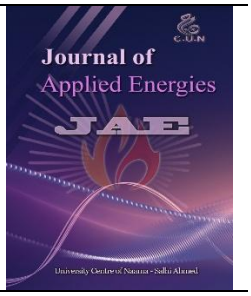
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Hydrogen energy for internal combustion engine, Issues and perspectives

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Abstract: Current internal combustion engines operate mainly on hydrocarbon-based fuel in the automotive transportation field. Their CO_2 emissions are inevitable because they are a combustion product and greenhouse gases responsible for global warming and climate disturbance. Hydrogen seems to be an alternative solution because its combustion does not generate greenhouse gases and it will help a longer preservation of conventional fuel reserves. This paper discusses the integration of hydrogen as alternative fuel in automotive transportation field. Issues and perspectives are considered.

Keywords: Automotive propulsion; Alternative fuel; Hydrogen combustion; atmospheric pollution; Hydrogen storage; Hydrogen properties; H_2ICE performances.

1. INTRODUCTION

Increased greenhouse gas emissions, air pollution and climate change are some of the most pressing global issues the world is faced with today. One of the largest sectors contributing to

pollutant emissions is the transportation sector, and many have identified a shift away from fossil fuels and towards renewable energies as a possible solution. Research has proven hydrogen to have a great potential as energy source in the automotive sector, and its application in internal combustion engines. Many research works are underway and below some published ones very recently.

Gurz et al. [1] have presented an overview on classification of the vehicles using hydrogen with different ways. The use of hydrogen in vehicles can be achieved into two main kinds. First, the hydrogen can be directly burnt in the engine combustion chamber or used in a fuel cell vehicle that using hydrogen to produce electricity. Hydrogen fuel cell vehicle technologies and their future advantages are pointed. The hybrid versions of the previous kinds have been also introduced.

Tsujimura and Suzuki [2] performed a study on a single cylinder diesel engine equipped with gas injectors at an intake port to evaluate performance of the hydrogen diesel dual fuel (hydrogen DDF) under various conditions of hydrogen rate injected, engine speed and engine loads. The experimental tests show that the hydrogen DDF operation could achieve higher thermal efficiency than a conventional diesel operation at relatively high engine load conditions. However, it is also shown that knocks can be appear before diesel fuel injection when relatively high fraction of hydrogen is injected. Consequently, such abnormal combustion limits, prevents high amount of injected hydrogen. The authors have finding a relationship between hydrogen fraction and engine performance. Finally, they indicate the merit and operative range of hydrogen DDF engine.

Unni et al. [3] modified a single cylinder engine for hydrogen and gasoline bi-fuel operation. The modifications are done on the test rig to ensure smooth operation without any undesirable combustion phenomena such as backfire and rapid rate of pressure rise. The engine performance and emission characteristics were optimized for hydrogen operation. The optimized engines were used in a fleet of three wheelers used for public transport. The hydrogen supply layout and safety feature of the vehicle developed is described. Field trials of vehicles are currently undergoing in a popular public gathering place in New Delhi, India.

Bicer and Dincer [4] achieved a comparative life cycle assessment of methanol, hydrogen and electric vehicles to investigate the impacts of alternative vehicles on the environment and human health. The results of this study show that electric vehicles yield higher human toxicity values due to the respective manufacturing and maintenance stages. Hydrogen driven vehicles result in a more environmentally benign option. Since the energy density of hydrogen is quite higher than methanol, hydrogen driven vehicles result in a more environmentally benign

option with respect to global warming and ozone layer depletion potentials. Su et al. [5] investigated a modified gasoline rotary engine with electronic spark control and fuel (gasoline and hydrogen) port-injection system to study the impact of hydrogen-addition on idle performance of a gasoline rotary engine. A hybrid electronic control unit was invented to manage the spark, fuel injection, hydrogen volume fraction of the total intake and overall excess air ratio. In this study, the engine was operating at the idle speed of 2400 rpm and stoichiometric conditions. The hydrogen volume fraction was gradually varied from 0% to 6.8%. Results showed that the coefficient of variation in speed and fuel energy flow rate were both decreased after the hydrogen-addition. Flame development and propagation periods were shortened owning to hydrogen-addition. The peak chamber temperature was enhanced after the hydrogen-addition due to the high adiabatic flame temperature of hydrogen. Cooling loss was dropped when hydrogen was added into gasoline. HC, CO and CO_2 emissions were reduced by 79.4%, 86.0% and 25.9% when hydrogen volume fraction was raised from 0% to 6.8%. Zambalov [6] presented a computational model of combustion simulation in the rotary engine. The combustion and ignition process in the hydrogen-fueled peripheral-ported rotary engine with single and dual laser ignition systems was studied numerically. Dynamics of hydrogen burning out in the combustion chamber is studied. Efficiencies of single and dual laser ignition systems are compared. It was shown that the H_2-fueled rotary engine with the dual laser ignition system has potential application in alternative automotive industry due to high efficiency and near-zero carbon-based emission.

