EXPERIMENTAL ANALYSIS OF A MULTI CYLINDER SPARK IGNITION ENGINE FUELED WITH HYDROGEN FUEL

Thesis

Submitted in partial fulfillment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY

by

PARASHURAM R. CHITRAGAR

DEPARTMENT OF MECHANICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,
SURATHKAL, MANGALORE-575025
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DECLARATION

I hereby declare that the Research Thesis entitled **“Experimental Analysis of a Multi cylinder Spark Ignition Engine Fueled with Hydrogen Fuel”** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Mechanical Engineering** is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any other Universities or Institutes for the award of any degree.

Register Number: **135059 ME13F02**

Name of the Research Scholar: **Mr**. **PARASHURAM R. CHITRAGAR**

Signature of the Research Scholar:

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Place: NITK-Surathkal
Date:

CERTIFICATE

This is to certify that the Research Thesis entitled **“EXPERIMENTAL ANALYSIS OF A MULTICYLINDER SPARK IGNITION ENGINE FUELED WITH HYDROGEN FUEL”**submitted by **Mr. PARASHURAM R CHITRAGAR (Register Number: 135059 ME13F02)** as the record of the research work carried out by him*, is accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy.**

Dr. Kumar G N
Research Guide
Date:

Chairman-DRPC

Date:

This Work is dedicated to

My

Beloved Father

Late

Shri. Ramanna R. Chitragar

and

Beloved Brother

Late

Shri. Prakash R. Chitragar

ACKNOWLEDGEMENT

This research has been kept on track and been seen through to completion with the support and encouragement of numerous people. It is a my pleasant task to express heartfelt thanks to all those who contributed in many ways to the success of this research journey and made it as a memorable experience for me.

First and foremost it is my great privilege to express my deep sense of gratitude to my supervisor **Dr. Kumar G N**, Assistant professor, Department of Mechanical Engineering, NITK Surathkal for his continuous panegyric efforts, ever helping attitude, continuous optimism, guidance and constant inspiration with a keen interest in the progress of present research and in bringing this work to completion. His valuable words of solace and encouragement especially during difficult times of private and technical life are ever remembered. I profoundly thank him.

I wish to express my sincere gratitude to **Dr. Narendranath S**, Professor and Head, Department of Mechanical Engineering, NITK Surathkal, for his appreciation and support all time during research work. I take this opportunity to acknowledge the former Head of Mechanical Engineering Department, **Dr. Gangadharan K V and Dr. Prasad Krishna** for their support and encouragement.

I am extremely grateful to Research Progress Assessment Committee members **Dr. Sitaram Nayak**, Professor Department of Civil and **Dr. Ashok Babu T.P** Professor and Dean (Faculty Welfare) for their valuable suggestion and inspiration, with a view of broadening the research output from various perspectives.

I extend my sincere thanks to **Mr. Chandrashekhar K, Mr. Raviraj**, **Mr. Vinay C A, Mr. Jayanth, Mr Jaya Shetty and Mr.Dinakar** of IC Engines and Fuels laboratory. **Mr. Mahesh B K**, Foreman, Department of Mechanical Engineering, NITK Surathkal for their kind help in carrying out the factual experiments and providing facilities.

I am thankful to **Dr. S.G.Koolagudi**, **Mr. Vighnesha Nayak, Dr. Shivaprasad K V**, **Mr. Parashuram Bedar, Mr. Venkatesh Lamani, Mr. Nuthan Prasad B S, Mr.**

Thirumoorthy M, Mr. Archit S. Ayodhya, Mr. Abdulrajak Buradi, , **Mr. Thippeswamy, Mr. Suhas B G, Mr. Srinivas Rao,** and all Research Scholars of the Mechanical Department of NITK Surathkal for their help and cooperation during this research work.

I am forever indebted to all the Teaching and Non-Teaching Staff members of Department of Mechanical Engineering, NITK Surathkal for their sociable support and encouragement. Besides this, several people of NITK Surathkal had helped me knowingly or unknowingly in the successful completion of this project. I thank one and all who shaped my life in better way. Overall it was a remarkable and memorable journey for me during my stay at NITK Surathkal. I salute NITK Surathkal for shaping my research career.

I am grateful to management council of Vidya Pratishthan's Kamalnayan Bajaj Institute of Engineering and Technology (**VPKBIET**, formerly **VPCOE**) for their noble support through QIP sponsorship and **Dr. M.G.Devamane,** Principal for his continuous help, encouragement and support for completing this study. I would like mention thanks to former Principals **Dr. S. B. Deosarkar** and **Prof. V. U. Deshmukh** and Head, Department of Mechanical Engineering of our institute for their kind support and guidelines during the study. I also express my sincere thanks to all my departmental and fellow colleagues (Teaching and Non-Teaching) of VPKBIET for their kind support during this research study.

I would like to pay high regards to my parents, my parent-in-laws, my siblings and all family members for their patience, sincere encouragement and inspiration throughout my research work and lifting me uphill this phase of life. I dedicate this work to my late father **Ramanna** and brother **Prakash** who were blessing me from sky.

Last but certainly not least I would like to express my deepest and most heartfelt appreciation and love to my wife **Mangala** and my kids **Giridhar** and **Prasanna** for their support, love and understanding over the years. I owe everything to them. I look forward with anticipation and excitement in continuing our wonderful life together.

Mr. Parashuram R. Chitragar

ABSTRACT

Sprawling use of automotive on one side and limited resources of crude oil with fluctuation in its price on other combined with alarming trend of environmental pollution and its control norms have created interest among researchers to look up alternative fuels for automobile use. Universally gaseous fuels are favorable substitute fuels due to their superior combustion properties and least emissions and also for ecofriendly in nature. Hydrogen as a fuel tops among them. Hydrogen's combustion properties like high energy content, wide range of flammability and low ignition energy with almost least toxic emissions are favorable to use it in an IC engine as an alternative fuel.

The present investigation describes combustion, performance and emission analysis of a four cylinder, four strokes spark ignited engine at different load, speed and different spark timings (2, 5 and 8 bTDC) using neat hydrogen. To achieve the objectives the engine was modified with ECU assisted hydrogen gas injector system keeping gasoline fuel line unchanged. Tests were carried out by using grade–III (99.985% pure) compressed hydrogen gas which is regulated by two stage pressure regulator. The exhaustive experiments were conducted and the result reveals that there was improvement in cylinder pressure, net heat release rate, and brake thermal efficiency for neat hydrogen operation. In contrast to them brake power was reduced. The CO, HC emissions were minimized while NOx were elevated when compared to gasoline. Among three spark timings, 8 bTDC spark timing results found to be favorable compared with other two spark timings.

Further tests were carried out for optimized spark and full load condition for neat hydrogen with turbocharging and water-methanol injection. Results revealed improvement of 4.48%, 5.34% in brake thermal efficiency, 6.05%, 1.22% in volumetric efficiency and 5.1%, 8.73% in NOx emissions compared with previous hydrogen operation.

Keywords: IC Engine, Alternative Fuels, Hydrogen, Turbocharging, Water-Methanol Injection.

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NOMENCLATURE

Symbol	Expansion	Unit
bTDC	Before Top Dead Centre	
BMEP	Brake Mean Effective Pressure	bar
BP	Brake Power	kW
BTE	Brake Thermal Efficiency	Percentage (%)
CA	Crank Angles	degree
CH_4	Methane/ Compressed Natural Gas	
C_3H_8	Liquid Petroleum Gas	
C_8H_8	Gasoline	
$C_{12}H_{23}$	Diesel	
CH_4	Methane/ Compressed Natural Gas	CH_4
cm^2/s	Square Centimetre per Second	
cm^3	Cubic Centimetre	
CnHm	Hydrocarbon Elements	
CNG	Compressed Natural Gas	
CO	Carbon Monoxide	Percentage (%)
CO_2	Carbon Dioxide	
DAQ	Data Acquisition	
DC	Direct Current	

DI	Direct Inection	
DI-H_2ICE	Direct Injection Hydrogen Internal Combustion Engine	
ECU	Electronic Control Unit	
EGR	Exhaust Gas Recirculation	
EGT	Exhaust Gas Temperature	^oC or K
EIA	Energy Information and Administration	
GDI	Gasoline Direct Injection	
HC	Hydrocarbon emissions	ppm
H_2	Hydrogen	
HECU	Hydrogen Electronic Control Unit	
H2ICE	Hydrogen Internal Combustion Engine	
HHE	Hybrid Hydrogen Engine	
HHGE	Hybrid Hydrogen Gasoline Engine	
H_2O	Water	
H_2O_2	Hydrogen Peroxide	
IC	Internal Combustion	
ICE	Internal Combustion Engine	
IMEP	Indicated Mean Effective Pressure	bar
IP	Indicated Power	kW

kg/m^3	Kg per Cubic metre	
kW	kiloWatts	
LH	Liquid Hydrogen	
LNG	Liquefied Natural Gas	
LPG	Liquefied Petroleum Gas	
MBT	Maximum Brake Torque	
mJ	Milli Joule	
m/s	Meter per Second	
Mg-Ni-Hydride	Magnesium-Nickel Hydride	
MJ/kg	Mega Joule per kg	
mm	Millimetre	
mm^2/s	Square Millimetre per Second	
MPa	Mega Pascal	
MPFI	Multi Point Fuel Injection	
NHRR	Net Heat Release Rate	J/degree
NOx	Oxides of Nitrogen	ppm
O_2	Oxygen	
OH	Hydroxyl	
PI	Port Injection	

ppm	Parts per Million	
RPM	Rotations per Minute	
SI	Spark ignition	
SOx	Oxides of Sulphur	SOx
TDC	Top Dead Centre	
Ti-Fe Hydride	Iron-Titanium Hydride	
TMI	Timed Maniflod Injection	
UBHC	Unburned Hydrocarbon	
WOT	Wide Open Throttle	

CHAPTER 1

INTRODUCTION

1.1 GENERAL BACK GROUND

The world is turning towards a sustainable energy with main emphasis on energy competence and use of non-conventional energy sources. Mankind is challenged by the rapid exhaustion of fossil energy reserves and degradation of environmental cleanliness. Worldwide fossil fuel consumption for energy production results in polluting natural habitat with harmful effects such as global warming, destroying ozone layer, causing acid rains and contaminating resources throughout the world and posing great danger for the health of humans, animals and plant life on our planet, all are critical concerns. At present restructuring of the energy system is required to lower the emission of CO_2 and thus risk of climate change. Because of limited reserves of the fossil fuel, progress of alternative fuel engines has fascinated more and more attention from the engine community. Study conducted by scientists and engineers believe in replacing the existing nonrenewable resources with a clean, efficient and economical alternative sources for the future energy needs and serve for the solution for global problems.

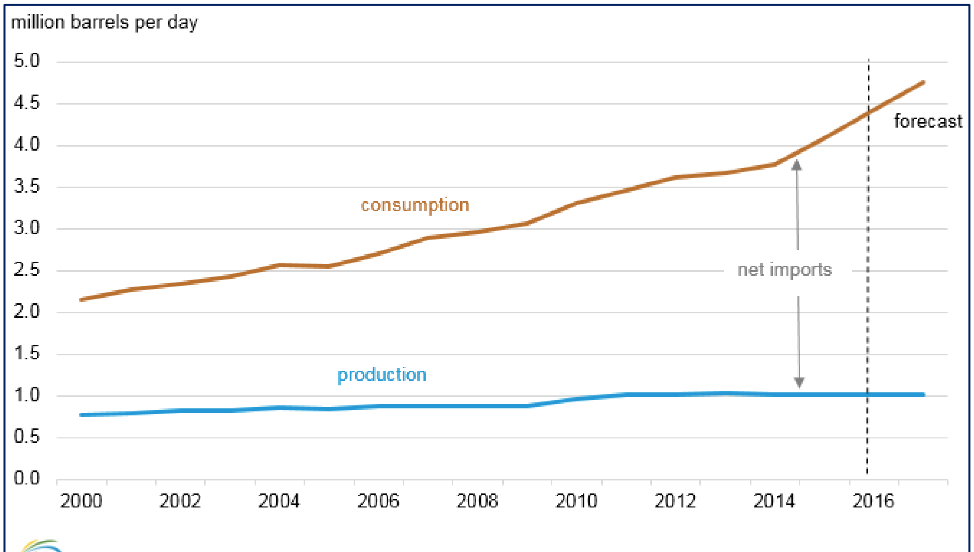
Energy can neither be created nor destroyed, but it can be transformed from one form to another. An energy crunch can be shunned by selecting novel energy sources, by enlightening the energy use at the customer and by curtailing losses in the energy supply system. This also comprises bypassing redundant energy conversion steps in between.

Conventional fuels have very useful properties than renewable energy sources that have made them useful during the last centuries, but unfortunately these are not renewable (Veziroglu 2008). Apart from this, the pollutants emitted by them (e.g. CO, CO_2, HC, NO_x, heavy metals, ashes, etc.) are larger and more harmful than those produced by a renewable energy systems. Considerable progress has been observed since the oil crisis of 1973 for the search of alternative energy sources.

1.2 ENERGY SCENARIO

Rapid economic growth has increased the burden on India's infrastructure which relates to all round developments including transportation and communication. India's power sector is growing rapidly thus increasing energy demand. But the energy sector continuous to lag behind depending on importing the fuel to fulfill the need.

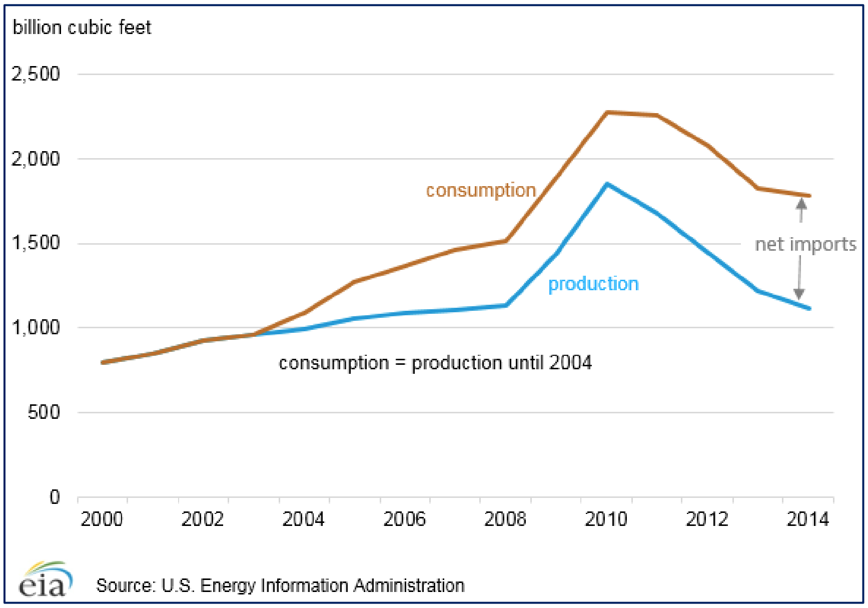
India was the fourth-largest energy customer in the world with oil and gas accounting for 37 per cent of its total energy consumption. In spite of having huge coal assets and progress in natural gas production, the breach between countries demand and supply of oil is flaring as demand in 2015 touched closely 4.1 million barrels per day (b/d), compared with 1 million b/d of total domestic liquids production as shown in figure 1.1. Even as economic growth of country continues, there is a scope for higher energy demand in the near future. India has increased its total net oil imports from 42% of claim in 1990 to 75% of demand as on today. India's crude oil imports touched more than 3.9 million b/d in 2015. Figure 1.1 shows the India's petroleum and other liquid production and consumption since 2000 to till now.



