International Journal of Engineering Studies.
ISSN 0975-6469 Volume 9, Number 1 (2017), pp. 79-87

http://www.ripublication.com

# A Review on the effects of Hydrogen Addition on Performance, Emission and Combustion Characteristics of the CI engine

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**Abstract**

At present scenario, the demand for the fuel has been increasing and people are much dependent on natural gas, conventional fuels which are non-renewable and their availability diminishes in the near future. This stresses out the urge to switch to the alternative fuels. So in this paper, the effects of performance, emission and combustion of the Compression Ignition (CI) engine fuelled with hydrogen and diesel is reviewed. It was observed that the unburned hydrocarbons and carbon monoxide discharge had reduced on addition of hydrogen to the diesel engine. Also the combustion duration and ignition delay decreased due to higher flammability of hydrogen and resulted in complete combustion. In addition to that, the volumetric efficiency decreased with hydrogen addition due to the lower density and higher velocity of hydrogen.

**Keywords:** Hydrogen; CI Engine; Performance; Emission; Combustion.

## INTRODUCTION

Concern for the environment is one of the primary factors and protection of the environment from the harmful pollutant is the responsibility of every individual. The increased atmospheric pollution and the currently increasing energy demands urged many researchers to do standout researches in the field of alternative fuels. In such an event, many had investigated the effects of hydrogen in CI engine. Bose et al. [1] found that crude oil availability will decline in the next 10 to 20 years and severe shortage of the fuel will be faced in the second half of this century. Moreover the higher hydrocarbon content in diesel and gasoline releases harmful gases such as CO and $CO_2$ which causes global warming and ozone layer depletion. Thus, in order to overcome from pollution and for the energy security in the future generation, it is always better to switch over to alternative fuels.

Hydrogen being one the best source of alternative fuel has many positive effects on combining with diesel in the compression ignition engine. Jyothi et al. [2] investigated the addition of hydrogen along with diesel in a dual fuel mode in a single cylinder four stoke engine. It was observed that the combustion efficiency was drastically improved based on the parameters such as the pressure rate, ignition delay, heat release rate, and mean gas temperature respectively. Talibi et al. [3] found that at higher engine loads, the injection delay period reduced in duration due to improved evaporation and homogenous mixture of fuel with air. Talibi et al. [3] found that at fixed diesel injection and engine load below Indicated Mean Effective Pressure [IMEP] of 5.5 bar, there was a reduction in particulate emission. Das [4] presented in his paper that, hydrogen aided in reducing the emission rate of the vehicle by decreasing the amount of particulates, sulfur dioxide, benzenes which are usually present in the engine exhaust and helped for zero ozone. Since the hydrogen allowed for lean mixture of air and fuel, the amount of unburned fuel was dramatically reduced and thereby also helped in controlling the nitrogen dioxide emission to some extent. It was concluded that the other parameters such as hydrocarbons and carbon monoxide emission can be controlled by regular maintenance and inspection. On looking at the performance of the engine with hydrogen addition, few researchers [5] conducted an experiment and found that, some of the parameters such as the brake thermal efficiency, indicated thermal efficiency, engine displacement increased and brake specific fuel consumption decreased with the increase in the hydrogen volumetric ratio. It was also found [6] that heat release rate increased with the addition of hydrogen along with diesel. Korakianitis et al. [7] found that volumetric efficiency of the engine was increased on direct injection of hydrogen technique rather than injecting the hydrogen on the intake manifold of the cylinder.

Many researchers have conducted experiments and studied the effect on the performance, emission and combustion characteristics with the addition of hydrogen in CI engines, yet it still lacks clarity. Different results were obtained in different research experiments and this necessitates the urge to carry out a review to bridge the gap. We take this as an opportunity to make a review on the performance, emission, combustion effects on addition of hydrogen with diesel in a CI engines.

## PROPERTIES OF HYDROGEN

The properties of hydrogen affecting the performance and emission discussed by some of the authors [8, 9] are given as follows. Hydrogen flammability is generally high with the value ranging from 4.1 to 75.6, and this helps in complete combustion process and lean mixture of air fuel ratio allows for the greater fuel economy. Generally hydrogen possess a small quenching distance which makes it difficult to cool them easily with a distance of 0.06mm than compared to gasoline fuel which possess a distance of 2mm.

Flame speed of the hydrogen is fast and the speed of the flame decreases as the engine runs with lean operation of the air and fuel, in order to obtain a good fuel economy. The adiabatic flame temperature of hydrogen-air mixture is high when the air fuel equivalence ratio is unity and it gradually decreases beyond this value. The Auto-Ignition Temperature (AIT) of the hydrogen is generally high which helps in the reduction of ignition delay and its value for hydrogen fuel being $585^0$ C helps in achieving higher compression ratio. Hydrogen helps in stoichiometric composition of air-fuel which helps in complete combustion process without leaving any unburned gases.