Wind [7] focused on the main differences/similarities and advantages/disadvantages of hydrogen-fuelled road automobiles to other drive-train technologies such as internal combustion engines (ICE), hybrid electric vehicles, range extenders, plug-in hybrids and battery electric vehicles. Further, the different hydrogen-fuelled drive systems are explained, namely fuel cell electric vehicles (FCEVs), hybrid FCEVs and hydrogen ICE vehicles. In addition to descriptions of the different drive systems, advantages and disadvantages in terms of efficiency, range, costs and other aspects are discussed. The possible technological solutions to realization of FCEVs are another discussion point. Challenges facing FCEVs, such as the buildup of a hydrogen-refuelling infrastructure, cost issues and commercialization efforts, are also described. The presentation closes with consideration of main markets and the possible technological and socioeconomic development.

This paper deals with some comments on hydrogen as alternative energy supply for internal combustion. Various aspects are succinctly discussed below.

2. HYDROGEN INTEGRATION IN AN INTERNAL COMBUSTION ENGINES

Due to certain hydrogen properties such as its lower ignition energy, wider flammability range, and shorter quenching distance, it is crucial to modify the internal combustion engine for hydrogen integration in order to prevent problems, such as pre-ignition and backfire from occurring. Certain modifications to the fuel delivery systems, the fuel mixture, as well as the temperature control in the engine system are all key technologies that need to be adapted in order to compensate for the addition of hydrogen.

2.1 Fuel delivery systems

The issue of pre-ignition and backfire mostly occurs during the fuel delivery stage. Pre-ignition occurs when the fuel-air mixture ignites in the combustion chamber before the intake valve closes, which in some cases can cause backfire. Backfire is when the ignited air-fuel mixture explodes back into the intake system [8]. Running the engine at higher loads and at higher fuel-air mixtures near open throttle leads to a greater chance for pre-ignition and backfiring. Therefore, in order to minimize such issues, the fuel delivery systems must be altered. In order to control the difficulties that arise from the fast- burning properties of hydrogen, it is important to keep the air and fuel mixture separate until combustion [8]. The fuel delivery systems for hydrogen can be categorized in one of three ways: central injection (carbureted), port injection, and direct injection.

In a central injection or carbureted system, the fuel is delivered by way of carburetor or a central injection system. This type of delivery method is advantageous because it does not require the engine hydrogen supply pressure to be as high. In addition, carburetors already exist in regular engines, and so converting it to run with hydrogen would be simple (Hydrogen Fuel Cell Technologies). Some drawbacks for such a system are that it is more susceptible to irregular combustion due to pre-ignition and backfire, due to the fact that a greater amount of hydrogen and air mixture within the intake manifold compounds the effects of pre-ignition.

During port injection, the fuel is injected directly into the intake manifold at each intake port, rather than drawing fuel in at a central point. Air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool the hot spots, which decreases the likelihood for premature ignition to happen. The inlet supply pressure for port injection tends to be higher than for the carbureted system, but less than for the direct injection.

Direct cylinder injection is technologically more sophisticated compared to the other two delivery systems presented above. Such a delivery system involves forming the fuel-air mixture inside the combustion chamber after the intake valve has closed. The fuel injection occurs during the compression stroke, and since the intake valve is closed during the injection, premature ignition and backfiring can be avoided. The power output for hydrogen direct injection is 20% more compared to that of a gasoline engine, and 42% more than hydrogen using a carbureted system. Although direct injection solves the issue of pre-ignition in the intake manifold, there is still some concern for pre-ignition to occur in the combustion chamber. In addition, since the mixing time for the air and fuel are reduced, the air-fuel mixture can be homogenous and could lead to a higher NOx content.

2.2 Fuel mixture

There are a number of ways of using hydrogen as fuel; it can be an additive in a hydrocarbon mixture (CNG or diesel), or as its own fuel source with the presence of air. There are two ways to burn pure hydrogen in an ICE, either in a lean or rich mixture. Compared to a rich mixture, lean mixtures have a low density of hydrogen to air. There is a tradeoff between the higher engine efficiency and lower NOx emissions using a lean mixture, to that of greater power output with a higher density fuel mixture [8]. For the case of using hydrogen combustion in the presence of hydrocarbons, the biggest criticism for such systems have been the substantial power loss compared to that of conventional fuels. To ensure an optimum balance of power, acceleration, and emission reduction for hybrid hydrogen systems, it is necessary to have injection and combustion technologies that can control the fuel compound and combustion [9]. According to literature, it is recommended to begin with a light mixture of about 5-10% volume of the mixture as starting point of introducing hydrogen as a clean fuel substitute for conventional fuels [10].

