A Review on Performance and emission characteristics of hydrogen enriched compressed natural gas engine.

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Abstract: *The decreasing rate of petroleum products and its fatal effects of greenhouse gas emissions have made many of researchers to focus on alternative fuels. So that it is needed to reduce emissions from vehicles and power plants are some prime factors that increase the necessity for development of alternative energy options. Hydrogen resources are available in abundant form in environment so it is possible to use this fuel in vehicles as it has great properties as compare to other fuels. Hydrogen and natural gas blends (HCNG) are a workable alternative fuel because of the efficient reduction in emissions and the increased engine efficiency. In this review paper, effects of hydrogen addition on an engine fuelled with HCNG under various conditions and details on the different mixture formation strategies and fuel properties are illustrated. In addition, the scope and challenges being faced in this area of research are clearly described.*

Key Words: **Hydrogen, Natural gas, Blend, Emissions, Engine, fuel, etc**

1. INTRODUCTION

Impending possible energy crisis in future, rising costs and toxic emissions associated with conventional petroleum fuels have caused researchers to search out and investigate the possibility of utilization of alternate clean and non-polluting fuels for internal combustion engines. With rising amount of cars and decreasing of oil resources, it seems that the use of alternative fuels is inevitable in the future [1].

Hydrogen has been regarded as a future secondary fuel for power system due to carbon-free operation. Rapid increase in the emission of green house gases and very strict environmental legislations are major motivating factors for the usage of hydrogen in fuel cells and internal combustion engines. It is an excellent additive to improve the combustion of hydrocarbon fuel due to its low ignition energy, high reactivity, diffusivity and burning velocity [2]. Hydrogen enriched compressed natural gas engine has also attracted many researches recently due to its potential to reduce harmful exhaust emissions, to increase engine thermal efficiency and it also seems to be a good choice since hydrogen, by its nature, has relatively fast laminar burning velocity and low ignition energy. Therefore, it is quite natural to think of blending hydrogen with NG to make it more suitable for lean operation, and this fuel blends is called HCNG or hythane [3].

2. LITERATURE REVIEW

Fanhua Ma et al. [4] have conducted experiment on six-cylinder, single point injection, SI natural gas engine. An online mixing system was used to blend hydrogen in a natural gas and the tank was developed to improve the mixture uniformity. This research has shown that the brake effective thermal efficiency increases with an increased percentage of hydrogen. Another effect of the addition of hydrogen was that the brake specific fuel consumption was reduced, the cycle by cycle variations are also reduced, and the thermal efficiency was increased. Emissions also improved with the addition of hydrogen. Compared to pure natural gas, HCNG reduces the HC emissions, which is in part due to the increased combustion stability that comes with the addition of hydrogen. However, due to the increased temperature and combustion duration by the hydrogen addition, an increase in NOx emissions was observed. When it compared to gasoline, it produces significantly less nitrous oxide, carbon monoxide, carbon dioxide and non-methane emissions. And when compared with diesel, it nearly eliminates the particulate matter which is often of great concern. Compared to pure natural gas, it has been concluded that the addition of hydrogen increases the NOx emissions while reducing the HC emissions. The combustion stability is also improved by the addition of hydrogen which plays a part in reducing the un-burnt hydrocarbon emissions.

In 2008, Kirby S. Chapman et al. [5] conducted research trails on V6 naturally aspirated, four-stroke engine with spark ignition. Three compressed natural gas bottles that were used to premix hydrogen and natural gas in prescribed concentrations. This research has shown that by blending hydrogen with natural gas thermal efficiency achieved about 2% and significant emission reductions of between 18% and 45% and he found optimal fuel blend was 20% hydrogen with 80% natural gas. Increasing the hydrogen percentage beyond 20% achieves a significant reduction in emissions and reduced the power produced by the engine. Further reduction in emissions can be obtained by retarding the ignition timing.