Source: U.S. Energy Information Administration, *Short-Term Energy Outlook*, May 2016

Fig. 1.1 India's Petroleum and Other Liquid Production and Consumption

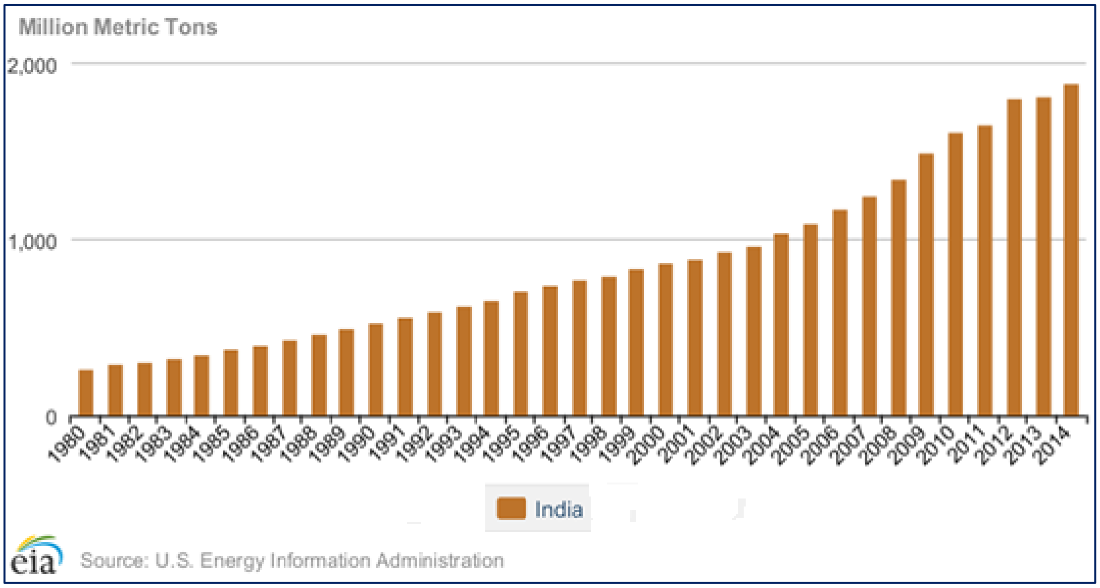
Energy Information and administration (EIA) believes demand to hasten in coming two years' timeframe as India's transport and industrial sectors continue to grow under economic development. India's present administration under Prime Minister Narendra Modi, has a objective of reducing India's import dependency on oil and natural gas to 65% by 2022 and to half by 2030. Figure 1.2 shows the India's dry natural gas production and consumption.



Source: U.S. Energy Information Administration

Fig. 1.2 India's Natural Gas Production and Consumption

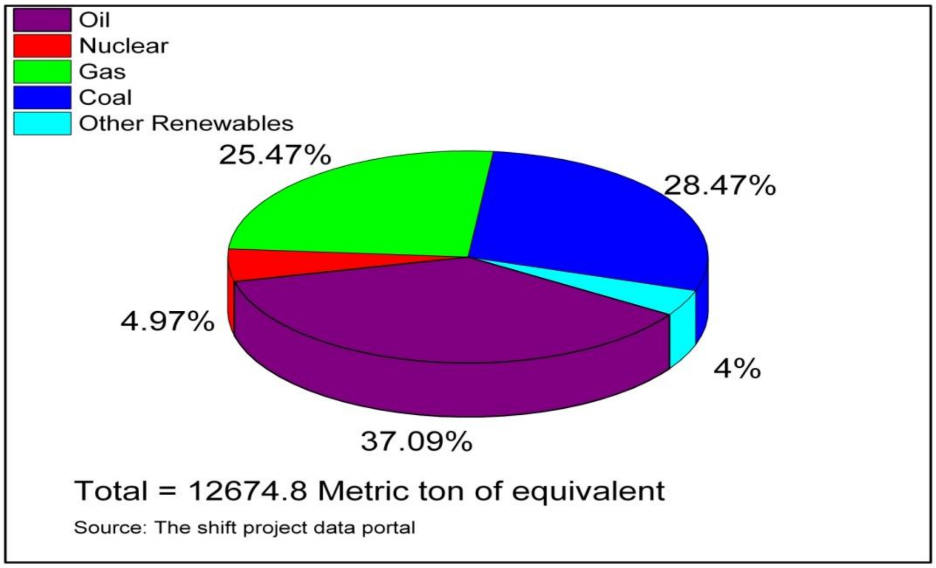
At present, the transport is exclusively based on petroleum products such as gasoline and diesel globally. Research shows that the involvement of transportation to the global anthropogenic emissions amount to 21% for CO_2, 37% for oxides of nitrogen, 19% for volatile organic compounds, 18% for CO and 14% for black carbon (Myung et al. 2012). Figure 1.3 depicts total carbon dioxide emissions from consumption of energy in India. The exploration for alternative fuels, which assures a harmonious correlation with maintainable development, energy preservation, efficiency and environmental protection, has become highly noticeable in the present context (Agarwal 2007).



Source: U.S. Energy Information Administration

Fig. 1.3 Total Carbon Dioxide Emissions from Consumption of Energy

Figure 1.4 indicates the world energy production shared more by oil, coal and gas in 2014 and figure 1.5 indicates the majority of energy production by coal and oil in India which represents dependency of India on oil imports.



Source: The shift project data portal

Fig. 1.4 World Energy Production

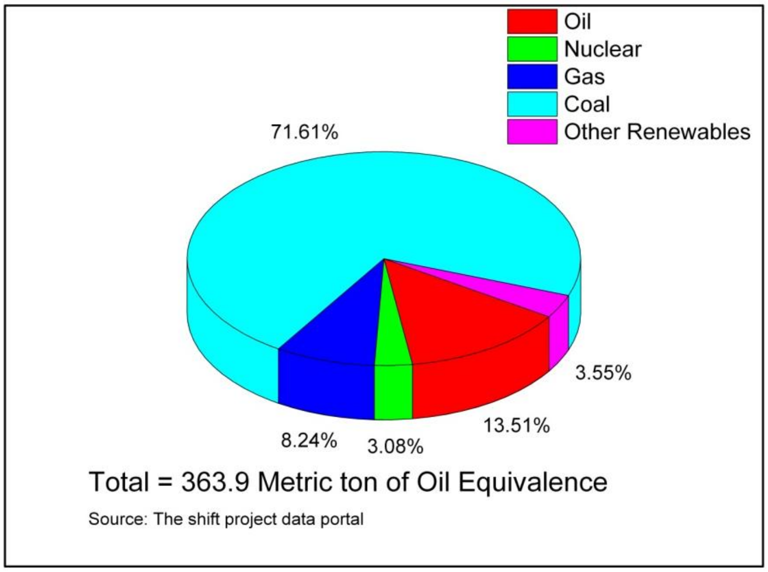


Fig.1.5 India's Energy Production

Sector-wise consumption of various petroleum products discloses that transport sector accounts for the largest share (50%) of the total consumption with agriculture sector for 18%, 11% for industry and 7% for power generation. The diesel fuel consumption is around four times higher than gasoline fuel consumption as shown in Table 1.2 (Das 2011).

Table 1.1Gasoline and Diesel Consumption in India (Das 2011; Nielsen 2013)

Year	Gasoline Consumption (Metric Tons)	Diesel Consumption (Metric Tons)	Ratio of Diesel/Gasoline
2006-07	9.29	42.9	4.61
2007-08	10.23	47.67	4.61
2008-09	11.26	51.67	4.59
2009-10	12.82	56.32	4.39
2010-11	14.19	60.07	4.23
2011-12	14.99	64.75	4.32
2012-13	15.74	69.08	4.39

Forecasted claim for crude oil over 2011–2025 is likely to rise by about 90 per cent, for diesel by around 110 per cent, and for gasoline by around 165 percent under probable future growth scenarios (Agrawal 2012).

In recent years automobiles have practiced number of changes targeted at achieving more environmentally friendly transport. Few of these vagaries have caused from technological improvements and cost optimization, nevertheless many were determined by government actions such as emission regulations. For future vehicles, there are many technical choices to be ecofriendly, since they will have to abide by stringent emission norms. Gasoline was the major fuel for running of passenger cars until the 1970s. The 1973 oil crisis steered to an increase in cognizance of the need for alternative fuels and propulsion systems. Due to increase of environmental concerns, emission limits were introduced in the late 1980s and early 1990s.

The spark-ignited (SI) gasoline engine is still the main choice for automotive sector. Emission from gasoline engines have been condensed intensely with the use of the three-way catalyst, combined with electronically controlled gasoline injection system. With a rehabilitated importance on fuel economy and reduction of CO_2 emissions which are connected to the fear of global warming, technologies such as gasoline direct injection and variable valve actuation have gained importance. Previously, diesel engines were primarily used for stationary purposes or for heavy-duty vehicles.

The drive created by the energy security, climate change and the rapid growing demand of transport fuel has led to a quest for clean burning fuel. Various present social complications and concerns raised by the air contamination and global warming might be solved by making use of alternative fuels. Potentiality of them as a fuel will improve environmental and sustainability issues and may replace gasoline operated IC engines in forth coming years.

The introduction of alternative fuels is helpful in two ways, one is to help in relieving the fuel shortage and other is to reduce engine exhaust emissions. During the last two decades, gaseous fuels such as liquefied natural gas (LNG), compressed natural gas

(CNG), liquefied petroleum gas (LPG) and hydrogen have been used broadly in commercial vehicles and favorable results have been obtained from the point of alternative fuels and emissions. The usage of hydrogen as a fuel is a long term choice to reduce toxic emissions. However, hydrogen at current is not economical with other fuels.

1.3 ALTERNATIVE FUELS FOR ENGINES

Various alternative fuels used today, include a host of liquid fuels such as methanol, ethanol, biodiesel etc. and gaseous fuels such as compressed natural gas (CNG), biogas, producer gas, hydrogen gas and liquid petroleum gas which have been tried out as substitute fuels in conventional internal combustion engines.

- **Alcohols** are well-known alternate fuel which consist mainly ethanol and methanol. It is same as gasoline in the sense of fueling, combustion, storage, handling etc. Alcohols are highly oxygen content fuels hence they require lower stoichiometric ratio. Methanol has high latent heat of vaporization; higher boiling point compared to gasoline. Calorific value of alcohol is comparatively less than gasoline, but is corrosive in nature. Gasoline octane rating are drastically increased by blends of ethanol and methanol, these blends also reduce un-burnt hydrocarbons (HC) and CO.
- **Natural Gas** is naturally occurring hydrocarbon gas mixture comprising of major content of methane and some parts of ethane, propane and butane. It can be used as compressed natural gas (CNG) or liquefied natural gas (LNG) in practice. It has higher octane number so it can be used in higher compression ratio engines & it also reduces CO and NO_x emissions. The major problem is volumetric efficiency; because it is gaseous fuel which replaces the air in combustion chamber and results in less power output.
- **Propane** is a gas at standard pressure and temperature but is compressible to liquid and it is also a product of natural gas processing and crude oil refining. Even though it has less energy content compared to gasoline, it has higher octane rating. It reduces toxic emissions in light duty bi-fuel vehicle.

- **Synthetic Fuel** is a liquid fuel with major composition of CO and hydrogen. It has lower heating value and lower heat release rate. It will increase compression ratio of an engine when blended with gasoline.
- **Hydrogen** is a clean, efficient and safer fuel. It does not have any carbon content. Most of the thermo- physical properties of hydrogen are far superior to properties of gasoline and diesel. It produces water as end product when combusted in an engine with oxygen.

Alternative fuels came into existence in 1970s, due to the motive of refuge of energy supply. By the end of the 1980s increasing concern about the ecological effect by vehicles inspired the interest in alternative fuels. The famous alternative fuels at the instant are LPG, alcohols (methanol and ethanol), natural gas and biodiesel. Fuels like hydrogen, dimethyl ether and synthetic fuels have not been reached the commercialization stage so far. Most automobiles working on conventional fuels are also capable of using alternative fuels such as LPG, natural gas, alcohols or bio-diesel. These automobiles are often referred as bi-fuel or dual-fuel vehicles.

To supplement the declining fossil fuels, researchers identified biofuels as a major renewable energy source. Especially, the alcohol fuels such as ethanol, methanol have been accepted as good alternative fuels for the vehicles equipped with SI engines because of several physical and combustion properties similar to gasoline. Generally gaseous fuels produce very low levels of pollutants and can be effectively utilized both in SI and CI engines. Gaseous fuels exhibit wide ignition limits and can easily form homogeneous mixtures with air to promote complete combustion with the possibilities of use of very lean mixtures. Also gaseous fuels possess high hydrogen to carbon (H/C) ratios, which will lead to reduction in carbon-based emissions.

Promising gaseous alternate fuels are natural gas (CNG, LNG), liquefied petroleum gas (LPG), hydrogen, biogas and producer gas. Each of these has its own advantages and is suitable for specific application. Compressed natural gas (CNG) and liquefied petroleum gas (LPG) are readily available petroleum based fuels, which are widely used in Indian urban areas for public transportation. Hydrogen, biomass and producer gas can be obtained from renewable sources. In the last four decades, there is a progressive interest related with use of renewable fuel sources in vehicles. The future scope of energy research is to pursue hydrogen fuel production by decomposing water using solar energy. Considerable fundamental research needs to be done on alternative fuels which are renewable & locally available.

1.4 HYDROGEN

From the Greek words “Hydro” and “genes” meaning “water” and “generator”. Hydrogen is used as chemical and space rocket propellant for more than 5 decades in huge quantities. During that time, hydrogen has been produced and utilized with a due respect for its physical properties by very robust infrastructure development. Hydrogen is the back bone of all other elements, comprising of one electron and one proton, and it reacts easily with other elements to produce compounds like water (H_2O).

Hydrogen has captivated peers of persons for epochs, including prophets like Jules Verne. A "Hydrogen Economy" is repeatedly encouraged as the definitive solution for energy and environment. Hydrogen societies have been framed for the campaign of this aim by publications, conferences and presentations. Hydrogen can be obtained from electricity and water. Hydrogen when burnt with oxygen produces no pollutants, but only water, which can return to nature. It can be combusted in very lean quantity however it is prone produce hydrogen peroxide (H_2O_2) and unburned hydrogen in such cases. These emissions are undesirable since unburned hydrogen is wastage of fuel and hydrogen peroxide is a basis of hydroxyl radicals which catalyze the production of photochemical smog.

Hydrogen is the supreme common chemical element on the earth, which does not exist in nature in basic form i.e., it has to be alienated from chemical compounds, by electrolysis from water or by chemical processes from hydrocarbons. The power for the electrolysis may come ultimately from clean non-conventional sources such as solar, wind and water or geothermal heat. Today, the use of hydrogen is governed by economic arguments and not by energetic attentions.

