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Case Study of Hydrogen as an Enrichment in SI Engine and Study of Various Parameters

Monis Alam

Delhi TechnologicalUniversity, Bawana Rd, Shiv Vihar, Sector 28, Rohini, Delhi 110042
monisalam007@gmail.com

Abstract: *Fossil fuels has been the major fuels used in transportation since last several decades, its good calorific value has made it desirable for its use. High degree of exploitation of the fossil fuels has caused severe damage to our eco system including diminishing fossil reserves, the problem of toxic emissions has to be dealt with so as to sustain a habitual environment in future. The major components of the toxic emissions are un-burnt carbon compounds and oxides of nitrogen. To reduce un-burnt carbon emissions a complete combustion of fuel has to be achieved, one way of doing is by adding hydrogen as enrichment to the fuel, the combustion of hydrogen releases high energy and this energy can be used to burn the un-burnt carbon compounds whereas this energy could also cause increase in oxides of nitrogen. In the present study hydrogen as an enrichment is used in gasoline and alcohol powered spark ignition engine. Emissions and load testing is deeply studied, parameters like ignition timing, injection timing, are considered and their effect on engine performance and emissions is commutated. Through a deep study of various researches it was concluded that induction of hydrogen causes good combustion and decrease un-burnt carbon compounds emissions, whereas the increase of oxides of nitrogen is also observed. While retarding the spark resulted in reduction of thermal efficiency, torque, and emissions of oxides of nitrogen while increase of un-burnt carbon compounds is also observed with it.*

Keywords: *Hydrogen, emissions, nitrogen oxides, spark ignition*

1. INTRODUCTION

Liquid fuels are currently the primary fuel used in transportation, petrol and diesel are the most common of its types, they are derived from dead fossil material dug deep into earth`s crust over a course of millions of years. Yet they are limited in quantity and can do irreparable harm to our environment and thus have to be used sustainably and wisely. According to the Environmental Protection Agency, the burning of fossil fuels was responsible for 79 percent of U.S. greenhouse gas emissions in 2010. These gases insulate the planet, and could lead to potentially catastrophic changes in the earth's climate.Most of the fossil oil is pumped from underground reserves and then undergoes various purification processes to form derivatives like fuel oil, gasoline, liquefied petroleum gas, and other nonfuel products[1]. For transportation, Liquid fuels such as gasoline and diesel are preferred over other crude oil derivatives due to their high storage capacity and they being more economical.

Increasing dependence on fossil reserves is pouring a heavy pressure on their existence and also effecting global health adversely, global crude oil reserves are expected to last till 2065[2]. Diesel engines are more efficient due to their high compression ratio but gasoline engines are preferred over them due to their low emissions and more energy to mass ratio. Even though liquid fuels have large energy density then gaseous derivatives of crude oil, their combustion in IC engine leads to formation of harmful by products which include unburnt carbon compounds and oxides of nitrogen. In 2013 transportation sector accounted for about 28% of total U.S. greenhouse emissions making it second largest contributor after electricity sector there has been an increase of 16% of greenhouse emissions since 1990. This historical increase is largely due to increased demand for travel and the limited gains in fuel efficiency across the U.S. vehicle fleet.

The number of vehicle miles traveled by passenger cars and light-duty trucks increased 35% from 1990 to 2013. The increase in travel miles is attributed to several factors, including population growth, economic growth, urban sprawl, and low fuel prices during the beginning of this period[3]. So there is an immediate need for more efficient and less polluting system for automobiles that could meet current need for sustenance of environment. For implementation of these measures alternatives fuels besides conventional fuels have to be considered for the purpose of transportation, completely shifting to a whole new fuel is a very long process and its implementation can be very time consuming so despite completely shifting to a complete new fuel altogether an alternate blend can be used of the conventional fuel with an alternative one. This is what have been reviewed in the present study. Hydrogen gas is chosen as an alternative fuel here which has been used with other conventional fuels in form of blends.