In 2007, Fanhua Ma et al. [6] Investigated effect of hydrogen addition 0, 10%, 30%, and 50% on natural gas (NG) engine's thermal efficiency and emission. He conducted an experimental research on an in-line 6 cylinder spark ignition NG engine using variable composition hydrogen/CNG mixtures (HCNG). He developed online hydrogen–NG mixing system which used to blend desired amount of hydrogen with NG. The results showed that hydrogen enrichment could significantly extend the lean operation limit, improve the engine's lean burn ability, and decrease burn duration as well as reduction in unburned hydrocarbon but nitrogen oxides was found to increase with hydrogen addition if spark timing was not optimized. Based on the results he concluded that adding hydrogen into NG was good for improving engine thermal efficiency. He also shown that Engine lean burn limit could be extended by hydrogen addition mainly due to hydrogen's broader burn limit and fast burn speed. 10%, 30%, and 50% hydrogen extended lean limit to 1.82, 2.09, and 2.4, respectively, compared to 1.71 for NG. By optimizing spark timing to MBT, engine efficiency could be rose with increase of hydrogen fraction, hydrogen enrichment was found to be not good for engine efficiency improvement at unchanged spark timing actually it dropped when 50% hydrogen was added in this study. Unburned HC emission was decreased with the increase of the amount of hydrogen added no matter whether spark timing was changed or not.

R. Sierens et al. [7] investigated effects of variable composition hydrogen (10%, 20%) natural gas mixtures on V8 spark ignited four stoke engine. He used gas carburetor for mixing of gas and air which causes reduction in volumetric efficiency and some power loss. He showed that, for lower bmep high efficiency can be achieved by increasing the hydrogen content. At the same time unburned hydrocarbon emissions were minimized, (for lean mixtures) NO_X emissions stay limited. He made a comparison between natural gas and two blends of hythane (hythane with 10 and 20% volume hydrogen respectively) and each time, spark timing was optimized for maximum power (MBT) and hydrogen addition of 10% increases efficiency moderately, whereas 20 % hydrogen gives no significant extra benefit (for the same λ-value). He seen that different fuel mixtures give very similar results the only major difference is the ability of hythane to run leaner, the more so the higher the hydrogen content.

In 2003, M. M. Gosal et al. [8] carried out Experimental investigations on a single-cylinder four-stroke motorcycle spark ignition engine operated on small percentage of hydrogen (5 to 30%) with CNG. Hydrogen and CNG were mixed in a developed mixer and supplied through the inlet manifold system. Performance and emission tests carried on the engine with this system showed a considerable improvement in power output and in thermal efficiency as well as reduction in brake specific energy consumption (BSEC), hydrocarbon (HC) and carbon monoxide (CO) emissions and he observed Power loss associated with CNG utilization had improved with the addition of hydrogen fuel (20 to 30%). Hydrogen blended with CNG enabled leaner operation and showed an improvement in BMEP and environmental benefit. Six different blends such as 95CNG5H2, 90CNG10H2, 85CNG15H2, 80CNG20H2, 75CNG25H2 and 70CNG30H2 were prepared online to carry out the investigations. When hydrogen and CNG blend supplied to the engine it causes to improve in the power developed nearer or more than gasoline operated vehicle as compared to CNG fuelled engine whereas 20 to 30% hydrogen blend has given the maximum improvement in power up to 25 to 50%. BTE increases as power increases, reaches to a maximum and then decreases for further increase of power, which was observed for all blends. He achieved higher BTE with CNG+H2 blend. Differences in the BTE produced between CNG and CNG+H2 blend fuel supply became much more significant at higher hydrogen presence (20 to 30%). The maximum BTE of a 70CNG30H2 blend was 32%. This was about 1.5 times that of CNG supply. The increase in percentage hydrogen and load causes the rise of exhaust temperature by 100 to 150°C. The concentration of HCs decreased with an increase in bmep up to a certain value and then it starts increasing. The minimum value with 70CNG30H2 is observed to be 0.1 g/kWh. The maximum value of NO_X is observed at 22 g/kWh for 30% Hydrogen. Hydrogen enrichment of natural gas enhances combustion characteristics of the engine brake thermal efficiency increases by 20% and brake specific energy consumption values decrease by 14% with increasing hydrogen. The tests showed that the optimum concentration of hydrogen in the fuel mixture for producing a power gain appears about 20-30% by volume over the range of conditions considered.