Hydrogen is not a new source of energy. Hydrogen is been known as a fuel possessing some exclusive and extremely desired properties, for application in engines (King and Rand 1955). It is very efficient, safe and clean fuel (Veziroğlu 2008). However, in future hydrogen will become more important, by its contribution in limiting greenhouse gas emission into the atmosphere. Therefore there is a need of implementing hydrogen technology worldwide at the earliest to abolish many of the problems and their consequences.

1.5 NECESSITY OF HYDROGEN

Fossil fuel prices have never stable, influenced by economic speed of the several countries. The exertion of controlling prices and the uncertain reserves are strong motivations for pursuing energy security. Fossil fuel usage associated global warming and local pollution is additional significant environmental and societal difficulties. These are strong drives for investigation, development and demos of alternative energy sources for transport.

The use of hydrogen as an energy carrier is one of the choices put forward in most administrative strategic plans for a sustainable energy system. Among the several alternatives considered today, hydrogen conceivably the ideal fuel in view of its immeasurable source potential and clean burning characteristics and thus promises to be the ultimate future fuel. Hydrogen can be produced directly from all primary energy means which include solar, wind and biomass which are all non-conventional fuel sources. A main benefit of forecasting H_2 usage for transportation and power generation is that it will minimize dependency on conventional fossil fuels and expand energy source for application in end-use energy areas. All conventional fossil fuels contain carbon atoms in addition to hydrogen and through the conversion of the fuel to energy, carbon dioxide gas is a major product formed. The combustion reaction of H_2 yields only water as a product, hence eradicating CO_2 a significant contributor to climate change as a greenhouse gas (Schefer et al. 2008).

Hydrogen potentially been identified as an alternative fuel because of its highly desirable properties much suited for engines (King and Rand 1955). Hydrogen is universally available and produced from largest available resource that is water, though with the expense of lot of energy. Combustion of hydrogen with oxygen produces water, whereas with air it produces oxides of nitrogen. This desirable fuel property makes hydrogen as a clean fuel with limited exhaust emissions from combustion devices and reduces greenhouse gas emission as well.

Hydrogen gas as a fuel has been used extensively for relatively longer time (Erren RA and Campbell WH. 1933). Moreover, large amount of hydrogen is used as a feedstock for series of claims in chemical industry, mainly in the enhancement of fossil fuel resources (Cox KE and Williamson KD. 1979). Hydrogen and fuel cell knowhow, once developed can upkeep climate change and energy security aims in numerous sectors of the energy system. Hydrogen can help to:

a) Realize very low-carbon specific motorized transport,

b) Assimilate high shares of variable renewable energy (VRE) into the energy system,

c) Support to the de-carbonization of the industry and the buildings sector.

Although the GHG extenuation potential of hydrogen technology is encouraging, important hindrances for deployment of hydrogen and fuel cell technologies need to be overcome. Most of hydrogen technology is still in the primary stages of commercialization and presently struggle to compete with alternative technologies, including other low-carbon options owing to high prices. Figure 1.6 depicts comparison of the present energy system with future hydrogen energy system pointing that hydrogen can tie the different energy sectors and transmission & distribution (T & D) networks and thus upsurge the operational flexibility of future low carbon energy systems.

1.6 PRODUCTION OF HYDROGEN

Hydrogen is derived from a wide range of primary resources, employing wide range of technologies. In spite of its profusion occurrence in the universe, it not found freely in nature like fossil fuels, as it counters very rapidly with other elements. For this reason, the massive majority of hydrogen is destined into molecular compounds.

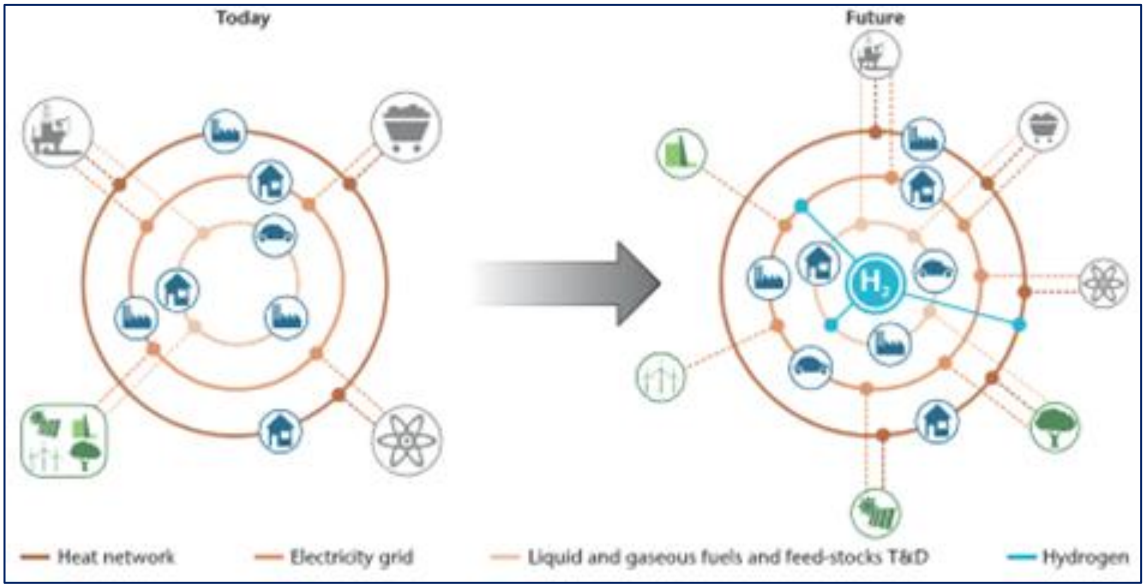


Fig. 1.6 Energy Systems Today and in Future (Source: IEA)

Primary energy is necessary to separate it from its original combined state. Any primary source of energy like solar, nuclear or hydro-electric energy can be used to break down water into H_2 and O_2 though economics are far from attractive. The hydrogen can be extracted from higher energy fossil fuels or lower energy water. Reforming is the process of extracting hydrogen from fossil fuels and extracting that from water is called electrolysis.

Different methods of hydrogen production include thermochemical water decomposition, photo conversions, photo biological processes, production from biomass, and industrial processes.

The following few methods are used to produce hydrogen.

- Thermal decomposition of water: In this method, heat at high temperature around 3000°C is used to break down H_2 and O_2.
- Thermal chemical method: This method is considered potentially most promising method of hydrogen production. It mainly rely on complex chain of interactions

between the water, primary energy and some specific recyclable chemicals such as lithium, iron, iodine and cadmium and is used to yield hydrogen at temperature noticeably lower than thermal decomposition.

- Electrolysis of water: In this method, electrical energy is used to split water into the H_2 and O2.
- Steam methane reforming method: This method of hydrogen production is a 3 step process to produce hydrogen. Initially, methane is restructured at elevated pressure and temperature to yield a gas mixture of CO and H_2. Then, catalytic change reaction is carried out to combine CO and H_2O to produce the H_2 product.
- Water gas shift reaction is the most suitable among the above mentioned methods and is commonly used today. A class of micro algae in the Rhodospiriallacea family can be used as the carbon monoxide source. This growth occurs in both dark and light, but the dark reaction which has additional property of splitting water and oxidizing CO in the equation given below.

$$CO + H_2O \qquad CO_2 + H_2 \qquad \Delta G = -20.06 \text{ kJ} \quad \Delta G = \text{Gibbs free energy}$$

The CO, CO_2 and H_2 all are in gaseous phase in this reaction. The negative value of Gibbs free energy for this reaction implies that no additional energy source is required. This biological approach runs at ambient temperature and can be easily implemented (Resnick 2004). Microwave irradiation method is a new technique adopted for water gas reaction. This method provides efficient energy to reactants. Brass based catalysts and ferrochrome based catalysts are used for high temperature and low temperature reactions (Chen et al. 2008). Figure 1.7 shows the hydrogen generation by different technologies in most developed countries.

1.7 HYDROGEN STORAGE, PORTABILITY AND TRANSPORT

In vehicle applications, the storage and transportability of ample quantity of hydrogen remains one of the most challenging task which yet to overcome. Hydrogen having a very low density poses a storage problem, requiring large size container. The three modes of hydrogen on-board storage are as follows.

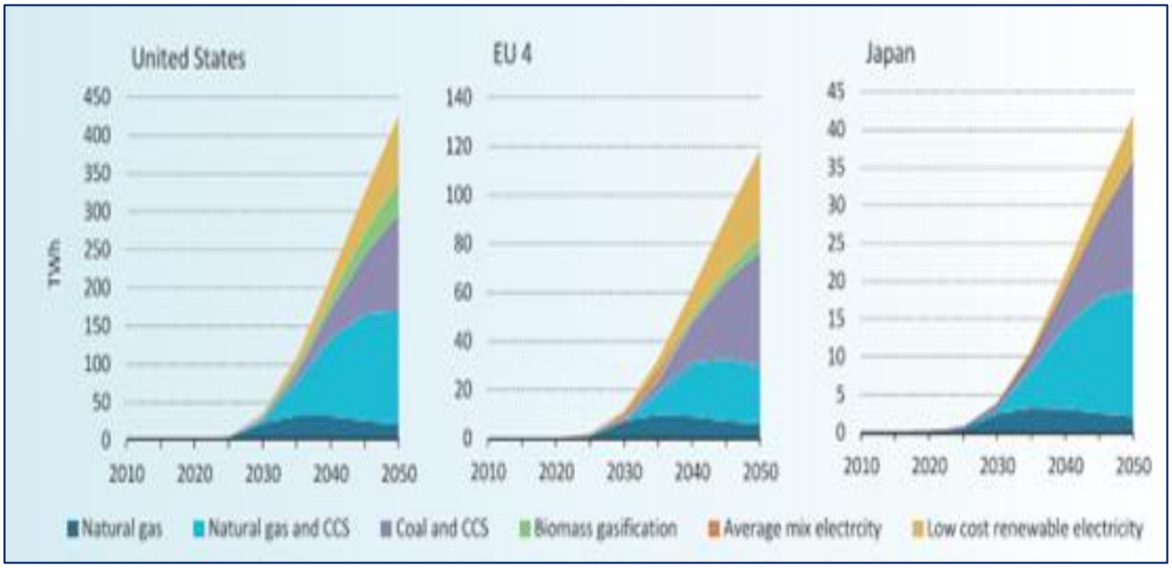


Fig. 1.7: Hydrogen Generation in Developed Countries. (Source: IEA)

- **Compressed Gas in High Pressure Vessel:** Hydrogen may be stored as a compressed gas in properly designed high-pressure cylinder vessels under a pressure of 140 to 700 bars. However, low density of hydrogen in relationship to other gaseous fuels indicates that tremendously high-pressure cylinders that are adequately light in weight and compact in volume need to be developed and used. An equal amount of H_2 gas can be stored under pressure of 19 times as bulky and 24 times as heavy as gasoline. This would mean that 1 gallon of petrol in fuel tank may have to be replaced with 2 cylinders of hydrogen containing at 140 bar each cylinder weighing 55 kg, but containing hardly 0.5 kg of H_2 gas. Therefore, use of compressed H_2 gas for automobile is out of question.

  The weight penalty can be reduced by using light metal alloy cylinders or by using fibre reinforced plastic. But the use of high pressure H_2 cylinders for cars is overruled owing to safety risk in case of accident. There are four types of cylinders namely Type 1 to Type 4. Type 1 cylinders are made of aluminium or steel materials and can withstand pressures up to 175 bars and 200 bars respectively. Type 2 cylinders are made of an aluminium tank with glass fibre winding. It has maximum pressure of 260 bars. Type 3 cylinders are made of composite materials which consist of aluminium and carbon fibre with maximum pressure of 300 to 400 bars. Type 4 cylinders are made of composite materials consisting of thermoplastic and carbon fibre and it can withstand maximum pressure of 700 bars.

- **Liquid Hydrogen:** Hydrogen can also be stored in liquid form by using specially designed storage tanks. However, the storage of H_2 in liquid form is not as bad as a tank capacity of 73 gallons is required to replace 20 gallons tank of gasoline. This size may not be very unwieldy especially because the liquid-hydrogen container weighs about 20 kg only. In addition, the temperature is to be lowered to 20 K. The liquefaction process requires 40% of the energy content in H_2 gas. Also, owing to low temperature permanent evaporation losses cannot be avoided even with insulation. The only advantage of liquefied H_2 provides fuel in most compact form. Special outlets would need to be arranged in garage areas in order to abate the potential fire risk from hydrogen (Cox and Williamson 1979).
- **Solid Metal Hydrides:** Hydrogen can also be conceded on board vehicles in the form of various metallic hydrides. It permits the precise release of hydrogen through the supply of heat, which may be from engine exhaust gas or engine cooling water. With the present state of art, metal hydride prefers to the most practical solution considering safety aspect but power to weight ratio is more. Three metal hydrides have been found suitable for the purpose and they are Mg_2 - Ni hydride, iron titanium hydride and Mg-Ni-Hydride. The Ti-Fe hydride dissociates at temperature as low as -10°C. Thus ambient air or cooling water can be used to release H_2 when the engine is running. But it has very poor storage capacity by weight.

  The Mg_2-Ni hydride and Mg-Ni hydride release H_2 at higher temperatures. The storage capacity for Mg-Ni Hydride is four times and Mg_2–Ni hydride and is twice as much as the Ti-Fe hydride. Owing to the high bonding energy, H_2 can release from these two hydrides only by exhaust gases.

> The volume density for hydrides is much better than that of pressure bottles and there are little chances for boil-off loss which is a distinct disadvantage with liquid H_2 and already gasified will easily disperse into the air. In case of hydride storage tank system, H_2 is released first from low temperature hydride for starting and initially running. Once the engine gets heated, the exhaust gases are used to heat the high temperature hydrides. While refueling to reach full capacity a pressure of 50 bars should be applied and temperature kept below 30°C. The filling time depends on the heat exchanging capacity of hydride (Domkundwar 2010).

These methods are practically restricted as they induce weight and cost while plummeting the suppleness of the fuel system and paying to an increase in adverse emissions. Also, transport of hydrogen with special alloys of some special metals remains an uneconomical choice and has narrow future prospective.

1.8 THE SPARK IGNITION ENGINE

The spark ignition (SI) engine is a type of internal combustion engine among the two most common reciprocating internal combustion (IC) engines. For better power output, fuel economy and emissions control of SI engines, good fuel metering and control is required. Fuel supply should take care of engine load condition and minimum variations for cylinder to cylinder and for cyclic variations. For power output, electronic controls are playing a major role by improving efficiency of these engines through upgraded mechanism of the fuel injection and ignition methods that control the combustion process. Combustion process in these engines must be accomplished as near as possible to TDC for best fuel economy. The products of combustion like carbon monoxide (CO), unburned hydrocarbons (HC) and oxides of nitrogen (NO_x) of SI engines are claimed as hazardous to human health.

1.9 UTILIZATION OF HYDROGEN IN FUEL CELLS

A fuel cell is an energy transformation device that transforms the chemical energy of a fuel into electricity without any intermediate thermal or mechanical processes. In principle, a fuel cell can function by making use of variety of fuels and oxidants. Hydrogen has believed as the utmost effective fuel for fuel cell use since it has advanced electrochemical reactivity than other fuels (Roche et al. 2010; Stambouli and Traversa 2002). Even fuel cells that work directly on other fuels tend to first decompose into hydrogen and other elements before the further reaction takes place. There are majorly two types of fuel cell available for operation. High-temperature fuel cells which operate at greater than 600°C and low temperature fuel cells which operate below 250ºC (Lanz et al. 2001).

