC), NOx, SO2, smoke, lead and other particulate matter [11-13]. These waste components not only directly harm human health, but also in the long term damage the biological world that is destroying the world of organisms that feed humans [14]. Depending on the type of engine and the type of fuel used, the amount of hazardous waste constitutes a different proportion. According to statistics in the US, pollutants emitted from these vehicles account for 40 ÷ 50% of the total HC content, 50% of the total NOx content and 80 ÷ 90% of the total CO content in the city area. The same problem occurs in other developed countries like Europe and Japan.

Research, development and application of alternative fuels is a common trend of many countries around the world to reduce dependence on fossil fuels [15,16]. At the same time, it also ensures energy security as well as reduces the impact on the environment, especially greenhouse gas [17,18]. Diesel engines are widely used in many fields: agriculture, transportation, generators ... due to the outstanding advantage of high efficiency. However, in combustion products, there are many toxic ingredients to humans and the environment, especially nitrous oxide (NOx) and particulate pollution (PM - Particulate Matter) [19,20]. One of the most effective ways to improve combustion efficiency on existing engines without much change in engine construction is to add a small amount of hydrogen gas or hydrogen-rich gas to the engine. Hydrogen has the characteristics of rapid diffusion, flammability and rapid combustion, so when ignited in the mixture with traditional fossil fuels in the engine cylinder [21,22]. It will increase the burning rate of the fuel mixture and help the fuel burn out, thereby increasing combustion efficiency and reducing the toxic emissions of the engine. However, storing liquefied hydrogen fuel is quite difficult, so hydrogen fuel is used as much as an additive to the gasoline or diesel fuel used on traditional internal combustion engines [23]. With this method, only a certain amount of hydrogen is used to add to the mixed intake sugar with the main fuel mixture. The goal is to increase fuel efficiency, make the combustion in the cylinder take place evenly, thus reducing the number of toxic gases released into the environment [24-26].

Hydrogen can be produced from fossil hydrocarbon sources, from water and biomass by methods such as steam reforming, incomplete oxidation, natural gas pyrolysis, recovery of H2 from reforming and water electrolysis [27]. Hydrogen can be used directly on an internal combustion engine in liquid hydrogen form (liquefaction temperature is -253oC under atmospheric conditions) or in compressed form (tank pressure up to 700 bar). The issue of safe and efficient hydrogen storage is still receiving great attention from researchers and businesses. Hydrogen is currently believed to be a potential source as a fuel cell to generate electricity. Although there are some difficult storage and cost issues, with great calorific value (by volume) and the raw material source is considered infinite, so hydrogen is currently seen as the "fuel of the future" [28]. Hydrogen-rich gas is a mixture of hydrogen gas and some other gases such as oxygen (in HHO), CO (in syngas) and some other impurities. Hydrogen-rich gas is often used on engines as a fuel additive by adding gas to the intake manifold to improve combustion and reduce pollution emissions [6].

Several H2-diesel fuel co-combustion studies have been conducted in literature with the hydrogen introduced in the intake manifold, and thus aspirated into the combustion chamber with the intake air [29]. Co-combustion studies undertaken on naturally aspirated engines have reported reductions in exhaust emissions of NOx and particulates at low H2 substitution levels, however, at higher H2 substitution levels, an increase in both exhaust NOx and particulate emissions has been observed [30]. NOx emissions were speculated to increase due to higher in-cylinder gas temperatures resulting from H2 combustion, while particulate emissions increased due to displacement of intake O2 by H2. Some researchers have attempted to mitigate these effects by utilizing exhaust gas recirculation (EGR) and intake air boost with H2-diesel co-combustion [29e32]. Khan et al. studied the effect of EGR with H2-diesel co-combustion and was able to achieve simultaneous reductions in smoke and NOx emissions [31].