**Table 1.** Properties of Hydrogen and Diesel.

| No | Property | Hydrogen | Diesel |
|---|---|---|---|
| 1 | Molecular weight(g/ mol) | 2.016 | 170 |
| 2 | Density at $160^0$ C and 1.01 bar(kg/m3) | 0.0838 | 833-881 |
| 3 | Net heating valve (MJ/kg) | 119.93 | 42.5 |
| 4 | Boiling point (K) | 20.27 | 436-672 |
| 5 | Cetane number | - | 52 |
| 6 | Specific gravity | 0.091 | 0.83 |
| 7 | Research octane number | 130 | 30 |
| 8 | Viscosity at $15.5^0$ C (Centipoise) | - | 2.6-4.1 |

## EFFECTS ON PERFORMANCE

The Brake Thermal Efficiency (BTE) which is defined as the ability of the engine to convert the heat energy associated with fuel into useful work is one of the fundamental parameter studied in the performance of an engine. Some researchers [10] made comparison by injecting the hydrogen by direct injection technique and injection of hydrogen via intake manifold. They observed that direct injection technique showed a 19% increase in thermal efficiency than compared to the latter one. It was so because; in the former one the uniform mixture of fuel- air leads to a more homogenous mixture resulting in a complete heat release rate. Ghazal [11] found that value of the BTE increased for a mixture of hydrogen addition in the range of 5 to 10% and the corresponding value of BTE increased from 42 to 45, whereas in the pure diesel, the value was just 40 which showed a decline from the former one. Saravanan et al. [12, 13] investigated the BTE by using the solenoid driven intake injection system and found that BTE increased by using hydrogen along with diesel in the above injection system. The BTE increase was attributed to the decrease in combustion period, increase in cylinder pressure and heat release rate.

On looking at the Indicated Efficiency (IE) many researchers [14] found that its value to be at 57.9% at 21.4 (l/min) of hydrogen flow rate and the value decreased to 49% of IE at 49.6 (l/min) of hydrogen flow rate. A few researchers [15] found that volumetric efficiency was maximum at 10% hydrogen mixture with a value of the efficiency being 0.73 and as the load increases to 80% the value of efficiency found to decrease to 0.65. This decrease was due to the higher velocity and lower density of hydrogen where it leads to displace air.

The Brake Mean Effective Pressure (BMEP) is defined as the average pressure which if imposed on the top side of piston uniformly from TDC to BDC of each power stroke required to produce the measured brake power output. It was found [16] that on addition of hydrogen, BMEP was higher and engine operation was found to be effective at higher load operations. Choi et al. [17] found a decline in BMEP with a drastic rise in the addition of hydrogen in an experiment and this was due to the lower availability of oxygen in lean mixture; thereby causing the value of BMEP to decrease.

On looking at the Specific Energy Consumption (SEC), an experiment [12] was conducted at varying concentrations of hydrogen in diesel and found a reduction in SEC with an increase in hydrogen addition. It was found that at 90% concentration of hydrogen and 65% of engine load, the SEC was 12.7, and increased to 16.7 (MJ/kwh) in the diesel operated condition. Some experiments [18] revealed that at lower engine load of 10Nm, the value of SEC showed an increase in both the diesel and in dual fuel mode. Sahoo et al. [19] had concluded that the value of SEC showed a decrease in its value at higher engine load in both the diesel fuel and in the dual fuel mode.

## EFFECTS ON EMISSION

Some researchers [2O] found that the unburned hydrocarbons and carbon monoxide emission level decreased to a higher extent by the addition of the hydrogen to the diesel as it helps in the complete combustion and thereby reducing the well wetting effect of the cylinder liner. Gatts et al. [21] found that on addition of hydrogen to diesel fuel at 15% load, a reduction in carbon monoxide level and unburned hydrocarbons was witnessed compared to the diesel fuel. Ghazal [11] found that the addition of hydrogen to diesel fuel at different engine speed and air fuel ratio, the carbon monoxide emission decreased to greater extent. This was possible because of the complete combustion of the fuel by hydrogen. Bose et al. [22] observed that on using hydrogen with Exhaust Gas Recirculation (EGR), a reduction of carbon dioxide was observed up to a certain point and then the value of carbon dioxide emission was found to increase as the value of EGR increased. The insufficiency of oxygen content leading to poor combustion resulted in the release of more $CO_2$ at higher EGR. It was observed that unburned HC discharge was 55 ppm without EGR, but at 10% EGR, the value of the HC increased to 108 PPM at 80% engine load.

Masood et al. [23] compared the induction and direct injection technique for hydrogen injection and found that on induction technique, the value of particulate matter decreased initially at lower crank angle and increased with rise in crank angle. In case of direct injection technique, the value of the particulate matter started gradually decreasing with crank angle. Some researchers [12] found that at 20 % load and 10% hydrogen concentration, the exergy efficiency was found to be just 13%. This was attributed to the lower exhaust gas temperature and poorer combustion, but as the load of engine increased to 80% with hydrogen content being 50%, the exergy efficiency was high due to the higher exhaust gas temperature.