Hydrogen fuel cells are being considered as ideal candidate for future vehicles, due to their high efficiency and near-zero emission (Neef 2009). The main hindrance in the use of fuel cells is their high cost and low reliability (Emadi and Williamson 2004).

1.10 UTILIZATION OF HYDROGEN IN IC ENGINES

The utilization of hydrogen in IC engines can be a part of combined solution to the problems of environment pollution and depletion of fossil fuels. The present technological advancement and infrastructure related to engines may be useful for addition of hydrogen as a fuel.

Hydrogen has wide flammability range in comparison with present fuels. As a result, it can be combusted in an IC engine over a wide range of fuel-air mixtures. It has very low ignition energy, significant advantage of this is that engine can run on a lean mixture and confirm prompt ignition. This also makes fuel economy to be greater and combustion is complete. But unfortunately, it serves as sources of ignition through warm gases and hot spots in the cylinder, producing problems of premature ignition. Prevention of this premature ignition is one of the challenges associated with hydrogen engine at present (Heywood 1988).

The high engine thermal efficiency and reduced exhaust losses can be achieved by the hydrogen as it possess high flame speed that makes engine to operate much nearer to the constant volume combustion than a petrol engine (Shudo et al. 2001). Auto ignition temperature of hydrogen is very high which indicates it is most suitable fuel for S I engines, and very hard to ignite hydrogen just by the compression process in diesel engines. With a higher calorific value, lower density and lower boiling point, hydrogen can be used for engine operation in vapor form and life of engine can be meaningfully improved with respect to gasoline (Yamin et al. 2000).

The homogeneity in the cylinder mixture directly relates to high diffusion speed of hydrogen which helps the fuel in complete combustion (Ma et al. 2008). Generally retarded spark timing techniques is being implemented for hydrogen engines to prove its power output and prevent knock due to its higher flame speed which is 5 times that of gasoline (Salimi et al. 2009, Li and Karim 2004). At present the production and storing of hydrogen is expensive, which also blocks commercialization of hydrogen engines in the market. The octane number of hydrogen fuel is 130 which are much more higher compared to gasoline hence have more resistance to auto-ignition.

Hydrogen has the maximum energy-to-weight ratio of any fuel as it is the lightest element and has no heavy carbon atoms. Precisely, the amount of energy produced during the reaction of hydrogen, on a mass basis is about 2.5 times that of the heat of combustion of common hydrocarbon fuels. Consequently, for a particular load the mass of hydrogen required is only about 1/3rd of the mass of other conventional fuel needed. But energy density of hydrogen on a volume basis is only 10.8 MJ/kg since it is very light, that may lead to reduce power output for hydrogen engines at stoichiometry conditions when compared to gasoline engines (Ji and Wang 2009b).

Hydrogen is safer compared to conventional petroleum fuels from several practical considerations. Hydrogen is a low density fuel which diffuses into air very rapidly, thus leakage creates a flare-up possibility limited to the space directly above the leak. Hydrogen has an extremely low ignition energy compared with gasoline and this is required to ignite an air fuel mixture which depends on (Φ) equivalence ratio. Hydrogen has very shorter quenching distance which causes the flame of hydrogen and air mixture propagate much closer to the cylinder walls effectively reducing the unburned hydrocarbon emissions even from crevice space.

One of the most important features of hydrogen fueled engine is least release of undesirable exhaust emissions compared to conventional fuel. To the extent that the involvement of the hydrogen fuel towards emissions is that there are no carbon monoxide, carbon dioxide, hydrocarbons and smoke. However impact of the lubricating oil to such emissions is present but tends to be rather negligible. Only main products of combustion emitted are oxides of nitrogen and water vapor, but with lean operation the level of NO_x tends to be significantly lower.

Compared to the fuels at present or under attention for future application, hydrogen offers many benefits. Its use in S.I. engines will not only eradicate the present-day problem of dependence on petroleum fuel, but it will also diminish vehicular pollution as it is a clean burning fuel. Gaseous fuels like hydrogen, methane and propane can be easily adopted by requisite amount in S.I. engines with little modifications.

1.11 PROPERTIES OF HYDROGEN

The physical properties of hydrogen are known to us. It is the smallest and lightest of all atoms with molecular weight of 2.016. Consequently, it is the lightest gas which is about eight times lighter than methane (represents natural gas). Hydrogen is an odorless, colorless, tasteless and non-toxic gas.

Hydrogen's density is about 14 times lesser than air at standard conditions (0.082 kg/m^3) and it is liquid below 20.3 K temperature (at atmospheric pressure). It has highest energy content (141.9 MJ/kg) per unit mass of all fuels which is almost 3 times higher than gasoline. Hydrogen is buoyant in nature, as well as highly diffusive with surrounding air. This makes hydrogen to disperse quickly in open areas and travel through very trivial spaces. That's why it is difficult to store hydrogen efficiently and also sometimes it permits hydrogen atoms to pierce into the molecular structure of some metals making it brittle. The specific physical features of hydrogen are quite different from some common fuels.

Some important properties of hydrogen are compiled in Table 1.2 comparing with gasoline, diesel, LPG and CNG.

Table 1.2 Physical and Chemical Properties of Different Fuels (Karim 2003)

Property	**Hydrogen**	**Gasoline**	**Diesel**	**LPG**	**CNG**
Chemical Formula	H_2	C_8H_8	$C_{12}H_{23}$	C_3H_8	CH_4
Octane/Cetane Number	130	85	30-45	103-105	120
Flammability (% by vol)	4-75	1-7.6	0.6-5.5	2.15-9.6	5-15.6
Minimum Ignition Energy (mJ)	0.02	0.25	---	0.26	0.29
Laminar Flame Speed at NTP (m/s)	2.65-3.25	0.37 - 0.43	0.22-0.25	0.382	0.34
Adiabatic FlameTemperature (K)	2318	2470	2600	2233	2310
Auto Ignition Temperature (K)	858	500-750	453-593	678-723	810-813
Quenching Distance at NTP (mm)	0.64	2.0	----	1.73	2.03
Density at 1 atm and 300K (kg/m^3)	0.082	730	830	2.26	0.754
Stoichiometric air/fuel mass ratio	34.2	14.6	14.5	15.67	17.3
Higher Heating Value (MJ/kg)	141.7	48.29	44.8	50.15	55.5
Lower Heating Value (MJ/kg)	119.7	44.79	42.5	45.7	43.73
Kinematic Viscocity at 300K (mm^2/s)	110	1.18	1.3-3.0	0.380	17.2
Thermal Conductivity at 300K (mW/mK)	182.0	11.2	130	19.82	18.0
Diffusion Coefficient into air at NTP (cm^2/s)	0.61	0.05	4.63	0.109	0.159
Toxicity to Humans	**Nontoxic:** Hydrogen, Diesel, LPG and CNG **Asphyxiant:** Hydrogen, LPG and CNG **Poisonous & Irritant to lungs & Skin**: Gasoline.				

Some of those properties make hydrogen more dangerous in certain situations, while other characteristics could make it potentially less hazardous. However, hydrogen can be used more safely in a wide range of applications and conditions by using proper safety controls as it was demonstrated in some industries.

Aceves (2012) elaborated through demonstrations and safety workshops that hydrogen remained as no more hazardous than other fuels and will be used in a way similar to that used for other fuels. Essential safety, handling procedures, codes and standards will be established and executed as needed to ensure public safety.

1.12 HYDROGEN HAZARDS AND SAFETY

Like any other fuel hydrogen also poses hazards if not properly handled or controlled. The risk of hydrogen therefore must be considered important relative to the common fuels such as gasoline, propane or natural gas. The safety concerns associated with hydrogen handling includes:

1.12.1 Fire

As we aware fire requires mainly three elements: fuel, an oxidizer (i.e., oxygen or air) and a source of ignition. Because of hydrogen's properties and physiognomies, the instantaneous dangers related with hydrogen leaks are fire, explosion, and asphyxiation. In the presence of air, it is possible that hydrogen is effortlessly get ignited by sources of heat, open flames, electrical sparks and static electric discharge. Hydrogen flames burn hot results in slight radiant heat and are undetectable by the naked eye. This can be challenging as the flames are difficult to detect and can be sprawled upon without warning. Hydrogen fires in confined spaces often result in explosions which can cause significant damage.

1.12.2 Explosion

Explosion is an extended version of a fire. Explosion occurs if the combustion is too fast to cause pressure waves which in turn produce sound waves. This is due to hydrogen's highest energy content per unit mass. Its presence itself can result in ignition if oxidizer is available near to it even with static discharge. Explosions often result when hydrogen is ignited in enclosed spaces.

1.12.3 Asphyxiation

Hydrogen gas is fragrance-free and nontoxic but if leaks may tempt suffocation by thinning the concentration of oxygen in air below the levels essential to support life. The quantity of hydrogen gas necessary to produce oxygen-deficient atmospheres is well within the flammable range; thus fire and explosion are the chief dangers associated with hydrogen and air atmospheres. Liquid hydrogen offers an additional hazard because of its extremely cold temperature of 20.3 K or below.

1.12.4 Tissue Damage

Hydrogen may cause damage of tissues when it is too cold. Liquid hydrogen (LH) is extremely cold, –423ºF (below 20.3 K). Contact with the LH or its cold vapors can cause extensive tissue damages.

1.12.5 Hydrogen Incidents and the Public's Insight

The acuity of hydrogen has been wrongly understood by vividly unforgettable images of three well-publicized events, namely

- The 1937 Hindenburg Airship disaster
- The development and proliferation of nuclear weapons, specifically the hydrogen bomb and
- The 1986 Space Shuttle Challenger accident.

In the event of the Hindenburg Airship disaster, hydrogen gas used to provide lift to the airship because of its buoyancy. It is true that the gas did ignite and burn; but it did so quickly, upwardly and away from the people below. Actually hydrogen did not cause the Hindenburg to explode. The blast was ascribed to a weather-related static electric discharge in later conditions which ignited the airship's silver-colored, canvas exterior covering. The passengers who galloped the airship down to the ground have survived. 35 out of 37 fatalities resulted from people jumping to the ground.

The hydrogen bomb uses hydrogen in the form of Tritium, which is hydrogen atom with three neutrons in the nucleus. Heat and nuclear reactions from the detonation of a nuclear fission bomb prompt a nuclear fusion reaction. These nuclear reactions require extremely high temperatures and pressures and are not similar to the simple chemical reactions.

The commission of government that investigated the 1986 challenger accident determined that the accident was not because of hydrogen. While the Shuttle had hydrogen as a fuel on-board for its main rocket engines, the main cause of the explosion was leaking hot plasma from one of its two solid-fueled booster rockets.

1.13 LIMITATIONS WITH HYDROGEN ENGINE

As the open literature emphasizes more about the performance of hydrogen operated engines highlights more about the positive features. But there are many limitations associated with use of hydrogen in IC engines too. Following section highlights about the limitations with hydrogen engine.

1.13.1 Abnormal Combustion:

The major disadvantage of hydrogen operated IC engine is control of the undesired combustion occurrences due to its wide flammability range, low ignition energy and rapid combustion speed of hydrogen (Liu et al. 2008). The main abnormal combustion anomalies in hydrogen engine are pre-ignition backfire and knock which will be discussed in this section.

1.13.1.1 Pre Ignition:

Pre-ignition is one of the unwanted combustion that needs to be evaded in hydrogen engine. It occurs inside the combustion chamber during the compression stroke, with actual start of combustion prior to spark timing (Al- Baghdadi and Maher Abdul Resul Sadiq. 2000). Pre-ignition event will occur before the start of combustion and produce an augmented chemical heat-release rate. In turn, this results in a quick pressure rise, higher peak cylinder pressure, acoustic oscillations and subsequently higher heat rejection that lead to rise in-cylinder surface temperature (Heywood 1988). The performance of H_2ICE powered vehicle decrease as pre-ignition limit on the peak power output of hydrogen engine in comparison to its gasoline equivalent (Kirchweger et al. 2007). High engine speed, load and operating conditions will also be susceptible to the occurrence of pre-ignition due to elevated gas and components temperature (Soberanis and Fernandez 2010). Therefore, evaluating the mechanism of pre-ignition and its control strategies with practical operational limits has been a primary focus of many investigations.

Source of pre-ignition;

- Hot exhaust valves or other hot spots in the combustion chamber.
- Hot spark plugs or spark plug electrodes.
- Residual gas or hot oil particles from previous combustion events.
- Combustion in crevice volumes (White et al. 2006).

Some steps to be taken to minimize the source of pre-ignition are:

- ✓ Proper spark plug design.
- ✓ Specific design of crankcase ventilation.
- ✓ Improved design of the engine cooling passage to avoid hot spot.
- ✓ Use of direct injection systems (Verhelst and Wallner 2009).

1.13.1.2 Backfire:

Backfire is another main problem to run an engine by hydrogen fuel. Backfire or flashback is the unrestrained combustion of fresh hydrogen–air mixture during the suction stroke in the combustion chamber and/or the intake manifold. When inlet valve opens, fresh hydrogen–air mixture is aspirated into the combustion chamber, in such situation if combustion chamber contain any hot spots, hot residue gas then backfiring occurs by igniting the fresh charge as hydrogen has low ignition temperature (Kirchweger et al. 2007). Backfire occurs during suction stroke while pre-ignition occurs at end of compression stroke earlier to ignition by spark plug in cylinder.

Backfire commences during the compression stroke through pre-ignition and then continues to the ignition of the intake mixture (Lee et al. 1995). Backfire results in increasing combustion rate and pressure in the intake manifold which is clearly audible and can also damage the intake system. The occurrence of backfire is more when mixture approaches stoichiometry and in case of PFI-H_2ICE where the hydrogen is injected previous to inlet valve opening to mix with air in the intake manifold before entering combustion chamber. While in DI-H_2ICE, as hydrogen injection starts after the intake valve closes the occurrence of backfire can be neglected (Verhelst and Wallner 2009).

Some of the strategies that are used to avoid backfiring are:

- ✓ Providing injection strategies that permit pure air to flow into the combustion chamber to cool impending hot spots before aspirating the fuel-air mixture.
- ✓ Optimizing the fuel-injection strategy combined with variable valve timing for both intake and exhaust valves.
- ✓ Allowing operation of a port injected hydrogen engine at stoichiometric mixtures over the entire speed range (Verhelst et al. 2010).

1.13.1.3 Knock:

Knock is defined as auto-ignition of the hydrogen–air end gas ahead of the flame front that originates from the spark. This trails a rapid release of the energy generating high-amplitude pressure waves called as knock. Knock can damage the engine due to increased mechanical and thermal stress caused by the amplitude of the pressure waves (Abbasi and Abbasi, 2011). The tendency of an engine knock is dependent on the fuel-air mixture properties and engine design. Knock is less likely for hydrogen in comparison with gasoline due to its higher auto-ignition temperature, finite ignition delay and the high flame velocity properties (White et al. 2006). Effects of engine knock are as following:

- ➢ Potential damage to engine components and undesirable engine performance
- ➢ Increased heat transfer to the cylinder wall.
- ➢ Extremely high cylinder pressure and temperature levels and increased emissions.