Ali Keshavarz et al. [9] conducted experiment on four-stroke, 4.2 L, V-6 naturally aspirated natural gas engine to study the impact of hydrogen/natural gas blends on engine performance, thermodynamic efficiency and exhaust gas. The engine was tested at throttle openings of 50% and 100% and equivalence ratios of 1.0 (stoichiometric) and 0.9 (lean) for hydrogen percentages of 10%, 20% and 30% by volume. The test results showed the reduction in NO_X and CO. The engine power and torque slightly decreased when the hydrogen concentration was increased. CO emissions for this engine were found to be very sensitive to equivalence ratio close to stoichiometric condition. A maximum reduction of 36% in CO emissions was measured at 30% hydrogen concentration and 2,600 rpm. After analysis he concluded that for equivalence ratio of 0.9 and 50% throttle opening, reduction in CO emissions associated with increase in hydrogen/natural gas blend from 20% to 30% is not significant. CO emissions was measured at equivalence ratio of 0.9 were higher for 50% throttle opening as compared to 100%. A maximum engine torque reduction of 1.5% was measured for 30% hydrogen and 50% throttle opening for equivalence ratio of 0.9 the maximum reduction in NO_X emissions measured is about 19% for 50% throttle opening. He concluded that by increasing hydrogen concentration from 20% to 30% did not reduce NO_X emissions. Maximum reduction in NO_X emissions was seen about 13% and 18% respectively for 20% hydrogen/natural gas blend for 50% and 100% throttle openings. The maximum reduction seen for BSFC with addition of hydrogen was about 7% and 9% for 50% and 100% throttle opening respectively.

1. For equivalence ratio of 0.9 and 50% throttle opening results are follows:-

a. Maximum reduction in BSCF of about 5%.
b. Maximum reduction in torque of about 4%.
c. Maximum reduction in NO_X and CO emissions of about 66% and 38% respectively.

2. For equivalence ratio of 0.9 and 100% throttle opening results are follows:-

a. Maximum reduction in BSCF of about 9%.
b. Maximum reduction in torque of about 6%.
c. Maximum reduction in NOX and CO emissions of about 61% and 31% respectively.

Biagio Morrone et al. [10] have developed a numerical model to predict the performance and emissions of an internal combustion engine fuelled by natural gas and hydrogen-natural gas blends. Exhaust gas recirculation (EGR) was investigated with the aim at improving engine efficiency and reducing NO_X emissions respect to undiluted charge. Results showed that HCNG blends improved engine brake efficiency, particularly at low loads and for the highest hydrogen content. NO_X emissions increased of about 4% for HCNG 10, 11% for HCNG 20 and 20% for HCNG 30 Further investigations, reveals that by adopting 10% EGR for HCNG blends, shows a large reduction of NO_X emission, over 80% compared with natural gas (without EGR), with a positive effect also on engine efficiency. The decrease in fuel consumption using HCNG blends together with EGR, compared with natural gas, was 5.4%, 6.6% and 7.7% for HCNG 10, 20 and 30, respectively. He seen increment in brake efficiency are higher at low engine loads and high speeds, with improvements of 3.7% for HCNG 10, 6.5% for HCNG 20 and 9.3% for HCNG 30, at 0.8 bar bmep and 2500 rpm and NOx emissions increased of about 4% for HCNG 10, 11% for HCNG 20 and 20% for HCNG 30.