Globally research have been carried out to decrease the reliance on carbon based fuels so as to decrease exploitation of environment by implementing new fuels in existing IC engines, hydrogen used in IC engines are the most promising of them, as it requires very less modification in existing spark ignition IC engines. Hydrogen as a fuel is primarily suitable only for spark ignition engine because of its high self-ignition temperature (around 536 degree Celsius) and low density, it will take a very high compression ratio for an engine setup to take hydrogen to a temperature above 500 degree Celsius. Following are the merits of hydrogen over gasoline used in spark ignition IC engine:

- Octane number:knocking tendency of an engine or its octane number puts a limit to the compression ratio of the engine. Since octane rating is a property of fuel, use of higher octane alternatives or use of fuel additives can enhance the octane rating and thus reduce the knocking tendency of the fuel. Octane number of hydrogen is more than 130, while that of gasoline is 80-90, high octane rating of hydrogen makes it very preferable for spark ignition IC engine.
- High calorific value: calorific value of the fuel gives us an idea about the energy density of the fuel, for the purpose of transportation we need a fuel with high energy density so that more of energy can be taken onboard the vehicle. GCV of hydrogen is 141790 KJ/KG while that of gasoline is 47300KJ/KG [4].
- The most important of merits is that there are no pollutants release on combustion of hydrogen CO_2 and CO release are negligible as water is the only byproduct of the combustion.
- Brake power and brake thermal efficiency of the engine is significantly increased by the addition of hydrogen as an enrichment with the fuel [5].

While there are some factors that limits our reach towards use of hydrogen as a fuel in vehicles, these are,

- The low density of hydrogen which limits the mass of hydrogen that can be stored in the cylinder as a compressed gas, density of hydrogen is 0.08988g/L at STP, while that of dry air is 1.225KG/m^3 at sea level at 15 degree Celsius.
- High cost of safety devices for the use of onboard hydrogen, hydrogen is very flammable and will burn in air at a very wide range of concentrations between 4% and 75% by volume. Which means that for a safe use the storage and piping of hydrogen has to be completely isolated from the outer air, even a small leak can cause the spontaneous combustion of hydrogen which will lead in a hazard.

2.VARIOUS WAYS OF USE OF HYDROGEN IN ICEs

2.1 USE OF HYDROGENAS A FUEL IN HCCI

HCCI is a new technique in combustion of fuels which uses a homogeneous mixture of fuel and air compressed until auto-ignition occurs near the end of the compression stroke, followed by a combustion process that is significantly faster than either Compression Ignition (CI) or Spark Ignition (SI) combustion [6]. HCCI technology claimed to improve the engine thermal efficiency while maintaining low emissions and can be implemented by modifying either SI or CI engines using any fuel or combination of fuels[7][8]. The combustion mixture is normally lean, and combustion takes place at multiple locations and is then burned volumetrically without discernible flame propagation. Combustion takes place when the homogeneous fuel mixture has reached the chemical activation energy and is fully controlled by chemical kinetics. Since the mixture is lean and it is fully controlled by chemical kinetics, there are new challenges in developing HCCI engines as it is difficult to control the auto-ignition of the mixture and the heat release rate at high load operation, achieve cold start, meet emission standards and control knock. The advantages of using HCCI technology in IC engines are:(1)high efficiency relative to SI engines – approaching the efficiency of CI engines due to the ability of theseenginestohighcompressionratio(CR) and fast combustion; (2)theabilitytooperateonawiderangeoffuels; and(3)theabilitytobeuse ordinaryengineconfiguration:automobileengines, stationaryengines, heavyduty engines orsmallsizedengines, while there are certain disadvantages such as release of unburnt carbon compounds and release of carbon monoxide[13]. As well as there are chances of knocking when operated under certain conditions, the performance of the system completely depends upon the type of fuel used since the performance also effects the emissions so it is the main factor for an engine to be running as more and more stringent emissions norms are implemented, so HCCI development has moved a level up these days. Due to its potential to replace conventional SI and CI engine there is a need to discuss this system with the use of Hydrogen[13].

2.2 COMPARISON OF PERFORMANCE

Low polluting tendencies of an engine depends upon its ability to produce a homogenous mixture, the main goal is to produce a near complete combustion of the fuel mixture. Technologies like Fuel-Stratified Injection (FSI), Turbo-Stratified Injection(TSI) and HCCI. All the above mentioned technologies areusedtoimprovethe combustion efficiencies byintroducingahomogeneousmixtureinsidethe combustion chamber[13].

2.3 FUELS USED IN HCCI ENGINES

The better a fuel is for a HCCI engine the better it has a capability to be vaporized in the combustion chamber before the auto ignition of the charge takes place. As auto ignition time plays a very important role in determining the engine performance with smooth engine operation and avoid knocking and misfiring. Different fuels have different auto ignition points, auto-ignition temperature decreases as the number of carbon atoms in the hydrocarbon increases.