Prevention of abnormal combustion

- ✓ Limiting maximum fuel-to-air equivalence ratio.
- ✓ Pre-ignition conditions can be restricted by using thermal dilution technique such as exhaust gas recirculation (EGR) or water injection.
- ✓ Injection of water is another technique for thermally thinning the fuel-air mixture.

1.14 EFFECT OF SPARK TIMING

Due to small ignition energy limit of hydrogen, burning hydrogen is easy and gasoline ignition systems can be used. Sometimes dual spark plug system is preferred for very lean air fuel ratios (130:1 to 180:1) as the flame velocity is reduce considerably.

Spark plugs for a hydrogen appliance should have a cold rating and non- platinum tips. Hot-rated spark plugs do not aid a useful function of ignition, since hydrogen does not comprise carbon, Platinum-tip spark plugs should also be avoided since platinum is a catalyst, instigating hydrogen to oxidize with air.

There is a necessity for timing the spark as the fuel does not completely burn the instant the spark fires. The combustion gases need certain period of time to expand and the rotational or angular speed of the engine can lengthen or shorten the time frame in which the burning and expansion should occur.

From the pressure-crank angle diagram shown in figure 1.8, there are three phases of combustion in an SI engines. Stage I (AB) is called ignition lag or preparation phase. It corresponds to the time for the development and growth of a self-propagating nucleus of the flame. Stage II (BC) is called the main stage. It corresponds to the propagation of the flame practically at a constant speed. Stage III (CD) is called afterburning. Although the point of peak pressure marks the completion of flame travel, it does not mean that at this point the whole of the heat of the fuel has been liberated. Even after the passage of the flame, further chemical adjustments due to re-association will continue to some extent throughout the expansion stroke (Gupta 2012).

1.14.1 Effect of Spark Timing on Cylinder Pressure

Figure 1.8 shows the effect of spark timing on cylinder pressure versus crank angle. If the spark timing is over-advanced, the combustion starts while the piston is moving upwards towards TDC. Hence the compression work increases. If the spark timing is too much retarded, the combustion process gets progressively delayed and thus the peak pressure occurs later in the expansion stroke and its magnitude is reduced. The expansion work (positive work) is also decreased.

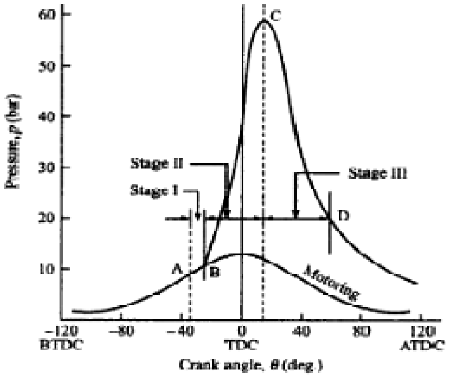


Figure 1.1 Pressure-crank angle diagram (Gupta 2012)

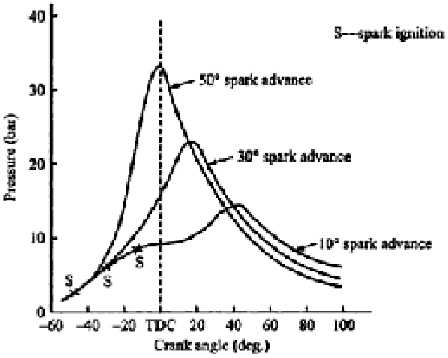


Fig. 1.8 Pressure-Crank Angle Variations for Different Spark Timings (Gupta 2012)

The optimum spark timing is the timing for which maximum brake torque is obtained. It is called the MBT timing. The spark timing that is advanced or retarded from MBT timing results in lesser torque. The MBT timing depends on the rate of flame development, propagation and termination. It also depends on the distance of the flame travel path across the combustion chamber (Gupta 2012).

The various factors affecting spark timing are as follows:

- Engine speed: Advancement of spark timing is necessary as the speed increases
- Mixture strength: In general richer mixtures burn quicker. Hence if the engine is working with rich mixtures, the optimal spark timing must be delayed, i.e. the spark occurs nearer to TDC.
- Part load operation: Part load operation of an SI engine is affected by regulating the incoming charge. On regulating a small quantity of charge entering the cylinder, the dilution due to remaining gases is also greater. In order to overcome the process of exhaust gas dilution and for the low charge density at part load operation the spark timing should be advanced.
- Type of fuel: The type of fuel will affect the spark timing. For maximum power and economy a slow burning fuel needs a higher spark timing advancement than a fast burning fuel.

Spark timing has a significant effect on the performance of an SI engine. Spark timing is itself affected by various operating conditions of an engine. Thus in conventional engines where there is no flexibility in changing spark timings based on various operating conditions, the engine performance gets severely affected. Therefore it is important to achieve optimum spark timing for any given condition of engine operation.

1.15 TURBOCHARGING

Turbo charging plays vital role in increasing the boost pressure of an internal combustion Engine and also reduce exhaust emissions. A turbocharger is a forced induction device that raises I C engine's efficiency and power output by imposing extra air into the combustion chamber because compressor can force more air into the combustion chamber than atmospheric thus improving engine’s power output. Turbocharger is a new technique to increase the mass flow rate of air to the engine ultimately to improve volumetric efficiency of an engine. The input energy can get from exhaust gas from an engine.

Turbocharger contains two major components as turbine part and compressor part. The turbine part gets power from rotating blades by exhaust gas (having high temperature and pressure) and the shaft from the turbine is coupled with compressor part. Rotating compressor blades of compressor increase the flow rate of air with slight increase of pressure. The turbine and the compressor power output are identical in a steady state condition. This increases volumetric efficiency of an engine which means sending more oxygen to combustion chamber for complete burning of fuel. With the use of turbocharger NO_x emission can also be decreased (Zhen and Yang 2013, Nicholas 2005, Baskharone 2006).In the present work use of turbocharger is made to improve the power output of engine operating on hydrogen.

1.16 WATER-METHANOL INJECTION

IC engines waste about 65% of the combusted heat energy. An addition of water with fuels permits the combustion heat to pool with oxygen of the water with unburned carbon in the exhaust. This yields a mixture of carbon monoxide and hydrogen. Hydrogen then burns producing additional power. Methanol is the simplest alcohol. It is a light, volatile, colorless, flammable liquid with a characteristic odor. However methanol is highly toxic and at room temperature it is used as a fuel.

The peak cycle temperature boost up whenever the load is increased, which makes an increase NO_x formation. Several methods have been tried to inhibit NO_x formation. Some of them are, use of EGR, Turbo-charging with intercooling, addition of diluents or water injection with the intake charge.

Injection of water into the intake manifold has been found to be an effective way to reduce NO_x emission in IC engines. It is a well-known fact that water does not burn, but it is excellent at absorbing heat due to its high specific heat capacity and latent heat of evaporation. Since it is a good absorber of heat, peak temperature in the cylinder will reduce so that the NO_x emission will greatly reduce. As water injection decreases combustion temperature it also decreases the probability of pre ignition and back fire. Water-methanol combination was used for regulating oxides of nitrogen without loss of power, efficiency and increasing the energy needed for ignition and thus sinking the reaction rate of hydrogen and air in the cylinder which is presumably the simplest and most effective method for control for NO_x emissions.

1.17 PRESENT WORK

The present work deals with experimental investigations on the combustion, performance and emission characteristics of multi-cylinder SI with neat hydrogen fuel with turbocharging and water- methanol injection. For experimentation, 44.5 kW capacity Zen MPFI SI engine has been made into test rig with all necessary instrumentation for measuring combustion, performance and emission parameters.

Engine test rig is modified to work with neat hydrogen after incorporating an aftermarket fuel injection kit with hydrogen ECU. The engine is coupled with an eddy current dynamometer for measuring the load on the engine. Sequences of experiments are carried out with engine operating parameters like speed, load and different ignition timings. To compare the results of experiments gasoline is used as a baseline fuel prior to hydrogen. Experiments are also carried out on the engine test rig with turbocharging for optimized ignition timing with full load and speed. To reduce the emission from the optimized result, the method of vaporized water-methanol injection is employed.

The waste heat from the engine exhaust gas is used to heat water-methanol mixture in a heat exchanger and it is converted into vapor state. The vaporized water-methanol at 10% of hydrogen fuel consumption is injected along with intake air. Engine combustion, performance and emissions are studied. Finally comparative study with baseline fuel is planned.

1.18 ORGANIZATION OF THE THESIS

This thesis has been presented with detailed experimental investigation carried out for performance, emission and combustion characteristics of four stroke four cylinder spark ignition engine with neat hydrogen as a fuel. This thesis comprises of following chapters.

Chapter 1: Introduction: - This chapter provides short introduction about present situation related to energy/fuel crisis and environmental degradation. Available alternative fuel for IC engines and their properties of different SI engine fuels have been compared. The need for hydrogen and hurdles accompanying it has been explained. The several production technique and storage systems and safety concerns for hydrogen have been reckoned.

Chapter 2: Literature Review: - Briefly discusses the comprehensive literature relating to the research and development of hydrogen operated spark ignition engine. It includes the fuel induction techniques, spark timing, engine performance, emission and combustion characteristics, Electronic control unit (ECU) and turbocharging with water-methanol injection for hydrogen operated spark ignition engine.

Chapter 3: Objectives & Methodology: - Based on the literature gap, the objectives of the present work and methodology are framed in this chapter.

Chapter 4: Experimental Set up: - This chapter describes the development of experimental test rig and the description of instruments used during experiments. The details of hydrogen set up, safety measures, scheme, procedure and methodology of experiments with brief introduction about combustion parameters are given in this chapter. The uncertainty and errors involved in the experimentations are also analyzed.

Chapter 5: Results and Discussion: - This chapter deals with the results obtained with detailed discussion. The results of engine performance, emission and combustion characteristics with neat hydrogen with various operating parameters such as loads, engine speeds, spark timings, turbocharging and water-methanol injection are discussed. Finally a comparative study has been done on engine performance, emission and combustion characteristics of neat hydrogen with above conditions.

Chapter 6: Conclusions and Scope for Future Work: - This chapter makes the concluding remarks of the present investigation and scopes for future work have been listed.

CHAPTER 2

LITERATURE REVIEW

2.1 HISTORY OF REVIEWS

Limited availability of crude oil reserves, environmental degradation by engines and most stringent norms for them have given new dimension in vehicle technology and many research activities over world are going in this field with two main objectives. First one is for alternative energy/fuel that may substitute conventional one, second is the processes that reduces the exhaust emission as well improves engine performance. With these concerns and objectives comprehensive literature survey has been carried out in the area of hydrogen as an alternative fuel for IC engines from several international and national journals, conference proceedings and other information sources to focus on identifying utilization of hydrogen fuel in I C engines. A brief review of the literature is summarized here to exploit and develop a neat hydrogen fueled spark ignition engine.

An outlook of the potential area of research in IC engines and advancement in technology in respect of the fossil fuel crisis and abatement of the environmental contamination problems associated with automotive has elaborated by several investigators (Rolf 2013, Alagumalai 2014 and Kalghatgi 2014). There are many alternative fuel options made available for IC engines through trials after realization of fuel crisis during world wars, which include both liquid and gaseous fuels like bio-diesel and natural gas. Most of early vehicle experiments were intended for burning a variety of gases, including propane and natural gas. In last few decades considerable works on usage of hydrogen as fuel in vehicular application have been more focused. Since it is a new concept, lot of work has to been focused on its salient features, limitations, power boosting methods and emission control techniques.

The salient features of the basic properties of hydrogen like low density, high energy content, low ignition energy, wide flammability range, high auto ignition temperature, high burning speed, high diffusivity and low quenching distance and the other engine-specific properties of hydrogen were enlisted by investigators through their review studies (White et al. 2006, Ciniviz and Kose H. 2012). However hydrogen has some of major drawbacks like, pre-ignition and backfires.

Utilization of hydrogen in an IC engine is not completely a new concept. Hydrogen has been acknowledged as a fuel having some distinctive and highly desirable properties for application as a fuel in IC engines for a quite long time (Cecil 1822, Erren and Campbell 1933) through paper which was presented before the Cambridge philosophical society. They evaluated attractive features and allied limitations that are impending in its extensive application as an alternative engine fuel. It was a stationary engine and the common principle of the engine was based on the property of hydrogen gas mixed with atmospheric air. The atmosphere pressure may be adopted as a moving force, closely the same manner as in the common steam engine. This has been considered the first internal combustion engine.

In 1854, Barsanti and Matteucci were granted an English patent for hydrogen burning in free- piston type engine, from this Benini built a prototype in 1856 (Genta et al. 2014). Even Otto, who considered the “father of modern IC engines”, used hydrogen in his work with gaseous fuels. He had unsafe experience with the use of hydrogen as a fuel for IC engine and hence returned to the use of gaseous fuels till the development of the carburetor which made gasoline fuel practical and safe (North 1992).

Rudolf A. Erren made first practical hydrogen-fueled engine in the 1920 with suggestion that, direct cylinder injection method can be used to reduce backfiring and converted over 1,000 engines to operate on hydrogen. His projects incorporated buses and trucks. In World War II, the Soviet Union converted many of the vehicles in the city to run on the hydrogen fuel, which was stored for using in floating anti- aircraft balloons (Erren and Campbell 1933). In 1970, Bockris proposed the idea of hydrogen as an alternative fuel for the gasoline in automobiles (Bockris and Appleby 1972).

The allies exposed a submarine transformed by Erren to hydrogen power after the World War II. Because of high temperature ash, residue from burned oil and dust, King observed hot spots in the combustion chamber which is the main cause for pre-ignition.

He traced that backfire occur at high flame velocity and high equivalency ratios. M.R. Swain and R.R. Adt developed modified injection techniques for a 1600 cm^3 Toyota engine with a compression ratio of 9:1 at University of Miami (Swain et al. 1996).

Ricardo conducted the first engine performance tests on single cylinder engine by hydrogen in 1924. He used various compression ratios for trial with an achievement of 43% peak efficiency at a compression ratio of 7:1. Roger B. won first place in the emissions category over 60 other vehicles in Urban Vehicle Competition with hydrogen-converted Volkswagen in the 1972 in collaboration with Brigham Young University. This success has led towards collaborative work among institutions and industries on hydrogen.

In 1975, Robert Zweig transformed a simple and elegant pickup truck to operate on compressed hydrogen. He used an extra intake valve to admit hydrogen separately from air to solve the backfiring problem (Zweig 1992). The hydrogen operated pickup trucks were displayed in public exhibits by American Hydrogen Association. Similarly Ciancia A and others performed test on Fiat Ducato engine in 1996 with and without water injection and revealed that power output was only 2/3rd of gasoline engine and no significant changes were seen with water injection (Ciancia et al. 1996).

A comprehensive literature survey by many investigators had elicited the paybacks of hydrogen as a fuel for I.C. engines due to fact of its high thermal efficiency and near zero exhaust emission levels. They noticed undesirable combustion phenomena like pre-ignition, backfire, knock, rapid rate of pressure rise and high NO_x production. They also revealed that these hurdles are mainly related with the way the hydrogen being supplied to the combustion chamber (MacCarley et al. 1980, Das 2002a, and Soberanis and Fernandez 2010).