2.3 Temperature control

Temperature control is always vital in ICE systems. Inadequate control of the temperature can lead to reduced engine efficiency, higher fuel consumption, engine damage, unreliable operation and various other risks. Even common efficiency problems such as pre-ignition (which is especially important for hydrogen ICE's) has been linked to bad temperature control, since it can be caused by hot spots in the combustion chamber [11]. Naturally, hydrogen's low ignition energy and wide flammability range makes good temperature control more difficult to achieve. However, by adjusting the ICE, it is possible to keep the engine

temperature more or less stable. The best-known method for preventing the formation of hotspots is the implementation of exhaust gas recirculation (EGR). By recirculating a percentage of the exhaust gas (usually around 20 to 30 %) back into the engine, the operating temperature is kept stable and helps avoid engine knock. This also reduces the formation of NOx because the peak combustion temperature is lowered. On the other hand, EGR is known to reduce the power output of the ICE since the introduction of exhaust gas reduces the amount of fuel in the combustion chamber.

A second much used method for prevention of pre-ignition and backfire is the use of water injection. Thus, spray nozzles are added to the engine. This involves the injection of water directly into the hydrogen (1.75 water to hydrogen by weight) before it is mixed with air (this method has been proven to be more efficient than injecting the water into the air-hydrogen mixture). Care must be taken that the engine's seals do not leak, since this could lead to the water mixing with the oil [8].

A third engine adaption that should be mentioned concerns the spark plugs. For a hydrogen ICE, cold rated spark plugs with non-platinum tips should be used. Normal spark plugs are hot-rated, which means that a certain amount of heat is maintained so that unburned carbon does not accumulate. Since hydrogen does not contain carbon, this function is unnecessary. The need for non-platinum tips is more noteworthy, because platinum is a catalyst, which causes oxidization of hydrogen with air [11].

Lastly, the need for crankcase ventilation is of more importance in a hydrogen ICE than in a normal engine. Just like in a gasoline engine, unburnt fuel can leak through the piston rings into the crankcase, which creates the need for proper ventilation. However, hydrogen has a lower energy ignition limit and thus has a better chance of igniting. Accumulation should be prevented. Ignition in the crankcase could lead to engine fires and a sudden rise in pressure – for this reason; a pressure relief valve should be installed on the valve cover.

3. ACHIVED PERFORMANCES COMPARED TO CONVENTIONAL FUEL

Comparing the hydrogen ICE to a gasoline engine gives a good idea of its performance. Gillingham [12] gives a good comparison of these technologies, as shown in Appendix As seen, the average engine efficiency of hydrogen ICE is higher than those of the gasoline ICE or gasoline hybrid ICE, but lower than that of the H_2 fuel cell vehicle. Its ranking for fuel economy is also second after the H2 fuel cell vehicle. Furthermore, according to Ceper et al. [13], H_2ICE vehicles commonly produce up to 10 times less N2 than gasoline engines and no CO2. One example of an actual H_2ICE vehicle is the Ford Focus-based C-Max, a 2.3 l H2

ICE with supercharger. This vehicle was able to attain emission scores well above the Sulev Tier 2 Emission Standards as well as 99% reduced CO_2 emissions. The vehicle's performance was comparable to gasoline; however, its fuel economy was 25% better.

4. CURRENT OPTIONS

Currently, there are three options for H2 vehicles: fuel cells, H_2ICE or hybrid H2 ICE. Though fuel cell vehicles are seen as the superstars of the future, this technology still needs some development and commercialization. Thus, the best current options are the slightly less efficient H_2ICE or hybrid. The hybrid is seen as the most adapted for commercial option, since it requires the least adaptation (changes costing less than 15% of the total vehicle cost) and also does not have the problems commonly associated with the H_2ICE, such as pre-ignition. Some car manufacturers, such as Alset Global, was even able to create a hybrid that can use hydrogen or petroleum interchangeably; a feat that makes the vehicle truly flexible (especially until the proper H_2 fuel refill infrastructure has been built) and thus more marketable and with a lower development risk. However, the hybrid also has slightly lower engine efficiency when compared to the H_2ICE [9]. Thus, the pure H2 ICE is currently the cleanest and most efficient commercially available hydrogen vehicle on the market. Yet in the future, the fuel cell design is expected to gain even more momentum.