Talibi et al. managed to achieve a 90% energy substitution of diesel by H2 in a supercharged engine, with N2 utilized as simulated EGR to dilute the intake air [32]. The authors were able to operate the engine at 42% brake thermal efficiency, with negligible levels of NOx and smoke emitted. More recently, Wu et al. investigated the effect of elevated intake air temperature in engine operating on H2 and diesel fuel [33]. Although a considerable reduction in exhaust emissions was achieved (41% NOx and 30% smoke emissions reduction), no significant impact of intake air temperature on engine performance and emissions were observed by the authors. This paper focuses on evaluating the potential of using hydrogen as additional fuel for diesel engines. The main part of this work is brief evaluations of engine performance and the emission characteristics of diesel-hydrogen dual-fuel engines, which are analyzed quite comprehensively.

HYDROGEN FUEL FOR INTERNAL COMBUSTION ENGINES

Hydrogen production

Hydrogen is the most common element in the universe but does not exist in mines, such as mineral-based oil and gas fields, which are often bound by other elements such as oxygen or carbon to form molecules of various substances. An energy source is needed to separate hydrogen from these molecules, which can then be used as fuel for combustion or in a fuel cell. This is considered a clean and sustainable energy source that can be applied to vehicles and stationary dynamics, thereby helping to diversify fuel sources and reduce dependence on traditional oil. Hydrogen is usually generated from two main sources: water and fossil fuels (Figure 1). Hydrogen generated by water separation is done by a variety of processes such as water electrolysis, photolysis, biochemistry and high-temperature water dissociation. Water electrolysis requires an electrical source to split water into hydrogen and oxygen [34]. According to this method, the source of fuel is infinite but consumes a lot of electricity, while electricity is often generated by fossil fuel sources.

As the water temperature increases, the energy needed to supply the reaction decreases, so waste heat from other processes can be used to heat the water and reduce power consumption. Cyclic energy available in nature can be used to produce hydrogen from renewable sources. Hydrogen can be produced from fossil fuels in a variety of ways such as reforming steam (commonly used for natural gas CH4), coal gasification ... Hydrogen production from natural gas is carried out by three different chemical processes including steam reforming, partial oxidation and a combined reforming process [35]. The process of reforming steam takes place at a temperature of about 700 ÷ 8500C, a pressure of 3 ÷ 25 bar, and a product containing about 12% CO is then converted to CO2 and H2 by the water-gas displacement reaction. Besides, hydrogen is also generated from biomass fuel by thermochemical, biochemical or mechanical separation processes. Hydrogen generation technology requires a large number of raw materials and is highly dependent on the quality of the biomass source, while the quality of the biomass source often varies with type and season. At the same time, the amount of hydrogen produced is small because hydrogen is only about 6% of the biomass. Therefore, this technology has only been carried out in research so far but has not been applied in industrial production [36].