Engine capacity to do work in each stroke is measured by the Indicated Mean Effective Pressure (IMEP), before considering all the losses. Reduction of intake temperature in a HCCI engine can be a cause of increase in IMEP while increase in the CR will have same effect [9]. Antunes, Mikalsen and Roskilly [10] have investigated the engine performance of an HCCI engine fueled with hydrogen, the conclusion they drew was that decrease in temperature is due to increase in IMEP. Hydrogen requires a lower air intake temperature than natural gas for the same CR, a very low density of hydrogen can be the reason for the same. Therefore it is important to control operating conditions of the HCCI system so as to achieve an optimized combustion point[13].

Hydrogen can operate as a single fuel in an HCCI engine but it is often unstable and is prone to generate knocking. Diffusivity of hydrogen is very high as compared to any other gas in air, it is about 3-8 times faster than that of natural gas, this property leads to very fast mixing of the hydrogen in the gas chamber and thus the charge can be considered as homogenous when premixed with air[11][12]. The heating value of hydrogen is thrice as compared to that of diesel (119.93MJ/kgcomparedto42.0035MJ/kg) while having a very high self-ignition temperature of range 858K. As single functioning of hydrogen is very troublesome and stability of engine cannot be guaranteed while the combustion takes place in the HCCI engine, so most of the researches uses hydrogen as an additive with a pilot fuel, rather than the major fuel itself [13].

Hydrogen-diesel combination in HCCI engines shows better results for most major quantities, while producing a higher efficiency compared to the single diesel mode and the natural gas–diesel mode. Fuel consumption is reduced with higher BTE of the engine and the engine BTE can be compared to that of hybrid engine. The HCCI engine has lower emissions levels of NOx, soot and particulates. However, HCCI engines still have unresolved issues, which are knocking and high levels of unburned HC and CO emissions. Knocking will start taking place if the energy ratio is more that 16% it is expected that chemical kinetics is the main influence of knocking [13]. Due to high diffusivity of hydrogen there is a very fast and efficient mixing and thus injection timing of fuel is not a deciding factor of performance and emissions.

2.4 HYDROGEN AS A BOOSTER IN A SI ENGINE

The effect of alcohol blending was studied in detail by Wei-Dong Hsieh et al. [15]. The author investigated the engine performance and pollutant emission of a commercial SI engine by using ethanol–gasoline blended fuels with various blended rates (0%, 5%, 10%, 20%, and 30%). Experimental results indicated that using ethanol–gasoline blended fuels, the torque output and fuel consumption of the engine slightly increase; CO and HC emissions decrease dramatically as a result of the leaning effect caused by the ethanol addition; and CO_2 emission increases because of the improved combustion. In this study, we found that using ethanol–gasoline blended fuels, CO and HC emissions may be reduced 10–90% and 20–80%, respectively, while CO_2 emission increases 5–25% depending on engine conditions. It was noted that NOx emission is closely related to the equivalence ratio, such that NOx emission reaches a maximum near the stoichiometric condition; and that NOx emission depends on the engine operating condition rather than the ethanol content.

G.Fontana et al. investigated the impact of hydrogen engine on gasoline engine [16]. Studies show that with hydrogen addition in gasoline engine at lean operations NOx concentration was found to be lower than for gasoline operation at low loads but gradually increased at higher load and concentration of CO_2, CO decreased as the BSFC of gasoline decreased.

Ethanol and methanol have been investigated in various research projects in blended form with gasoline [17-21]. Properties such as miscibility with gasoline, improved combustion process as reported by research, high auto-ignition temperature and lower NOx due to lower in-cylinder temperatures place ethanol and methanol as an attractive alternative when blended. Another major advantage lies in the fact that the blended fuels do not impose any additional requirements to the current SI engine technology. However, properties such as low energy density and lubrication requirements with increasing blending % impose several restrictions to the use of high percentage blends. Also, better combustion lowers HC and CO emissions but at the same time increases CO_2 emissions.

Bo Zhanget et al. carried out an experimental investigation on the cold start stability of hydrogen enriched methanol engine [22]. Because of short quenching distance and enhanced combustion due to the presence of hydrogen, CO and HC emissions are reduced dramatically by hydrogen enrichment. HC and CO emissions of the engine are dramatically reduced within 19 sec of the onset of the cold start of the engine. Thus it can be concluded that hydrogen addition helps the cold start stability of methanol engines.