Xin Wang et al. [11] carried out an experimental study on a spark ignited engine fueled with compressed natural gas and hydrogen blends. Effects of ignition timing, hydrogen fraction, engine speed, throttle opening, coolant and oil temperature were investigated. The results indicated that lean combustion limit could be obviously extended by adding hydrogen into compressed natural gas. He had drawn following results:

1) By reducing engine speed, lean combustion limit of the engine could be extended with fixed throttle opening.

2) Lean combustion limit increased with throttle opening when engine speed remained a constant.

3) Lean combustion limit had a positive correlation with coolant temperature under a certain operating condition.

4) A lubricant oil temperature increase corresponded to an initial decrease followed by an increase in lean combustion limit under a certain operating condition.

Toshio Shudo et al. [12] carried out experimental research on four stroke cycle single cylinder spark ignition engine. He supplied Hydrogen continuously into the intake manifold, and methane was directly injected into the cylinder with the gas injector. Results showed that combustion system achieved a higher thermal efficiency due to higher flame propagation velocity and lower exhaust emissions. An increase in the amount of premixed hydrogen stabilizes the combustion to reduce HC and CO exhaust emission. The increase in NO_X emission can be maintained at a lower level with retarded ignition timing without deteriorating the improved thermal efficiency. The lean operation enables improvement of thermal efficiency and reduction of HC and NO_X exhaust emission simultaneously. The hydrogen premixing tends to increase NO_X exhaust emission, but the increase can be maintained at lower levels with retarded ignition timing without deteriorating thermal efficiency.

3. HYDROGEN FUEL INDUCTION METHODS

Fuel supply techniques play an important role in determining the characteristics of an IC engine. Homogeneity of mixture dependant on how which gases (hydrogen and CNG) mixing each other and it is only dependant on the induction system of the engine. Therefore the methods to supply hydrogen into an engine and the corresponding design of a hydrogen supply system become one of the key problems to be solved in the research on a hydrogen engine. The fuel induction technique for an internal combustion engine can be classified into three categories such as Carburetion, inlet port or inlet manifold injection, and direct cylinder injection.

Carburetion is the oldest and simple technique for inducting the fuel - air mixture into the cylinder. The power output of the engine mainly dependant on the throat of the veturi. The technique of carburetion was used to operate hydrogen engines by many researchers. The advantage of this technique is that it does not require a high pressure hydrogen supply. This technique also allows the fuel to mix uniformly with the air before being allowed into the cylinder, leading to a more efficient combustion. However, this technique reduces power by 15%. Hydrogen addition in carburetor arises some problems such as small power output, abnormal combustion (e.g. backfires, pre ignition, high pressure rise rate and even knock) and high NOX emission would occur. Variation in brake thermal efficiency, hydrocarbon emission, carbon monoxide emission, nitrogen oxide emission and carbon dioxide emission are compared with different hydrogen blends, CNG and gasoline in following graphs for carburetion type of induction system.

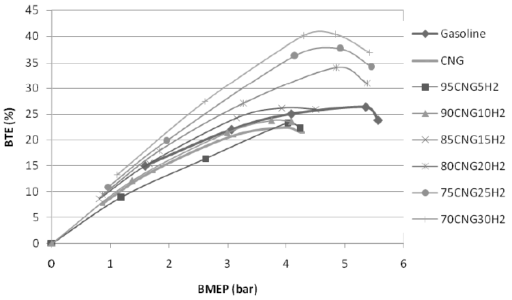

Fig -1: Brake thermal efficiency as a function of brake mean effective pressure for different hydrogen blends. [8]