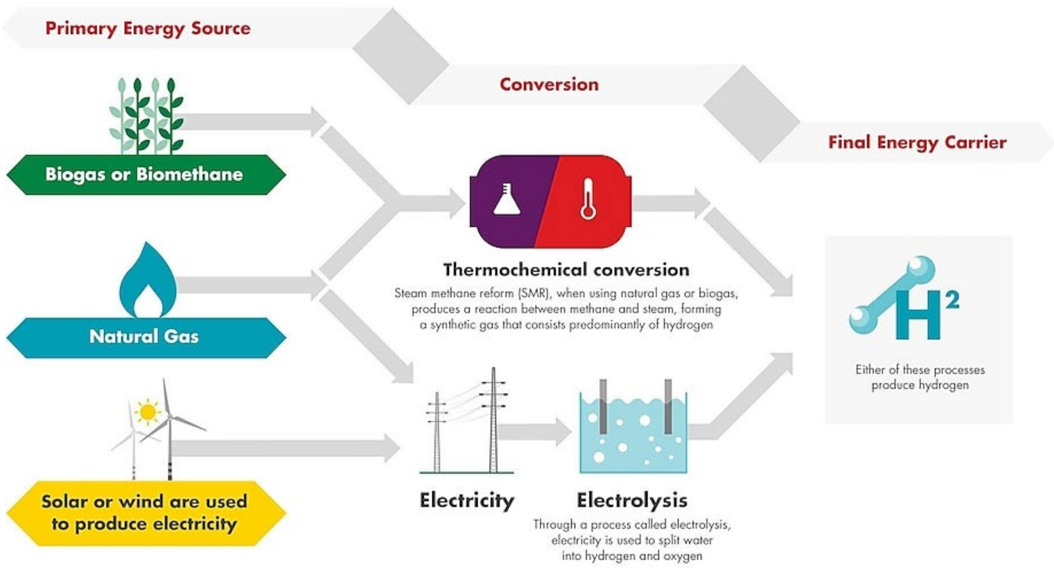

Figure 1. Methods for hydrogen production [37]

Properties of hydrogen fuel

Hydrogen can be used as a single fuel on a forced combustion engine or as an auxiliary fuel on both gasoline and diesel engines. Hydrogen reacts with air to create a clean product, mainly water and has no components polluting CO and HC, so it does not pollute the environment and does not cause greenhouse effects like when using fossil fuels. Besides, this fuel has the advantage of fast-burning, high octane number (over 130), good anti-knocking.

Therefore, engines using hydrogen fuel can work at very high speeds, with a large compression ratio, which can increase the power and efficiency of the engine. Limited mixture composition to ensure good fire ability is very wide, so the engine can work with very thin mixes, contributing to increasing the economy of the engine. However, hydrogen fuel has some disadvantages of very low mole calorific value compared to gasoline and diesel fuel. It means that if the engine structure is not changed when switching from a gasoline or diesel engine to a full hydrogen engine fed into the intake manifold, the engine power will be greatly reduced. The physical and flammable properties of hydrogen that directly affect the ability to use it as a fuel in internal combustion engines have been detailed in Table 1 [38].

Table 1. Hydrogen fuel properties [37]

Properties	Values
Density at 1 atm and 300 K, [kg/m^3]	0,082
Diffusion coefficient into the air, [cm^2/s]	0,61
Low calorific value, [MJ/kg]	119,7
Energy density, [kJ/m']	
- At 1 atm, 15 °C	10.050
- At 200 atm, 15 °C	1.825.000
- In a liquid state	8.491.000
Volumetric composition in the theoretical mixture (stoichiometric) with air (% volume)	29,53
Air / fuel mass ratio of theoretical mixture (stoichiometric)	34,5
Theoretical air volume (kg / kg fuel)	34,5
Combustible heat of the fuel mixture with 1 kg of air in stoichiometric (MJ / kg air)	3,37
Flammability limit (lambda)	0,14 ÷ 10
Flammability limit (% fuel vapor volume)	4 ÷ 75
Minimum ignition energy required, [MJ]	0,02
Film speed [m / s]	3,2 ÷ 4,4
Octane number	> 130
Auto-ignition temperature [K]	858

The data in Table 1 show that hydrogen has a small density of only about 11% of methane and 1.6% that of gasoline vapour at the same pressure. A small density of hydrogen will reduce the energy density of this fuel. Hydrogen has a diffusion coefficient that is 3 times higher than methane and more than 12 times more than gasoline, so its ability to create a homogeneous mixture with the air in the engine is much better than that of methane and gasoline. Besides, due to its high diffusion coefficient plus small density, when hydrogen is leaked to the outside environment, it will be easy to diffuse and fly away. Therefore, the risk of fire, explosion and fire are much lower than that of the other two fuels [24]. Hydrogen has the highest mass calorific value of all other engine fuels.

The calorific value of hydrogen is 119.7 MJ / kg, almost three times that of gasoline. However, due to the small density of hydrogen, its energy density is smaller than that of methane and gasoline. Furthermore, the volumetric composition of the fuel in the mixture with the air is greater than that in the case of the other two fuels. Therefore, the capacity of a hydrogen engine is likely to be lower than that of a gasoline or methane engine if the engine is of the same cylinder capacity and refuelling the intake manifold. This should be considered when designing a hydrogen engine to ensure the required engine power. In a direct fuel injection engine, if the same speed and cylinder capacity, the hydrogen engine will have more power [39].