On the addition of hydrogen, an increase in Nitric Oxide (NO) and Nitrogen dioxide ($NO_2$) was obtained. Here the NO content was in the range of 90-95% and $NO_2$ was in the range of 5-10% [24]. Korakianitis et al. [25] found that at the speed of 750 and 1000rpm, a rise in the NO and $NO_2$ emission was witnessed to some extent. These trends were due to the high temperature achieved through complete combustion by the hydrogen addition and with the help of the high pressure that was developed inside the cylinder. Saravanan and Nagarajan [12] found that the value of the NO increased at the starting stage where the air-fuel mixture was rich and the value of the NO decreased with leaner mixture. The decrease in NO value was due to the leaner mixture (lower equivalence ratio) and the value of NO being least at 0.53 of air- fuel ratio with 20% hydrogen. The value of NO was maximum at an air fuel ratio of 1.2 with 20% hydrogen. Similarly on comparing the NO with engine load, it was observed that at a maximum of 90% hydrogen with 60% load, the NO emission was considered to be least with 575 ppm.

## EFFECT ON COMBUSTION

Liew et al. [26] discovered that on adding hydrogen to the diesel, the time taken for the process of combustion was reduced to a greater extent than using diesel fuel. This was possible because of the higher flammability of the hydrogen. On carrying out some experiments, a few [26] found that at 6% hydrogen addition with diesel, the combustion period was reduced by 23% than pure diesel. Also the combustion duration at various proportion of hydrogen with different load was observed and it was found that the loads of 30 and 70 % with 15% hydrogen content showed a decline in combustion duration. It was found [27] that, the ignition delay was reduced on addition of hydrogen to a single cylinder four stroke engine, than using pure diesel. They found this by conducting an experiment with air fuel ratio by changing the timing and duration of the injection. They found that power to weight ratio of the vehicle increased by 14% than the pure diesel fuel. Das et al. [28] conducted an experiment by varying the engine load and found that value of the ignition delay increased with hydrogen addition and this was due to the lesser amount of oxygen availability leading to the ignition in the delay period.

Santoso et al. [14] studied the effect of variation in cylinder pressure on addition of the hydrogen in a single cylinder diesel engine and found that the value of the pressure decreased with the hydrogen enrichment. A graph was plotted between the cylinder pressure and crank angle and it showed that as the value of crank angle increased, the value of pressure decreased. At 21.4 (l/min) of hydrogen flow rate the value of cylinder pressure was 70 bar whereas at 48.9 (l/min), the cylinder pressure had decreased to 60 bar. This shows the reduction in cylinder pressure with the increase in the hydrogen enrichment but this was only at lower loads. Liew et al. [26] who conducted an experiment at high engine loads found that the value of cylinder pressure increased with hydrogen enrichment. Saravanan and Nagarajan [12] found that with the high hydrogen enrichment, the maximum pressure was obtained at 5 $^{0}$ Crank Angle (CA) or above that. Korakianitis et al. [25] found the value of the peak pressure was achieved at CA of 4 $^{0}$ or above.

Bose et al. [11] found some of the parameters such as the Heat Release Rate (HRR), and mean gas temperature on the addition of hydrogen to diesel and their values were found to increase. The mean gas temperature was found to be 1924$^{o}$C at 10 $^{0}$ CA after Top Dead Center (TDC), and this was possible only because of the high auto ignition temperature of the fuel blends used. Some authors [26] also found that at the engine load of 30% and 70%, the value of HRR increased with the hydrogen addition, whereas at lower engine loads (15%), the value of HRE decreased.

## CONCLUSION

In this paper the effect of the addition of hydrogen to the diesel engines on the performance, emission and combustion characteristics were reviewed and the following conclusions are evident.

- The BTE of the engine increased on hydrogen addition by induction technique due to decrease in combustion period. Also the indicated efficiency and volumetric efficiency decreased with increasing engine load at high hydrogen mixture.

- The Brake Mean Effective pressure was observed to decrease at higher hydrogen mixture but it was comparably high with pure diesel fuel. Specific Energy Consumption decreased on addition of hydrogen at high load.

- It was observed that on using hydrogen with diesel the amount of unburned hydrocarbons and the carbon dioxide emission level decreased due to the lower carbon content on dual fuel mode, but there was an increase in NO emission due to complete combustion in dual fuel mode.

- On the addition of hydrogen the combustion period reduced due to higher flammability of hydrogen and the ignition delay increased due to the insufficiency of oxygen at high hydrogen content. The cylinder pressure decreased at lower engine loads and increased at the higher engine load. As a whole, it is evident that hydrogen can be used as a fuel in CI engines with necessary engine modifications and hydrogen remains as a potential fuel candidate for the future energy demands.

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