The laboratory of transport technology (University of Ghent, Belgium) has specialization in alternative fuels for more than 30 years. Major gaseous fuels like, Natural gas, LPG, and hydrogen and their blends is the subject of research. In first stage, Valmet 420D a normal aspirated diesel engine with direct injection was transformed to a spark ignited engine for the use of hydrogen. The tests presented several inadequacies of the available gas injectors: leakage, unequal response time (opening delay) and low durability (Sierens and Rosseel 1995). Wankel (rotary) engine is converted by the Brookhaven National Laboratory to operate with hydrogen. It has worked well with hydrogen than conventional engines.

Ford Motor Company began development of Ford ZETEC a hydrogen fueled IC engine in 1997. The pistons, cylinder head, ignition system, wrist pins, connecting rods, piston ring lands and fuel injectors were all modified to improve combustion by hydrogen. The experimental results showed that hydrogen as a fuel for an IC engine has sole properties such as higher fuel economy and low carbon related emissions due to high octane number. Testing indicated that torque output reduced by 50% at high speed and 35% at low and mid speeds compared to gasoline. At stoichiometric ratio of 0.25, the best specific fuel consumption occurred and unburned exhaust emissions of hydrogen drastically increased (Van Blarigan and Keller 1998; Sierens and Verhelst 2001; Verhelst et al. 2007). NO_x concentration increased dramatically as stoichiometric ratio increases above 0.5. Hydrogen engine was operated with a supercharger which results improvement in the performance (Natkin et al. 2003).

Nissan Motors and Musashi Institute of Technology found that turbocharging or supercharging a hydrogen fueled engine will help achieve higher power, efficiency and lower NO_x emissions (Furuhama and Fukuma 1986). Sandia National Lab demonstrated that a hydrogen fueled engine can provide the necessary power with a drive-cycle efficiency approaching that of the fuel cell vehicle of the future. Lab test data shows that the engine obtained higher thermal efficiency and lower NO_x emissions when running on hydrogen (Verhelst et al. 2006).

2.2 REVIEW RELATED TO FUEL INDUCTION TECHNIQUES FOR HYDROGEN FUEL

This section includes information about the fuel induction methods for hydrogen fuel in IC engines. The configuration of a hydrogen fueled engine is similar to that of a conventional IC engine. But if a traditional engine without any alteration was fueled by hydrogen then problems like low power output, high NO_x emission and abnormal combustion would result. Therefore its fuel induction and combustion system essentially needs suitable alterations. The techniques of supply of fuel for an IC engine can be classified into four classes such as carburetion or central injection systems, inlet manifold injection, inlet port injection and direct cylinder injection.

Fuel induction techniques have been found to play an important role in the overall performance of hydrogen fuelled engine. Particularly for gaseous hydrogen fuel adaptation in I.C. engines considerable research work has been carried out by Das L.M. in 1987, where reviewed the merits and demerits of various fuel induction methods for hydrogen (Das 1990).

In port fuel injection system the fuel-air formation takes place outside the combustion chamber. Fuel is injected directly into the inlet manifold at each intake port after the beginning of the intake stroke. The air is introduced independently at the start of the intake stroke to dilute the hot residual gases and to cool hot spots if any. As less gas is in the manifold at any time, pre mature ignition is not severe and/or probability of occurrence is reduced. But when air and hydrogen fuel are outside the combustion chamber the hydrogen displaces air, thereby dropping 20 to 30% power compared to gasoline.

An exhaustive research effort has been carried out by BMW since 1979 on port fuel injection of hydrogen engines. At stoichiometric air-fuel ratio operation, BMW found that with external mixture formation, hydrogen displaces approximately 30% of the articulated air. BMW suggests that a direct supply of hydrogen at injection timing of 40 deg. to 60 deg. CA bTDC to the combustion chamber will permit the engine to have the best power density and indicated mean effective pressure greater than gasoline. (Wallner et al. 2008, He et al. 2006)

Direct injection of hydrogen into the cylinder has all the merits of the late injection as described by manifold injection. In addition it essentially precludes the possibility of backfire and pre mature ignition by displacement of intake-air (Aleiferis and Rosati 2012, Ghazal 2013). Hydrogen direct injection provides many benefits including significant power density, avoidance of abnormal combustion anomalies and improved volumetric efficiency compared to PI method with hydrogen ICEs (Verhelst et al. 2012; Welch et al. 2008).

Specific fuel induction techniques such as parallel induction and late injection, rapid ignition and mixing techniques (LIRIAM) have also been tried out for suppressing back fire and for smooth operation of hydrogen engines (Lynch 1983). It was observed that direct injection systems suffer from higher values of cyclic variation as compared to manifold injection systems (Kim et al. 2005).

Das (1990, 2002b) revealed from his experiments that the carburetion is not a suitable method for hydrogen engine, because it contributes to uncontrolled combustion in the engine cycle. The symptoms of backfire were experienced at unscheduled points in the engine cycle with continuous manifold injection operation. Moreover, tests with timed manifold injection showed that the engine was able to run smoother and reduce substantially the undesirable combustion anomalies when compared to continuous manifold injection over a wide working range of speed and equivalence ratio. Therefore the appropriately designed timed manifold injection systems can overcome this problem and backfire in hydrogen engine (Das 2002b, Liu et al. 2008).

As far as the direct cylinder injection is concerned, it intrinsically precludes backfire. However, limited tests with direct injection indicated that it is very tough for the injector to persist in the severe thermal environment of the combustion chamber over a prolonged engine operation. The other problem which is characteristic of cylinder injection is the short duration allowed for mixing of hydrogen and air after injection. This often results in incomplete combustion. Thus, after exhaustive tests on the research engine with various fuel induction techniques, timed manifold injection was found to be the most pragmatic mode of hydrogen fuelling.

To make use of the characteristics of hydrogen, Swain et al. (1996) designed an intake manifold. The important feature of the design is the usage of hefty passages with low-pressure drop and high intake velocities, which is possible with hydrogen fueling. It was revealed 2.6% increase in peak power output with the usage of large diameter inlet manifold compared to that for a small diameter. He et al. (2006) modified Ford SVO four cylinder gasoline engine into hydrogen fueled SI engine. They adopted Intake port fuel injection (PFI) system because it provides better cylinder fuel distribution system and minimizes the effects of back flash.

The tests were done with a gas carburetor on a GM-Crusader V8 engine by (Sierens and Rosseel 1998) after converting it for hydrogen and allied gas (natural gas and hythane) use. The engine was fitted with a sequential timed multipoint injection scheme in order to get a better control of the combustion, which has benefit of resistance to back fire, but this imposed a restriction of rich mixture operation. This limitation can be reduced by the use of a multi-point sequential injection system and direct injection in the combustion chamber. Cryogenic storage and pump is even better, but at present not technically available for mass production (Furuhama 1995).

Four cylinder hydrogen fueled SI engine is modified (Guo et al. 1999) with fast response solenoid valves for injection of hydrogen and its electronic control system. Study showed that the no observation of abnormal combustion and performance of the engine were improved by means of fast response solenoid valve operated hydrogen injection system. It was also revealed good switch characteristics and very fast response, thus it might satisfy the working necessities of the injection system. For smooth functioning of hydrogen engine the fuel injector actuation is important. Various authors investigated different mechanisms for fuel supply and found electronically controlled actuation provides better flexibility of controlling the hydrogen fuel supply. (Sierens and Rosseel 1995, Sorusbay and Veziroglu 1988, Soberanis and Fernandez 2010 and Sopena et al. 2010)

The Indian Institute of Technology Delhi (IITD) tested and converted spark ignition engines to hydrogen engines using carburetion mode and ECU fuel injection system and concluded with following inferences: extensive range of fuel-air mixtures is possible with hydrogen fuel. Low throttling works better and alteration needs higher compression ratios up to 11:1. Hydrogen is found to be 30 to 50% more efficient than gasoline (Das et al. 2000 and 2002b). The researchers from our country also inferred some conclusions on the application of hydrogen along with diesel fuel in diesel engines by reducing compression ratios from 16.5:1 to 14.5:1. Only a small amount of hydrogen is sufficient with diesel fuel as it has high rate of combustion. Tests were carried out using neat hydrogen and blending with other fuels such as CNG, LPG and diesel in the laboratory. The engine was optimized for the different operating conditions and it was demonstrated and proved hydrogen can be used as a substitute fuel for conventional fuels (Hari Ganesh et al. 2008, Subramanian et al. 2007)

2.3 REVIEW RELATED TO PERFORMANCE, COMBUSTION AND EMISSION PARAMETERS OF HYDROGEN FUEL IN S I ENGINE

This section provides information about the previous work carried out using hydrogen as fuel for evaluating performance, combustion and emission parameters.

May and Gwinner (1983) used hydrogen with surplus air for starting and idling an SI engine. At part load both hydrogen and gasoline were provided to engine and at full load gasoline alone fueled the engine to avoid the power loss. It was noticed about 25% improvement in engine efficiency at part load. El-Emam and Desoky (1985) premeditated the combustion properties of hydrogen-air mixture and established that it has higher self-ignition temperature than a gasoline-air mixture and the maximum energy mass coefficient and enhances knock resistance.

Sher and Hacohen (1989) found that the problems like uneven distribution of fuel into cylinders and cold fuel evaporation can be avoided by hydrogen and nitric oxides are only the toxic products of using it. Conventional SI engine fueled with a blending of hydrogen-gasoline can function with ultra-lean mixture thus leading to finest fuel economy and fewer pollutant emissions. Karim (2003) reported that hydrogen engine desires to be some 40–60% bigger in size than gasoline engine operation for the same power output. This could impose some drop in engine speed, amplified mechanical and motoring losses and reduced tolerance to knocking.

D'Andrea et al. (2004) examined the effect of various equivalence ratios and engine speeds on combustion of a hydrogen blended gasoline engine. They found that with the increase of hydrogen blending fraction, combustion duration decreases and the nitrogen emission increases. Li and Karim (2004) investigated the effects of change in key operating variables such as intake temperatures, spark timings and compression ratios on knock-limiting equivalence ratios both experimentally as well as analytically in the hydrogen-fueled SI engine at constant speed of 900 rpm. The occurrence of knock was recognized directly from the observation of cylinder pressure variations with time. They found that the engine achieves peak power production efficiency of about 38% for 0.36 equivalence ratio. To avoid knock, the spark timing is significantly retarded when the engine operates around the stoichiometric region mixtures.

Subramanian et al. (2006) concluded after investigating for parameters of combustion and effect of equivalence ratio on stability by three load points, WOT condition and adjust of spark timing to Maximum Brake Torque (MBT) at every point of operation, throttling is essential to improve brake thermal efficiency and to reduce cyclic variations for a hydrogen fuelled engine at low loads and better equivalence ratio is 0.4. Kahraman et al. (2007) experimentally investigated for disparities of torque, power, brake thermal efficiency, brake mean effective pressure (BMEP), exhaust gas temperature and emissions of NO_x, CO, CO_2, HC, and O_2 and are compared for gasoline and hydrogen in a conventional four cylinder carbureted SI engine. The compressed hydrogen is used by external mixing. The test results demonstrated loss of power at low speed and boost of power at high speed for hydrogen. NO_x emission is about ten times lower for hydrogen fueled engine, wherein light traces of CO and HC emissions found for hydrogen engine.

A direct-injection single cylinder spark ignition hydrogen engine was developed by Mohammadi et al. (2007) and focus was made on the effects of injection timing for the engine parameters, combustion features and NO_x emissions for a wide range of engine loads. It was revealed from the research that knock and backfire can be prevented by injecting hydrogen during the intake and compression stroke. For high engine output conditions, late injection of hydrogen proposes a great reduction in NO_x emission due to the lean operation.

Subramanian et al. (2007) conducted experiments on a single cylinder hydrogen fueled engine to evaluate the performance, emission and combustion features at different equivalence ratios and constant speed of 2500 rpm with WOT. The experiment results revealed that maximum power output of the hydrogen fueled engine is reached about 78% of the rated power with gasoline due to a decrease in volumetric efficiency. They concluded that, spark delaying does not seem to be a very effective way to control NO_x for hydrogen fueled engine. Kawahara and Tomita (2009) visualized an auto-ignition inside the end-gas region owing to flame propagation and pressure waves that happen during knocking when carried out tests in a hydrogen spark-ignition engine. They explored that the strong pressure waves are generated owing to large amount of unburned mixture caused by the auto ignited kernel explosion.

Rahaman et al. (2009) focused effect of engine speed and air fuel ratio on the prediction of performance of a single cylinder hydrogen fueled SI engine. The speed varied from 2500 till 4500 rpm and air fuel (A/F) ratio from stoichiometric to lean limit. The injector was fixed in the middle way of the intake port. The experiment revealed increase in BMEP and brake thermal efficiency, but decrease at higher air fuel ratio and higher speed. The volumetric efficiency of hydrogen fueled engine is a serious problem and reduces the power. Experiments was conducted by Verhelst et al. (2009) on a Volvo make 4 cylinder 16 valve gasoline engine with a cubic capacity of 1783 and a compression ratio of 10.3:1 with some modifications. They explored that at low loads the hydrogen brake thermal efficiency are higher by 40–60% relative to the gasoline. The brake thermal efficiency of hydrogen at high speed is about 18% higher relative to gasoline.

Ali et al. (2010) presented a comparative study for performance and emission characteristics of six alternative fuels with gasoline using a 4 cylinder, Mazda B2000i SI engine by numerical and experimental analysis and eventually concluded that volumetric efficiency of hydrogen operating engine was lowest and power produced by gasoline is highest. Ji and Wang (2009b, 2010) reconnoitered the performance of a hybrid hydrogen-gasoline engine at idle, stoichiometric and lean conditions by their papers varying the flow rate of hydrogen. Results indicated that hydrogen addition at lean conditions might improve the indicated thermal efficiency, lower the cyclic variations, extend the combustion span, and reduce the HC, CO and NO_x emissions.

Soberanis and Fernandez (2010) discussed the most significant developments and advances made on the IC engines which work with mixtures of gas/hydrogen in their study describing merits and limitations of the combination of hydrogen and gas as a fuel and associated anomalies during the combustion. They concluded that efficiency of an engine fueled with hydrogen can exceed than that realized with a gasoline engine. In laboratory tests, the power output of hydrogen fueled engine has reached about 80% of a gasoline engine.

Sopena et al. (2010) modified Volkswagen Polo 1.4 gasoline fueled SI engine in to Hydrogen Operated Internal Combustion Engine (H_2ICE). The experiment results revealed that H_2ICE reached maximum brake power of 32 kW at 5000 rpm and best brake torque of 63 N-m at 3800 rpm. Zhao et al. (2010) conducted experiment on single-cylinder, Gasoline Direct Injection (GDI) engine with a centrally located spray-guided injection system with different load conditions. They concluded that the combustion was speeded up by adding hydrogen. The Maximum Brake Torque (MBT), ignition advance was condensed also were cycle-by-cycle variations in combustion. Developed efficiencies and lesser NO_x emissions are possible when DI combustion combines with EGR owing to decrease of heat losses to the cylinder walls (Tanno et al. 2010). Current research activities with hydrogen direct injection propose that peak engine efficiencies about 45% are attainable.

Rahman et al. (2011) conducted experiments on four cylinders Direct Injection (DI), hydrogen fueled engine to investigate the performance and optimum injection timing. The GT- Power commercial software was utilized to develop engine model. Engine speed was varied from 2000 to 6000 rpm, the equivalence ratio from 0.2 to 1.0, while injection timing was varied from 110 deg. CA bTDC until top dead center. The results show that the engine speed and air fuel ratio strongly impact the optimum injection timing and engine performance. The power and torque rises with the reduction of engine speed and air fuel ratio. Indicated efficiency rises with increase of air fuel ratio while decreases as of engine speed. The indicated specific fuel consumption (ISFC) drops with increase of air fuel ratio from rich conditions to lean while reduces as of engine speed. The injection timing of 60˚ bTDC was the overall optimum injection timing with conciliation.