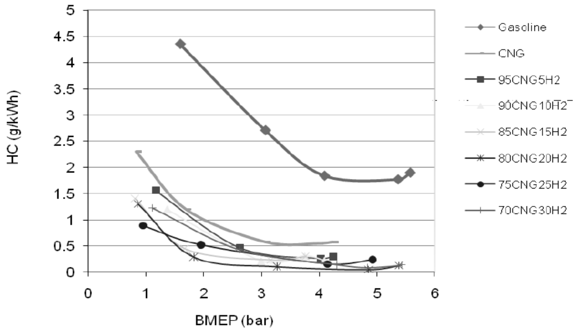

Fig -2: Hydro carbon emissions vs brake mean effective pressure for different hydrogen blends. [8]

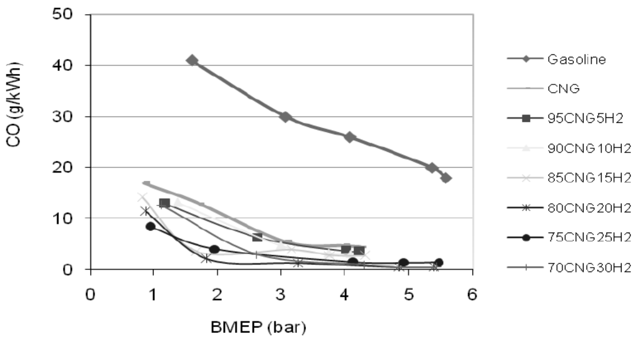

Fig -3: Carbon monoxide emissions vs brake mean effective pressure for different hydrogen blends. [8]

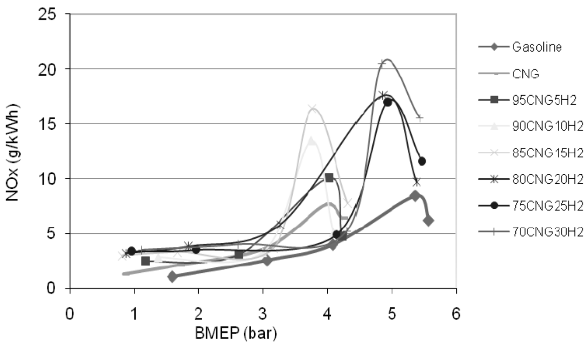

Fig -4: Nitrogen Oxide Emissions vs Brake Mean Effective Pressure for different Hydrogen blends. [8]

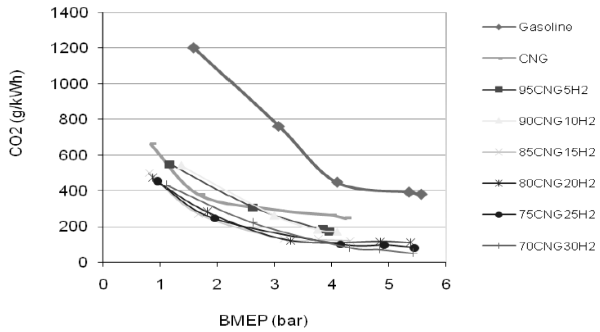

Fig -5: Carbon dioxide emissions as a function of brake mean effective pressure at constant throttle for various hydrogen blends. [8]

The port injection system injects the fuel directly into the intake manifold. Hydrogen is injected into the intake manifolds at this condition premature pre-ignition can be reduced. In port injection, the inlet supply pressure is higher than the carburetor, but is less than the direct injection systems. There are various system for injecting fuel into intake manifold such as a constant volume injection (CVI), electronic fuel injection (EFI) system. In inlet manifold or port injection method, the injection of the fuel is scheduled to start sometime after the inlet valve is opened. This increases the cooling effect of pre-inducted air. This eventually eliminates the hot spots and the pre-ignition. This also reduces the peak combustion temperature and leads to reduction in NOX emission shown in Fig-12.