5. STORAGE AND CONTROL

Hydrogen can be stored in three different forms: gaseous, liquid and solid. Firstly, there are composite tanks, which is the most common option to store hydrogen in gaseous form. Therefore, this option is nowadays commercially available. The pressure inside the tanks ranges from 350 to 700 bars, so the compressor needs a relatively high energy input. Other main problems concerning this option are the large volume required and the costs. Another option to store hydrogen in gaseous form is the use of glass microspheres. Spheres can be charged with hydrogen at high pressure and temperature by permeation, they store the hydrogen by being cooled down to room temperature. For discharge, the spheres are heated again. This option is still not well developed, since the permeability of the spheres varies too much and causes hazards. Concerning the liquid storage, cryogenic liquid hydrogen is the most common storage option. The fuel has to be cooled down to -253°C. The energy density is significantly higher compared to hydrogen in gaseous form, but complex insulation and the efficiency of the liquefaction process have to be improved. Other options are the use of

borohydride as a liquid storage medium, or rechargeable organic liquids. For the last option, hydrogen is produced onboard by dehydrogenation of an organic liquid. Due to the complexity of the technology, both of the options still need development. For the third option, the solid storage of hydrogen, carbon or other high-surface materials that store the small molecules, or rechargeable hydrides, can be used. One common problem for the solid storage is the desorption temperature, which can be between 0 °C and 100 °C, and would be difficult to manage for car tanks. Hence, solid storage technologies still need significant development to reduce the weight, recharge time, pressure and cost.

6. PRESENT STATUS IN EUROPE

In Europe, the use of hydrogen in internal combustion engines is still in the research phase, and little detailed information is available. So far, the majority of cars that were bought in 2013 were still relying on diesel and fossil fuels. However, there are plans and projects by the European Commission and by companies that aim to take first steps towards the implementation of hydrogen vehicles.

HyWays (European Hydrogen Energy Roadmap) is an integrated project funded by industry, research institutes and the European Commission. Its main goal is to investigate the potential of hydrogen technologies in Europe, clearly stating the advantages and problems that may be brought about with a shift towards hydrogen as energy source, and to produce a well-accepted set of steps that need to be taken in the future. To that end, stakeholders from multiple member states are invited to workshops to be able to adapt measures to technological and socio-economic realities. It was forecast that most of Europe's hydrogen would mainly be produced as by-product, from steam-methane reforming and electrolysis up until 2020. Until 2050, energy demand would evolve, so stakeholders are expecting centralized electrolysis and thermo-chemistry from renewable energy sources to emerge. Main challenges include cost reduction and policy support. HyWays concluded that the introduction of hydrogen to energy systems could lead to a considerable decrease in CO_2 emissions, as well as increase security of energy supply as the energy system becomes more diverse. The introduction of hydrogen represents a great opportunity for the economy of Europe as it could establish itself as a car manufacturer and energy equipment manufacturer, as well as creates employment opportunities.

The Fuell Cells and Hydrogen Joint Undertaking (FCH JU) has similar goals to the HyWays project. It is a public private partnership that supports research, technological development and demonstration (RTD) activities in fuel cell and hydrogen energy technologies in Europe. Its three members are the European Commission, Hydrogen Europe, and the Research Group N.ERGHY. Its main tasks include the coordination and funding of a number of research and implementation projects.

One of such projects is H2ME2, which was launched in June 2016 by H2ME (Hydrogen Mobility Europe, with funding from FCH JU and the involvement of 37 partners across Europe. The aim of the project is the introduction of 1230 fuel cell vehicles and 20 additional hydrogen-refueling stations (HRS) to the European network. The deployed vehicles are fuel cell electric cars and fuel cell range-extended vans, including the Daimler B-class F-cell, Honda Clarity, and Symbio RE Kangoo. Fuel cell extended vehicles (FCEV) can be refueled in 3 to 5 minutes, but the infrastructure is lacking now. HyICE is a project that ran until 2007, coordinated by BMW, with the involvement of the European Commission. Its aim was to optimize an internal combustion engine that could outdo gasoline and diesel engines regarding efficiency and power density. Direct Injection (DI) and Cryogenic Port Injection (CPO) were studied, as the most promising principles of mixture formation. The result was a new simulation tool for hydrogen combustion for the development of future production engines, as well as an answer to ‘the demand for greater fuel efficiency and engine performance at a reasonable price’. Hydrogen engines are considered to be on a high technological level, needing only infrastructure and policies. Fields that have been identified to be researched further are logistics and storage.

Automotive companies such as BMW and Ford also conduct research in the hydrogen field. BMW has been working on the development of hydrogen ICE since 1979, and their seven series cars can run on either hydrogen or gasoline. MAN has produced several hydrogen ICE busses for a number of projects since the early 1990s, the latest having been developed under the EU project HyFLEET:CUTE.

7. CONCLUSION

An overview of hydrogen use as an alternative fuel for internal combustion engines is presented in this article. The comparison with engines supplied by fossil or conventional fuel is achieved. The challenges that remain to be overcome on the technically and safely sides are

addressed. The current options of hydrogen use and the present status in Europe are considered.

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