Moreno et al. (2013) conducted experiment on two cylinders SI Engine to verify the effect of hydrogen at various volume fractions for performance and emissions. It was perceived that hydrogen supplementation with the gasoline fuel improves combustion for the ignition timing selected. This enhancement is more significant at low speeds, because at high speeds hydrogen effect is weakened by the high turbulence. Especially at stoichiometric conditions, the high NO_x emission was measured owing to increment in the combustion temperature that hydrogen produces. Higher rate of heat release were observed for blend with more hydrogen content.

Wang et al. (2014) examined the performance of a naturally aspirated commercial gasoline engine manufactured by Beijing Hyundai motors. Hydrogen injection system was supplemented to the engine intake manifolds to find the engine performance. Initially engine was operated with gasoline and performance was compared with 3% hydrogen blended gasoline by varying throttle and air fuel ratios at engine speed of 1400 rpm. The experimental results revealed that, brake thermal efficiency of the 3% hydrogen-blended gasoline engine running at the WOT and lean conditions was higher than that of the pure gasoline engine due to reduced residual gas fraction and throttling loss. Further, the emissions at the WOT and lean conditions gains lower emissions of CO and HC than the gasoline engine. NO_x emissions are increased due to the raised cylinder temperature and oxygen concentration at higher engine load.

Unni et al. (2017) confers the trial results on single cylinder 3-wheeler engine for vehicular application on field by highlighting the modifications for smooth operation for hydrogen without any combustion anomalies. Engine reported to develop torque of 13.2 Nm @ 3200 rpm while functioning at lean conditions. Such 15, three-wheeler vehicles developed taking care of safety. The Billings Energy Corporation, Missouri, converted a U.S. postal Jeep with a special gaseous carburetor to operate on hydrogen hydride. The fuel consumption is 3.9 km/liter by gasoline whereas by hydrogen it got 4.9 km/liter thus improvement was 24%.

Over many decades, the use of hydrogen as a fuel has been endeavored by numerous investigators apart from the above literature. The information about their outcomes is accessible in the open literature. Provision of all details is beyond the scope of this section but it has been revealed by way of several successful experimental projects that hydrogen in many respects is much better than existing automotive fuels (Balat 2008; Berry et al. 1996; DeLuchi 1989; Sun et al. 2012; Verhelst and Sierens 2001; Verhelst et al. 2006; White et al. 2006. Shivaprasad et al. 2016 and Chitragar 2017).

2.4 REVIEW RELATED TO PERFORMANCE & EMISSION PARAMETERS OF HYDROGEN FUEL WITH ELECTRONIC CONTROLLED FUEL INJECTION SYSTEM (ECU).

This section provides information about the previous work carried out using hydrogen as fuel for evaluating performance, combustion and emission parameters with ECU unit.

Hari Ganesh et al. (2008) converted a single cylinder conventional SI engine to work with hydrogen using the timed manifold fuel injection (TMI) technique by adopting solenoid operated gas injector for analysis of performance and emission characteristics with hydrogen and gasoline. Injection timing and length was controlled by developed electronic circuit, spark timing was fixed to minimum advance for best torque (MBT) and engine was operated at WOT condition. For evaluation of results, the same engine was also run on gasoline. From the results, it was found that there is a decrease of about 20% peak power output, 2% greater brake thermal efficiency for hydrogen than gasoline. A lean limit equivalence ratio of about 0.3 could be reached with hydrogen as compared to 0.83 with gasoline. CO, CO_2 and HC emissions were insignificant with hydrogen however NO_x emission was 4 times higher than that of gasoline at full load power. The best ignition timing for hydrogen was much delayed when compared to gasoline.

Ji and Wang (2010) experiments on an altered 4 cylinder hybrid hydrogen gasoline engine (HHGE) furnished with an electronically controlled hydrogen port injection (PI) system and hydrogen electronic control unit (HECU) demonstrated that the engine BMEP was improved by hydrogen addition at low load conditions. However, at high engine loads, it yielded smaller BMEP than the original engine. The engine BTE was noticeably raised with the increase of MAP for both the engines. They endorsed that the hydrogen addition is effective in improving gasoline engine operating instability at low load and lean conditions. HC and CO emissions were decreased but NO_x emissions were increased with the increase of engine load. For CO_2 emission, the influence of engine load was insignificant.

(Sainz et al. 2011) modified original engine-generator to bi-fuel operation (hydrogen/gasoline) with electronic fuel-injected power unit at the laboratory of I C Engines of the public university of Navarre. An electronic management unit was developed with several sensors like throttle position, oil temperature and all sensors were mounted for proper operation of the power unit. The fuel system was altered from carburetor to injection scheme for both hydrogen and gasoline fuels. The ignition system was altered to electronic spark ignition in order to evade wasted sparks.

Ceviz et al. (2012) performed experiments on a 4 cylinder FORD make SI engine with electronically controlled fuel injector with four equivalence ratios 1.0 to 1.3 and four air fuel ratios. The hydrogen was supplemented to gasoline in the amounts of 2.14%, 5.28% and 7.74% by volume. The test engine was operated at 2000 rpm. From the test measurements, it is found that specific fuel consumption (SFC) reduced by about 12% and engine thermal efficiency enlarged by about 18% for 5.28% hydrogen-gasoline ratios respectively, as linked to gasoline operation. Addition of hydrogen to the gasoline-air mixture decreased HC emissions by 13% when 5.28% hydrogen added to the gasoline-air mixture. However, NO emissions augmented by 91% with hydrogen addition.

An experimental study on effects of hydrogen fractions (0-25%) by Shivaprasad et al. (2015) on high speed Lombardini gasoline engine has revealed higher efficiency and reduced emissions. Similar experiment by Du et al. (2016) with 0% ~11.09% hydrogen fraction on SI gasoline engine with lean burn combustion and emission characteristics was conducted on a modified premixed gasoline engine equipped with ECU monitored hydrogen direct-injection system. With the growing hydrogen addition fraction, the combustion speed increased, mean effective pressure and thermal efficiency are enhanced. Flame development and propagation duration are condensed, the peak cylinder pressure increased and its corresponding crank angle advanced. The maximum rate of heat release, mean gas temperature and the rate of pressure rise increased, while HC, CO emissions decreased and NO_x emissions increased.

Salvi et al. (2016) investigated experimentally on single cylinder, forced air cooled hydrogen powered spark ignition (SI) generator set, which was transformed from gasoline with rated power 2.1 kVA at 3000 rpm for effects of compression ratio and EGR on backfire, performance and emission characteristics in a hydrogen fuelled spark ignition engine. The test was carried out at different compression ratios; various spark timings and exhaust gas recirculation (EGR) up to 25% by volume. Additionally, the experimental trails were conducted on the engine with different start of gas injection (SOI) in order to find the backfire limiting start of injection (BFL-SOI). The outcomes exposed that engine operation at higher compression ratio upgraded the brake thermal efficiency and reduced the backfire occurrence. However, NO_x emission amplified with increased compression ratio. In order to reduce the NO_x emission at source level, the engine was functioned with retarded spark timings and different EGR percentage. The relative NO_x emission was reduced up to 10% with the spark time retarding of 2 CA bTDC from MBT whereas it reduced about 57% with 25% by volume EGR. The delay in gas injection could decrease the chance of backfire occurrence and the BFL-SOI reduced with increased compression ratio. A notable point emerged from this study is that retarding the spark time is not a suitable strategy for NO_x reduction; whereas the EGR at the optimum level (20%) is a superior strategy that could reduce the NO_x emission up to 50% as compared to base hydrogen engine without EGR in hydrogen fuelled SI engine.

2.5 REVIEW RELATED TO EMISSIONS FROM THE HYDROGEN FUELED ENGINE

This section provides information about the work done using hydrogen as fuel for evaluating emission parameters. In recent years, IC engines have been critiqued for their role in environmental degradation through exhaust emissions like CO, NO_x and UBHCs. Hydrogen is measured to be clean and efficient substitute fuel among the available one. There are many reports on experimental and analytical evaluation of IC engine with hydrogen as a fuel in it. A main benefit of hydrogen over other fuels is that its major oxidation product is water vapor only. The hydrogen during its combustion with air produces only undesirable oxides of nitrogen.

Stebar and Parks (1974) used hydrogen complemented fuel as a means of prolonging the lean limit operation in a gasoline engine in order to control NO_x. A single-cylinder engine was verified by the addition 10% hydrogen on mass basis. The lean limit was extended from 0.89 to 0.55 plummeting NO_x emissions to near minimal levels. However, as a concern of running on lean mixtures, the HC emissions increased. Parks (1976) inspected experimentally the emission characteristics of a hydrogen rich fuel of a single cylinder SI engine. The results indicated that at an equivalence ratio of 0.8, rising hydrogen energy fraction from 0.13 to 0.48 dropped the HC emission by 15-60% respectively and augmented NO_x emissions.

Lucas and Richards (1982) performed an investigation on an engine which was fueled by only hydrogen during idling and as load increased then gasoline was added with a constant hydrogen flow rate. This dual fuelling mode condensed fuel consumption up to 30% and because of lean operation, CO emissions were reduced due to completeness of combustion. In addition, report on measurements of a single-cylinder furnished with a supercharger and exhaust gas recirculation (EGR) system for hydrogen engine is highlighted by Kumar et al. (1985). The results have shown that at supercharged intake pressures of 2.6 bars, NO_x level below 100 ppm for $\Phi < 0.4$, and when operating EGR combined with supercharging depicted substantial increase in the power output while restricting tailpipe emissions of NO_x.

Hydrogen fueled SI engine emissions and their control methods have been comprehensively studied by Das (1991) and concluded that ultra-lean combustion (i.e. $\Phi = 0.5$) can minimize NO_x emissions in IC engines effectively, which is adequately similar with low temperature combustion. He amassed data from numerous sources for tailpipe emissions with exhaust after-treatment for NO_x emissions, and further at $\Phi > 0.95$ emission of NO_x are near zero with the use of a 3-way catalytic converter.

In University of California Riverside, Heffel (2003) piloted the experiments on hydrogen fueled SI engine to discover the effect of EGR and 3-way catalytic converter on engine performance and NO_x emissions. All the experiments were trialed on a four cylinder, Ford ZETEC engine specially designed to run on 100% hydrogen using a lean-burn strategy at a constant engine speed of 3000 rpm and different fuel flow rate varying from 1.63 to 2.72 kg/h. It had a compression ratio of 12:1 and used a sequential port fuel injection system. Every test started by working the engine with the EGR valve closed and running the engine at lean burn condition. The engine parameters at this primary condition were then measured and recorded. From experiments it is concluded that lean burn strategy can produce more torque than EGR strategy, if the NO_x emission is not considered. However, EGR strategy can produce almost 30% more torque than the lean-burn strategy if low NO_x emissions (<10 ppm) are a requirement. The results demonstrated that EGR is an effective means to lower NO_x emissions.

Subramanian et al. (2007) have investigated different methods of controlling the oxides of nitrogen and found cold EGR method is one of the solution at high loads and no effect at lower load because of small percentage of EGR presence. Soberanis and Fernandez (2010) reported in their technical paper that the emissions of air-hydrogen mixtures consist mainly of nitric oxides due to the higher flame velocity and temperature of hydrogen fuel. Emissions of unburned hydrocarbon (UBHC) are because of the product of lubricant oil and engine coolant oil. Hydrogen combustion at small load, reducing injection time and delaying the spark can lessen emissions of NO_x and avoid abnormal phenomena of combustion.

A four cylinder gasoline engine was converted into a HHGE by Ji et al. (2012). The experimental results indicated that the HHGE was started successfully with the pure hydrogen, which produced 99.5% and 94.7% reductions in CO and HC emissions compared to original gasoline engine. Moreover HC, CO and NO_x emissions were effectively reduced for the HHGE due to eased engine cyclic variation and shortened combustion duration. Mariani et al. (2013) found that the addition of hydrogen in the fuel-air mixtures resulted in the 16% reduction of CO_2 emission.

Kherdekar and Bhatia (2017) simulated a hydrogen operated SI single cylinder engine for minimization of NO_x emissions. Based on literature, experimental data, global kinetics based model, transient spark energy delivery model and modeling of heat transfer is developed for predicting NO_x emissions. A thermodynamically consistent rate expression for NO formation is used, which predicts a maximum in-cylinder NO concentration with time due to the decrease in temperatures during the power stroke and the reversible nature of NO formation. Results reveled NO emissions depend not only on the peak in-cylinder temperatures, but also on transient evolution of in cylinder temperature profile. Convective heat transfer from engine to coolant is found to limit heat transfer. Back-fire predicted at high equivalence ratios.

Using kinetics based approach, the effect of various operating variables such as engine speed, equivalence ratio, compression ratio and spark advance on the NO emissions is predicted by the model, It is found that the equivalence ratio strongly affects the peak in-cylinder temperature, whereas the engine speed governs the amount of time available for NO formation. Consistent with reported data, the phenomenon of back-fire is predicted at high equivalence ratios. Optimum values of the equivalence ratio and compression ratio are suggested to optimize the power output and NO emissions.

2.6 REVIEW RELATED TO SPARK TIMING FOR HYDROGEN FUEL

In this section, discussions on research papers which are related to spark timing and ECU operation of SI engines have been presented.

Study of influence of ignition energy, fuel injection timing and spark timing on gasoline engine under various air/fuel (A/F) ratio at idle condition was carried by Han et al. (1999) for performance evaluation and revealed that 20 mJ ignition energy, 90^{o}bTDC fuel injection timing was best for the idle stability; while the optimal spark timing will be in the range of 10^{o} – 20^{o} bTDC. Sierens and verhelst (2001) investigated the distinctive characteristics related to the use of hydrogen as a fuel in I.C. engines. They studied the ignition characteristics, the choice for fuel injection pressure and quality of lubricating oil, use of oxygen sensors with advantages and limitations of power regulation by changing the air fuel ratio as compared to the throttle regulation.

Ji et al. (2010b) conducted experiment on hybrid hydrogen engine (HHE) in order to find out the effect of spark timing on engine performance at lean condition and at fixed engine speed. During the test, the hydrogen blending in the intake was raised from 0% to 3% by adjusting the hydrogen injection duration. The spark timing was varied from 20 deg. to 50 deg. CA bTDC with an interval of 2 deg. CA for a specified hydrogen addition level. The test results revealed that the indicated mean effective pressure (IMEP) initially raised and then reduced with the advance of spark timing. The optimum spark timing for the maximum the IMEP was retarded for the hydrogen fueled SI engine at a specified excess air ratio. NO_x and HC emissions were constantly reduced with the spark timing retardation.

Jabbr et al. (2016) work deals with the advanced replications of the combustion process using a commercial software package for engine performance and emissions of a single cylinder SI engine fueled by hydrogen. The extended Zeldovich mechanism with coefficients for carbon-free fuel was employed to investigate the most accurate formation rate of nitrogen oxide (NO_x) emissions within the engine. The first part of this work focuses on simulating the engine performance and emissions at different equivalence ratios, EGR and ignition timing. The second part of this work focuses on IC engine optimization for the operating parameters. The best operating conditions for least hydrogen NO_x formation engines were obtained by solving the multi-objective problem of maximizing engine power.