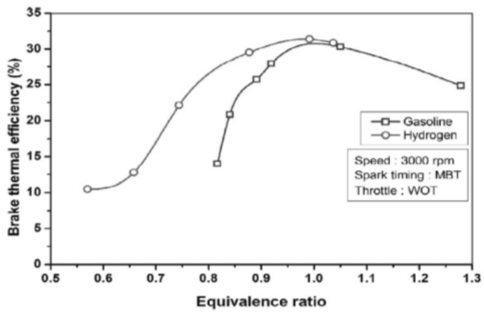

Fig -6: Variations of brake thermal efficiency with equivalence ratio. [13]

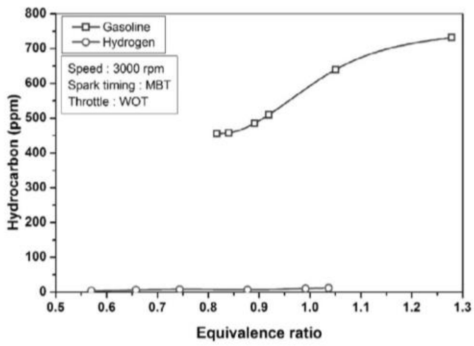

Fig -7: Variations of hydrocarbon emission with equivalence ratio. [13]

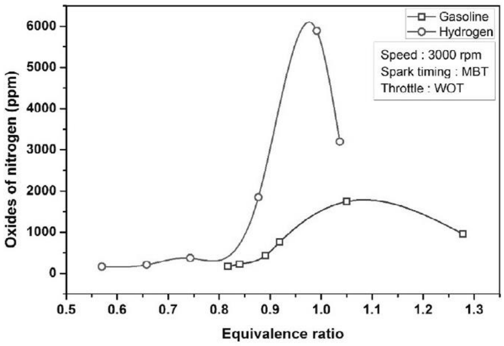

Fig -8: Variations of oxides of nitrogen with equivalence ratio. [13]

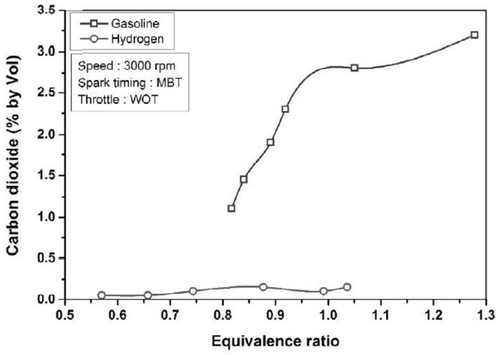

Fig -9: Variations of carbon dioxide emission with equivalence ratio. [13]

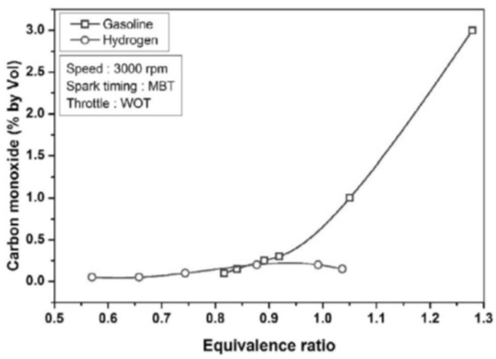

Fig -10: Variations of carbon monoxide with equivalence ratio. [13]

In direct in-cylinder injection, hydrogen is injected directly inside the combustion chamber with the required pressure. Hydrogen addition by this method improves the ignitability of the fuel mixture. This results in shorter ignition delays and in a shorter time for the flame to spread. The power output of a direct injected hydrogen engine was 20% more than for a gasoline engine and 42% more than a hydrogen engine using a carburetor. Direct injection solves the problem of pre-ignition in the intake manifold. The high pressure injection of hydrogen creates high turbulence in the fuel - air stream. So that, mixing of the fuel with the air and forms more homogeneous mixture of fuel and air. The addition of H2 reduces CO, HC, and PM emissions shown in following Figs. These reduction results are more as compared to other induction system. The main reason for reductions in CO, HC, and PM is enhanced oxidation occurring because of improved combustion stability and higher concentrations of reactive radicals. The NOX emissions are increased by H2 addition at both low and high loads. This is in part due to hydrogen's higher flame temperature this can be reduced exhaust after treatment. Effect of hydrogen content on carbon dioxide, carbon monoxide, hydrocarbon, nitrogen oxide emission is shown in following Figs. [14]