Flammability limit is a characteristic burning range for a fuel's ability to burn fuel with air at certain fuel/air ratios. Hydrogen has a very wide combustion range between 4% to 75% of the hydrogen volume contained in the fuel-air mixture (equivalent to □ = 1.4 □□10). Hence, hydrogen can work with very poor mixers. Usually, the poorer a mixture has a fire limit, the more exhausted the fuel will burn, thus improving the economy. Besides, poor fires will lower the end temperature of the combustion process, reducing the amount of NO pollution in the exhaust gas. When the engine works with a poor mixture, the engine power is low because the density of the fuel in the fuel-air mixture is low. Therefore, in a hydrogen engine, it is possible to adjust the mixture composition according to the load so that it can ensure economical operation at small loads and large capacity at large loads [40].

The ignition energy required to burn hydrogen fuel is much lower than the ignition energy required to burn methane and gasoline, so the advantage of a hydrogen engine is its simple ignition system and low cost. However, this can make it difficult to control the self-ignition problem of the fuel. Spots in the cylinder wall can easily ignite fuel even when the intake valve is not closed, resulting in a burn against the suction neck or a sudden increase in the cylinder in the hydrogen-supply engine entering the road. The load makes a knock, causing damage to the engine. This issue needs to be addressed in the design of a hydrogen fuel engine [41].

Hydrogen has a high burning rate, and hydrogen flame spread faster than gasoline. When $\lambda = 1$, the burning rate of the mixture (air and hydrogen) is 6 times higher than that of the mixture (air - methane) and 10 times that of the mixture (air - gasoline). Besides, the rapid-fire rate makes the hydrogen fuel engine characteristics less sensitive to chamber shape changes. The fast burning speed will help to easily burn out, which increases combustion efficiency but makes the combustion pressure and temperature high during combustion of the engine. Therefore, when the engine works near the optimum air-conditioning ratio, it leads to high combustion gas temperature and easy NOx formation. Also, it can cause noise and vibration due to the rapid increase in pressure in the combustion chamber [42].

Ignition temperature is an extremely important parameter, it determines the compression ratio of the engine, which is decisive to the useful thermal efficiency of the engine. Hydrogen has a high self-ignition temperature, so it can improve the compression ratio without fear of explosion, contributing to improving engine efficiency. The higher the compression ratio, the more efficient the engine can work with poor air-conditioners. Hydrogen's self-igniting temperature is as high (858 K) as twice that of gasoline, so this is a great advantage of hydrogen fuel [43].

SOLUTIONS USING HYDROGEN AS FUEL FOR INTERNAL COMBUSTION ENGINES

Internal combustion engines use only hydrogen fuel

Because hydrogen has a high-octane number and a high self-ignition temperature, it is well-suited for fuel in forced-combustion engines. As in a gasoline or gas engine, the fueling and mixing of a hydrogen engine can also be done by feeding hydrogen into the intake manifold or injecting directly into the engine cylinder. However, in a gasoline engine, fueling the intake manifold or injecting directly into the cylinder does not have much effect on the amount of the intake air because the fuel when fuel is still in liquid form and has a greater density than gas fuel. A hydrogen engine is different, the method of hydrogen supply to the engine greatly affects the intake of air and therefore will greatly affect the engine capacity. Figure 2 shows several methods of fueling into a hydrogen engine. Their effect on the amount of the intake air in the air-fuel mixed condition has an air excess coefficient of 1 compared to gasoline engines that create a mixture in the intake manifold. With options for supplying hydrogen to the internal combustion engine as above, the option of supplying hydrogen gas to the intake manifold is often used because of the simple, cheap fuel supply system. However, to accept a 15% reduction in engine power compared to gasoline [44]. Figure 3 illustrates different ignition strategies in hydrogen internal combustion engine.