E Sher et al. studied the effect of hydrogen addition in gasoline engine on emissions and performance of the engine [23]. They concluded from his research that combustion efficiency, which is the parameter that takes into account the cycle-to-cycle variation in the model, increased by 3 per cent, when 10 per cent of hydrogen was introduced. The increase of the combustion efficiency was found to be linearly dependent on the amount of hydrogen enrichment. Also a significant reduction in the BSFC, of the order of 10-20 per cent, is achieved with hydrogen-enriched gasoline for a hydrogen-fuel mass ratio of 2-6 per cent. The energy conversion gain is prominent at partial loads and depends only to a limited extent on the engine speed. An increase in the amount of hydrogen enrichment improved the BSFC at a declining rate, depending mainly on the engine load. Above 6 per cent of hydrogen enrichment, BSFC decreased marginally throughout the experimental range. A reduction in BSFC, of the order of 20-23 per cent was achieved by operating the engine under very lean mixture conditions, where lower throttling was used and pumping work was reduced. Unlike the uneven operation of the gasoline fueled engine at a low equivalence ratio, the hydrogen enriched gasoline engine showed a very smooth operation in the neighborhood of the minimum value of the BSFC.

Amaya et al. did a comparative study of emissions and performance of hydrogen boosted engine powered with gasoline methanol and gasoline ethanol blend [14]. Among the emission criteria, NOx and CO are considered most harmful in terms of health hazards. From the study it can be concluded that for 40% and 60% of the load applied, the values are optimized in terms of emissions and thermal efficiency. 40% load shows a lower thermal efficiency as compared to the 60% as compared with the 60% thermal efficiency of simple gasoline use. However, 40% load values highlight the major advantage in terms of emissions with least compromise with thermal efficiency. Thus the enrichment strategy adopted in this investigation is suited for medium loads and shows a compromise with emissions or thermal efficiency on either extreme load values. CO_2 concentration increased at high loads showing significant complete combustion at high loads. Combustion of M10 and E20 is increased with the help of enrichment of hydrogen and the concentrations CO_2 and CO is drastically decreased with the enrichment of hydrogen. Hydrogen proved to be more effective in case of E10 as the CO concentration was lower for E10-hydrogen than M10-hydrogen, especially at higher loads. Due to the presence of nitrogen in the air of cylinder and high temperature and pressure produced by the hydrogen enrichment the reaction of nitrogen with oxygen takes place and thus drastically increasing the concentration of nitrogen oxides. The Exhaust Gas Temperature for M10 and E10 increased by 11 ˚C and 15 ˚C respectively due to hydrogen enrichment. Unburnt hydro carbon concentration also dropped significantly. At higher loads E10 proved out to be better than M10 in terms of BTE, CO and HC. But M10 proved out to be better in terms of NOx and CO_2. Increase in temperature of combustion chamber due to combustion of hydrogen and alcohol-gasoline mixture was lower than temperature running on hydrogen-gasoline blend at all loads. Also lesser modifications were required for the combustion of hydrogen with the blends. The study is very well applicable with the engines that already uses blend of alcohol and gasoline, enrichment of hydrogen can be done so as to increase the performance and emissions characteristics of the engine.

3. CONCLUSIONS

Hydrogen can be considered as a future fuel, due to its high energy density by mass, through it high amount of energy can be carried in, while there will be a problem in the storage because of a very low density, very high amount of volume is required to store same mass of gas in the cylinder, further high range of combustibility supports backfiring of the hydrogen gas, and thus very proper and appropriate devices have to be used to contain hydrogen gas on board. Hydrogen-diesel combination in HCCI engines shows better results for most major quantities, while producing a higher efficiency compared to the single diesel mode and the natural gas–diesel mode. Fuel consumption is reduced with higher BTE of the engine and the engine BTE can be compared to that of hybrid engine. The HCCI engine has low emissions levels of NOx, soot and particulates. However, HCCI engines still have unresolved issues, which are knocking and high levels of unburned HC and CO emissions. Because of high temperature and pressure reached by the gas in the chamber there is a very high probability of formation of oxides of nitrogen. Thus it can be concluded that by inducing hydrogen as a supporting fuel in the combustion chamber a cleaner combustion takes place because high temperature helps the combustion of unburnt hydrocarbons but the high temperature is also a causing factor of nitrogen of oxides.

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