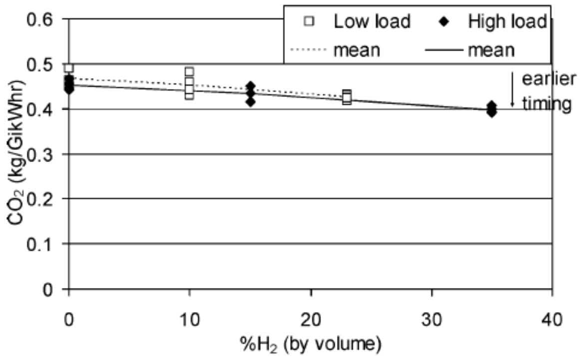

Fig -11: Effects of hydrogen content on carbon dioxide emissions. [14]

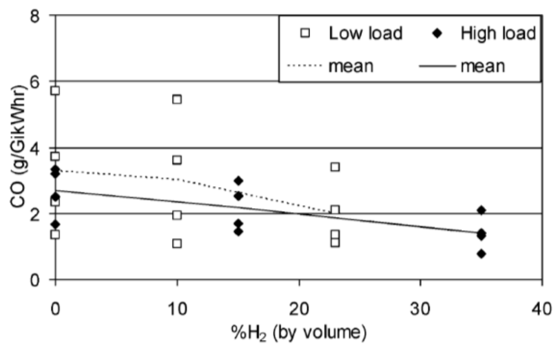

Fig -12: Effects of hydrogen content on carbon monoxide emissions. [14]

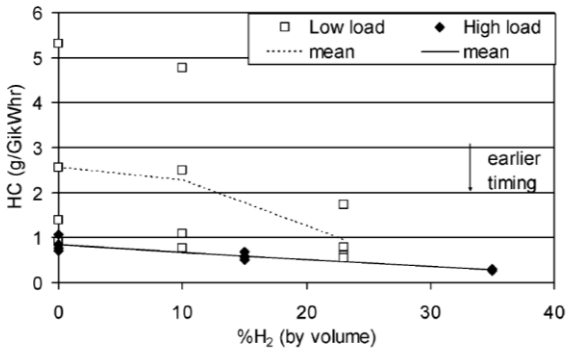

Fig -13: Effects of hydrogen content on hydrocarbon emissions. [14]

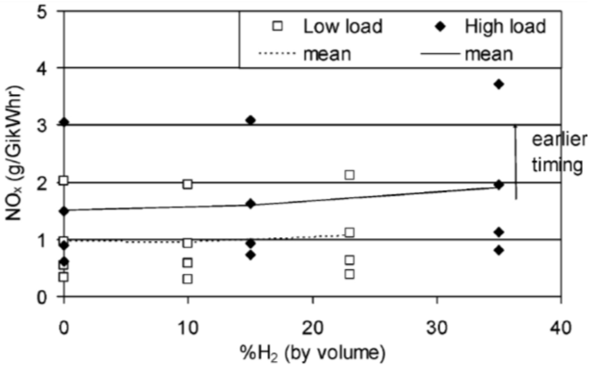

Fig -14: Effects of hydrogen content on nitrogen oxides emissions. [14]

4. CONCLUSION

Hydrogen has multiple resources it is available in abundance, but not in usable state it can be converted into usable state by multiple processes. It is possible to use hydrogen in spark ignited as well as compression ignition engine with a certain modification in existing system. The factor to be considered while designing experimental setup are storage for hydrogen, fuel induction system, homogeneity of fuel, hydrogen percentage for blend, compression ratio, ignition timing, lean homogeneous air fuel mixture, complete and instantaneous combustion, measuring equipments.

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