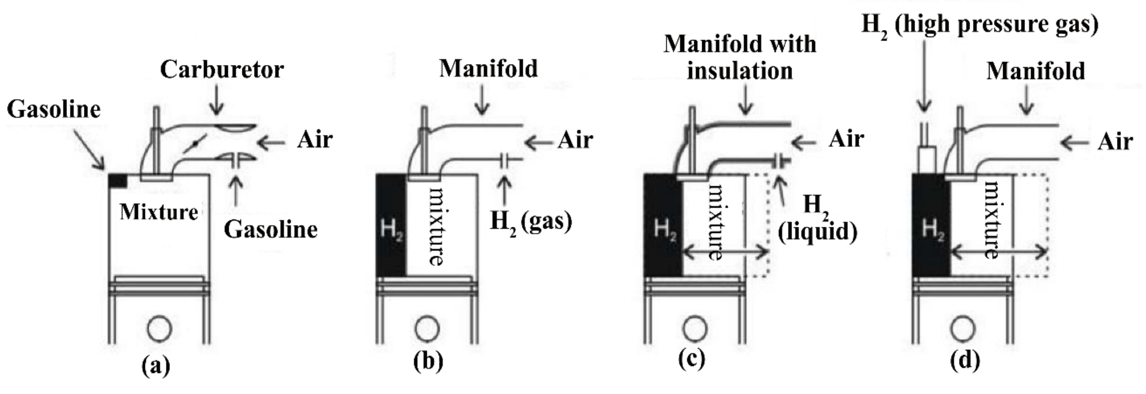

Figure 2. Various fueling hydrogen into internal combustion engines

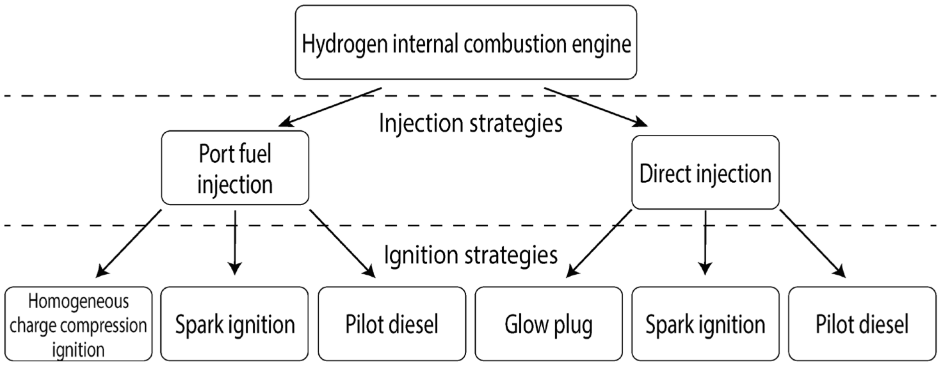

Figure 3. Ignition strategies in hydrogen internal combustion engine [45]

Theoretically, the thermal efficiency of a hydrogen engine is greater than that of a gasoline engine because hydrogen has a higher screw number, allowing for a higher compression ratio of a gasoline engine. The burning of hydrogen with oxygen results in a water-only product. However, in internal combustion engines that use hydrogen fuel, hydrogen burns with the air, so in addition to water, the combustion products may also contain NOx. NOx is created in the combustion chamber because nitrogen reacts with oxygen at high temperatures during the combustion of the fuel. Besides, the exhaust gas of an engine may contain CO, CO2 and HC due to the lubricating oil burn in the combustion chamber [46]. However, studies on emissions of hydrogen engines show that NOx is the main emission component of hydrogen engines, accounting for over 95% of the total amount of toxic emissions generated by the engine.

The amount of NOx formed in a hydrogen engine depends on many factors such as the mixture composition (air excess coefficient), hydrogen supply and mixture method, compression ratio, early ignition angle, engine speed, and exhaust gas recovery rate where applicable. Direct injection of low-pressure hydrogen gas into a cylinder will significantly reduce NOx emissions at a small load compared with the method of supplying gaseous hydrogen to the intake manifold. In medium and large loads, the method of direct injection of high-pressure hydrogen gas into the engine cylinder and liquid hydrogen injection into the intake pipe, in turn, has lower NOx emissions [47]. The power of a hydrogen engine is highly dependent on the air/fuel ratio and the method of fueling and mixing within the engine. As mentioned above, theoretically, for mixtures with air residue coefficient □ = 1, in the case of supplying hydrogen gas to the intake manifold, the engine power will be reduced by about 16% compared to the engine. If the engine is running by gasoline, hydrogen is injected directly into the cylinder, the engine power can be up to 21% higher than the gasoline engine.

Another experimental study was performed on a Corolla 1.8 engine equipped with a hydrogen injection system into the intake manifold to be able to compare the technical performance and emissions of an engine when running with hydrogen fuel and when running with gasoline [48]. Research results have shown that engine power when running on hydrogen is generally only 50% of that when running on gasoline. The maximum achievable capacity of a hydrogen engine is only up to 60.5% of the engine's maximum power when running on gasoline. Thus, when the current gasoline engine is switched to hydrogen fuel, the capacity is greatly reduced. However, since automobile engines are often designed to have a large capacity reserve, if switching to hydrogen fuel, they can still maintain power to operate in street conditions and on the road [23].

Hydrogen engines need the same large capacity as that of a gasoline engine, but the capacity of a new hydrogen engine is often designed to be larger than the capacity of a gasoline engine of the same gram of power to compensate for the power reduction. Another way to increase the power of a hydrogen engine is that one can use pure hydrogen on a compression-ignited diesel engine as shown in the study [49]. The author has shown that the engine power when running pure hydrogen by direct injection and combustion by compression is increased 14% and engine efficiency is up to 43% compared with 28% when running on diesel fuel. However, because hydrogen has a high self-ignition temperature, heating the intake air must be heated to ensure normal engine work, which complicates the engine structure. On the other hand, due to the high combustion temperature causing the maximum pressure in the cylinder to rise, the engine vibrates. Therefore, the use of pure hydrogen on compression-ignited diesel engines is of little concern [50].

The internal combustion engine uses additional hydrogen

The use of hydrogen as an additional fuel in an internal combustion engine involves using a small percentage of hydrogen in combination with conventional fuels to improve the economy, engineering and emissions of the engine. In liquid-fuel engines such as gasoline and diesel, hydrogen addition is usually done by feeding hydrogen into an engine's intake manifold to mix with the intake air entering the cylinders, while the main fuel is supplied in the normal way, but with a reduced flow rate, it does not darken the mixture. In gas engines such as natural gas, biogas, hydrogen can be supplied by a separate system or mixed with these gases in the tank before being fed to the engine. The addition of hydrogen gas to an internal combustion engine that uses fossil fuels results in a combustion mixture of hydrogen, fossil fuel and air. Because hydrogen has flammable, rapid burning and high combustion temperature, it burns fossil fuels when burning, contributing to increased efficiency and reducing engine toxic emissions [51]. Figure 4 provides the principle of adding hydrogen on the intake manifold for a diesel engine [52].

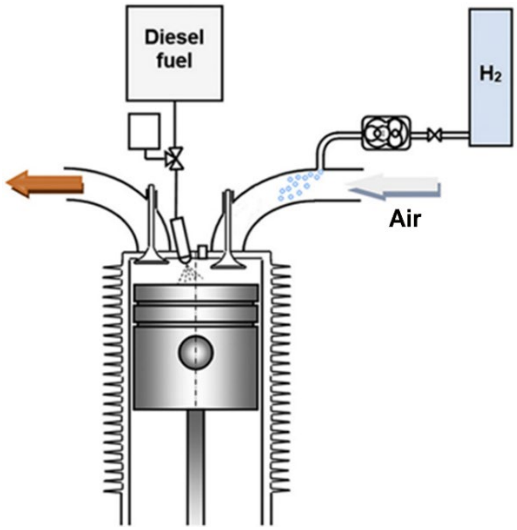

Figure 4. The principle of adding hydrogen on the intake manifold for a diesel engine

On the other hand, since the additional hydrogen fuel accounts for only a small proportion of the total fuel used of the engine, even though there is a low energy density, hydrogen will have little effect on the reduction of engine power. Also, due to the small amount of hydrogen used, it is not as difficult to produce, transport and supply hydrogen for a continuous engine as it would with a full hydrogen fuel engine. There have been quite a few published studies showing that the economic, technical and emission performance of hydrogen-supplemented engines are significantly improved compared to conventional fuel-only engines [53, 54]. The research results of adding hydrogen to the intake manifold on diesel engine showed that the efficiency, fuel consumption and emissions of the engine are significantly improved. According to Çalık, when the addition of hydrogen in combination, slightly delayed diesel injection timing can reduce smoke emissions by 0% and the NO drops much lower than when running on diesel alone while the engine power is not reduced [55].

Research shows that in all modes of engine thermal efficiency increase when hydrogen is added compared to without hydrogen while the average beneficial pressure of the engine varies slightly [56, 57]. CO, HC emissions and smoke levels are reduced compared to when running with only diesel fuel and the change is stronger as the ratio of added H2 increases. The fuel consumption rate of an H2 supplemented engine is lower than that of an engine that runs on only diesel fuel. The experimental results of Yıldırım et al. on a one-cylinder diesel engine supplemented with hydrogen by direct injection showed that when using pure diesel fuel, the smoke obtained was 4.8 BSN but when hydrogen is used in combination, the smoke is reduced to 0.3 BSN [58]. Thermal efficiency increases from 23.59% with diesel fuel to 29% with hydrogen addition. This result is because hydrogen improved the combustion of the engine. Emissions such as HC, CO and CO2 all fell sharply, particularly NOx decreased from 6.74 g / kWh to 3.14 g / kWh.

The study established a series of virtual experiments using different types of biodiesel in blends with volume ratios of 20% and 40% [55]. Hydrogen enriched by pumping into the inlet manifold at rates of 3 L / min and 6 L

/ min. Results were obtained on a 4-cylinder diesel engine that does not operate at different engine speeds under no-load conditions. Their data showed that CO, HC and NOx emissions decreased compared to biodiesel without hydrogen supplementation. In another study, the engine efficiency and the exhaust emissions of a diesel engine using diesel fuel and hydrogen-enriched biodiesel were investigated [59]. Results obtained at a constant engine speed of 1100 rpm and engine load (40%, 60%, 75% and 100%) show that engine load significantly affects NOx emissions, with an increase in THC emissions, while CO2 and CO emissions decrease. In terms of efficiency, thermal efficiency is reduced, while the values of peak pressure in the cylinder and the value of the peak exothermic speed increase at all engine loads with hydrogen addition compared to diesel and biodiesel [60].

CONCLUSION

Hydrogen gas has a very small density, the energy density per unit volume is very small, so it is used in an internal combustion engine, it is necessary to compress to very high pressure or be liquefied. One simple solution to use hydrogen gas or a mixture of hydrogen-rich gas for an internal combustion engine is to supply a small amount of hydrogen gas or a mixture of hydrogen-rich gas into the engine intake manifold or the engine cylinder. Hydrogen in this case acts as a fuel additive or a catalyst to promote combustion more thoroughly. The effect of adding hydrogen to the intake manifold of a compressed combustion engine is significantly reduced in the emission components of HC, CO, CO2, PM and soot. However, the NOx content increases with the addition of hydrogen, but this problem can be controlled with solutions such as spray strategy, using EGR systems, spraying water vapour onto cylinder walls as well as using post-generation remedies. The efficiency of diesel-hydrogen dual-fuel engines with different hydrogen injection systems found that the solution of hydrogen injection into the intake manifold was better and reduced emissions components compared to the technology that provides hydrogen by the carburettor and sprayed into the intake manifold.

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