2.7 REVIEW RELATED TO HYDROGEN WITH TURBOCHARGER AND WATER/STEAM INJECTION

In this section, discussions on research papers which are related to turbocharger and water/steam injection have been presented.

Subramanian et al. (2007) Studied use of water injection with the retardation of the spark ignition timing for dropping NO levels in hydrogen powered engines. In his work a mono cylinder hydrogen powered engine was run at various equivalence ratios at wide throttle position. NO levels were found to increase after an equivalence ratio of 0.55 and an extreme value of about 7500 ppm was observed. Results discloses that large drops in NO emission is possible with a significant fall in thermal efficiency for retarded spark ignition timings but severe drop in NO levels to even as low as 2490 ppm were realized with water injection.

Verhelst et al. (2009) has studied the potential use of supercharger in a hydrogen engine. It was proved that, output power can be improved by using supercharger and EGR. The engine was operated above equivalence ratio of 1 and resulted in power outputs of up to 30% higher compared to gasoline. Ma et al. (2010) tried experimental investigations to study the effect of 55% hydrogen volumetric ratio on performance and emission characteristics in a turbocharged lean burn natural gas engine. The experimental investigation carried out at several operating conditions including manifold pressure, excess air ratio and different spark timing. It was found that the addition of hydrogen at a high volumetric ratio decreases burning length and produce higher thermal efficiency. The CO emissions were lowered and NO_x emission could be kept satisfactory low with high hydrogen content under lean burn conditions at optimized spark timing.

Investigation of idle characteristics of turbocharged hydrogen fueled SI engine under various equivalence ratio and ignition advance angle carried out by Ma et al. (2011) and concluded that with the increase of equivalence ratio, the ignition timing conforming to the maximum indicated thermal efficiency decreases slowly, maximum cylinder pressure and NO_x emission increases. Experimental consequences on a single-cylinder research engine with simulated turbocharged action at an engine speed of 3000 rpm and full load caused an estimated brake thermal efficiency of almost 44% at very low NO_x emissions levels (Obermair et al. 2010).

The water injection system can be used to reduce the combustion temperature and thus nitrous oxide production. Water was injected as a fine vapor right into the manifold of the engine which dropped backfiring and improved power. Alberto (2011) reported that direct injection clubbed with port water injection can be used to prevent the occurrence of all abnormal combustion phenomena and brings the advantages of high power densities. Occurrence of backfire may be eliminated by very high pressure and high flow rate with direct injection implemented close to the ignition near top dead center and contributes to reduce the probability of knock.

For the safety concern in using hydrogen as a fuel (Aceves et al. 2012) were developed a web based class for laboratory researchers to address hydrogen safety information.

2.8 SUMMARY OF LITERATURE REVIEW

After going through a detailed literature survey it has been summarized that the use of hydrogen in IC engines has an integrated advantage to the depletion of fossil fuels and to safeguard the environmental pollution. Several works has been done with hydrogen as a short term alternative fuel for the gasoline engine. Review concludes that hydrogen provides adequate desirable properties as a fuel in internal combustion engines. It will provide the positive effect on the exhaust emissions except for NO_X emission. There are good predictions for increased efficiencies, reduced emissions and high power density with hydrogen. Direct injection will give good agreement to boost power and reduce or eliminate the combustion anomalies like pre ignition and backfire, whereas manifold injection yield lesser power compared to gasoline due to low density and high diffusivity and hence less amount of air available for combustion to end within the combustion chamber.

Some of the most notable points from the literature survey are as follows:

1. Hydrogen can be used in IC engines as lean as possible in comparison with other fuels for a range of compression ratios, but it results in lowered power output for any size.
2. Hydrogen is carbon free fuel which results in no hydrocarbons, carbon monoxide, and carbon dioxide. Main products of combustion are only NO_x and water vapor. The level of NO_x can be minimized significantly with lean operation for hydrogen compared with other fuels.
3. High-speed engine operation can be ensured with hydrogen as it possesses fast burning characteristics.
4. Cyclic variations reduce enormously with hydrogen fuel. This leads to a have improvement in efficiency, reduction in emissions and quieter and smoother operation.
5. Hydrogen can be added as a best blend relatively in small fractions with some of the common fuels.
6. The gas is highly diffusive and buoyant which make fuel leaks disperse quickly, reducing explosion hazards associated with hydrogen engine operation.
7. The hydrogen has lower volumetric efficiency that needs to be exploited so as to boost the power output.

2.9 RESEARCH GAP

On the basis of the extensive literature work detailed above, the following research gaps have been identified.

- Most of the previous work has been carried out in different type of engines which includes carburetor type SI engines, single cylinder engine and with hydrogen-gasoline blending. There are limited test results available on multi cylinder MPFI SI engine fueled with neat hydrogen.

- Extensive research works have been reported on the use of hydrogen for performance and emission characteristics of SI engine. But limited studies found related to combustion on neat hydrogen fueled in multi cylinder SI engines with multi point fuel injection systems.
- Work related to supercharging or turbocharging with neat hydrogen fuel is limited.
- Work related to water-methanol induction or injection with neat hydrogen is limited.

On account of this, the experiments have been conducted to investigate the effect of neat hydrogen on modified and electronically controlled four cylinder 4-stroke MPFI spark ignited engine at various engine operating parameters like load, speed and spark timings along with turbocharging and water-methanol injection.

CHAPTER 3

OBJECTIVES AND METHODOLOGY

3.1 MOTIVATION FOR PRESENT INVESTIGATIONS

The utilization of hydrogen as an automobile fuel has been trailed in very limited basis with variable degrees of success by several investigators over many years, and much pertinent evidence about their conclusions is available in the open literature. However, these reported data do not show consistent agreement between various investigators. There is also a need to focus on outcomes achieved in some particular engines and for slightly changed operating conditions which will make the hydrogen to become a widely accepted and used fuel for engine applications on roads.

Hence, there exists a definite need to carry out more investigations for the efficient utilization of neat hydrogen in an IC engine for evaluation of performance, combustion and emission parameters. Such a study is likely to establish the appropriate design for improving the performance of hydrogen fuel on four cylinders, four stroke SI engine. In view of this status, the present investigations were proposed to carry out with the following objectives, so that hydrogen engine can be operated without any back fire and optimally controlled exhaust emissions.

3.2 OBJECTIVES OF THE PRESENT INVESTIGATION

In recent years, the increased prices of liquid fuels derived from crude oil and rising concern about environmental contamination have raised interest in alternative engine fuels. Hydrogen is one of the gifted alternative fuels due to its greater combustion qualities and availability in abundance. The present study deals with experimental investigations of four cylinders, four strokes modified MPFI SI engine by using neat hydrogen for engine performance, emissions and combustion characteristics. The engine operating parameters like speed, load (throttle opening position) and ignition timings are varied. A specific objective of the research work is:

To develop multi cylinder engine for neat hydrogen operation with minimum emissions. Emphasis is to be given on optimization of operating parameters like, load, speed and ignition timing using ECU. The optimized engine should run without any back fire.

The detailed objectives of the investigation are as presented below.

1. To study the performance, combustion and emission characteristics with base gasoline fuel at various loads, speed and spark timings.
2. To modify the existing four cylinders MPFI SI engine to work with neat hydrogen fuel at various load and speeds.
3. To study the performance, emission and combustion characteristics of four cylinders 4-stroke SI engine with neat hydrogen at various load, speed and static ignition timing. The emissions are to be sampled without any after treatment device.
4. To study the performance, emission and combustion characteristics of same engine with neat hydrogen at various load, speed and with different spark timings.
5. To study the performance, emission and combustion characteristics of same engine with neat hydrogen at full load, max speed and at optimized spark timing with turbocharging.
6. To adopt a water-methanol injection system in the intake manifold utilizing waste exhaust heat from the engine and to study the effect of water-methanol injection to verify the performance, emission and combustion of the above engine setup with turbocharging for optimized condition.
7. To analyze and compare the performance, combustion and emission results obtained from tests for both the fuels (Hydrogen and gasoline).
8. To make a comparative study of the hydrogen fuel and water-methanol injection system with baseline fuel (Gasoline) on engine performance, emission and combustion characteristics.

3.3 SCOPE OF INVESTIGATION

The experimental investigation was carried out on a multi cylinder spark ignition MPFI engine converted into an electronically controllable stationary SI engine with neat hydrogen. Load and speed conditions are varied and compared with base fuel gasoline. Static ignition timing is advanced and retarded by 3 bTDC to get optimized condition for performance, combustion and emissions. A separate turbocharger has been selected based on the exhaust gas energy and fitted into the engine. Necessary modification has been done in the exhaust and intake manifold. Finally vaporized water-methanol system has been developed for a turbocharged MPFI engine to bring better combustion, performance and emission characteristics. The exhaust emissions were measured in real time with exhaust gas analyzer, with the samples being taken as raw sample i.e., without any exhaust after treatment devices in between the sampling point and the engine exhaust manifold.

3.4 METHODOLOGY OF THE PRESENT INVESTIGATION

1. Comprehensive literature survey was carried out to know about the present status of use of hydrogen fuel in IC engine.
2. Modification of an experimental test rig in the laboratory with necessary instrumentation for generating experimental data using base fuel i.e., gasoline and neat hydrogen for analyzing and comparison purpose.
3. Experimental investigation on the four cylinder SI engine for generating baseline data (i.e., for performance, combustion and emission parameters) using gasoline at different speed (1500 to 3000 rpm in steps of 300 rpm) and load conditions (25% - 100% in steps of 25%) at static ignition timing of 5deg. bTDC.
4. The modification of the ECU for hydrogen operation by interfacing sensors and injector with ECU.
5. Experimental investigation on the above engine with neat hydrogen operation for above mentioned speed and load conditions at factory set static ignition timing (5deg. bTDC).
6. Experimental investigation on the above engine with neat hydrogen operation for above mentioned speed and load conditions at different ignition timing (2deg. bTDC and 8deg. bTDC).

7. Experimental investigation on the above engine with neat hydrogen operation for optimized ignition timing for full load and max speed condition with turbocharging.
8. Experimental investigation on the above engine with neat hydrogen operation for optimized ignition timing for full load and max speed condition with turbocharging and water-methanol injection.
9. Analyzing and comparing all the above experimental findings for optimum condition for both neat hydrogen and gasoline operations.

3.5 FLOW CHART OF EXPERIMENTS

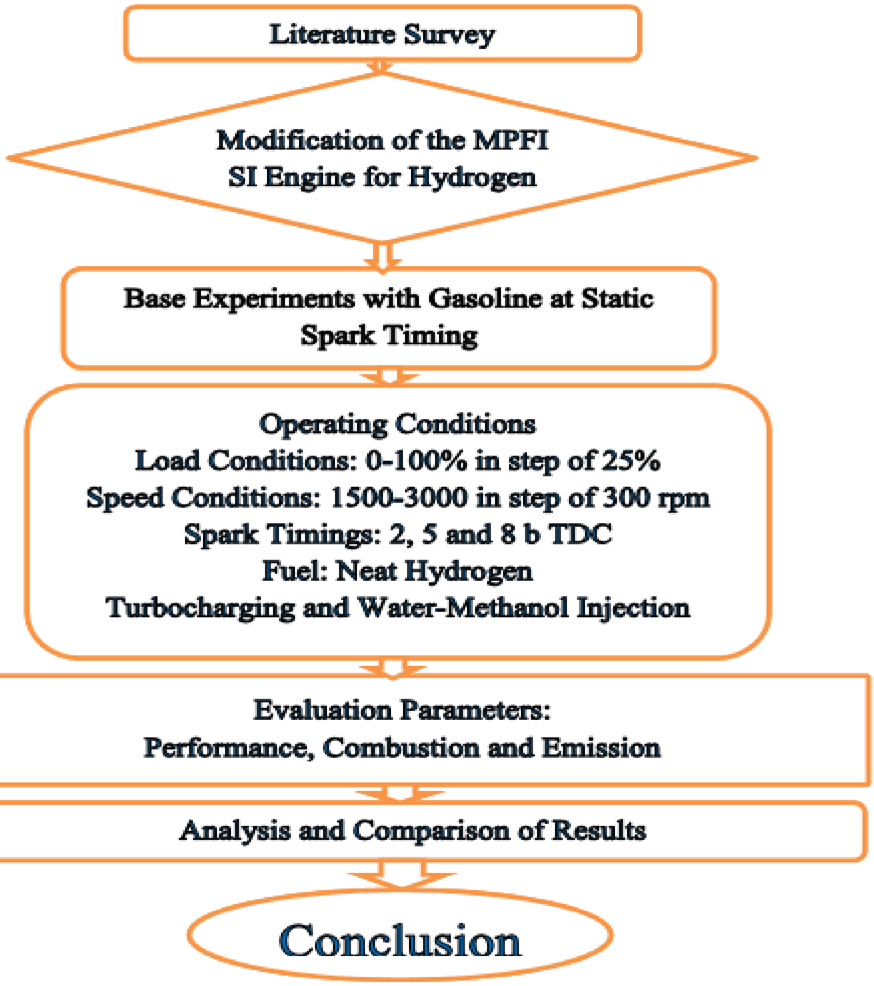


Fig 3.1 Flow Chart of Experiments

CHAPTER 4

EXPERIMENTAL SET UP AND METHODOLOGY

The aim of this chapter is to describe the components of the research engine test facility, plan of work and methodology applied to achieve the objectives framed under present research work. The discussion also includes engine modifications, experimental parameters, measurement techniques and instrumentation for the course of the research.

SI engines are simply adjustable to gaseous fuels however minor alterations for the supply of the fuel in suitable quantity are applied. A fuel supply scheme that can be altered as per the engine’s need is worth enough to make the engine work. But in case of hydrogen fuel, there are certain extra issues related to safety and backfire-safe operation throughout the entire operating region.

Compared to gasoline, hydrogen’s low energy per unit volume yields less energy in the cylinder hence produces less power than that with gasoline operation. Supercharging/Turbocharging might help remedy to this by compressing the incoming fuel/air combination earlier to cylinder entry.

4.1 ENGINE SET UP

The engine setup consists of a four-stroke, four cylinder SI engine of Maruti Zen (max. power of 44.5 kW at 6000 rpm) with multi point port fuel injection (MPFI) system. Engine is assisted with software to acquire experimental data for this project. The engine has a single overhead camshaft layout with 4 valves per cylinder (2 intakes and 2 exhausts). Fuel is injected into the intake port by a single fuel injector located in each intake runner. The engine is linked to an eddy current type dynamometer which is used to absorb power and control engine speed. The test rig is provided with essential instruments for combustion pressure and crank-angle measurements, airflow, fuel flow, temperatures and load measurements. These signals are interfaced to a digital computer through an 8 channel engine interface. The setup consist of a stand-alone panel box which includes fuel tank, fuel measuring unit, air box and manometer, differential pressure transmitters for air and fuel flow measurements, process and engine indicator.

For water flow measurement, rotameters are provided on cooling water and calorimeter (for heat balance sheet) side. Figure 4.1 shows the schematic diagram of the experimental setup, while figure 4.2 shows photographic view of the engine test rig.

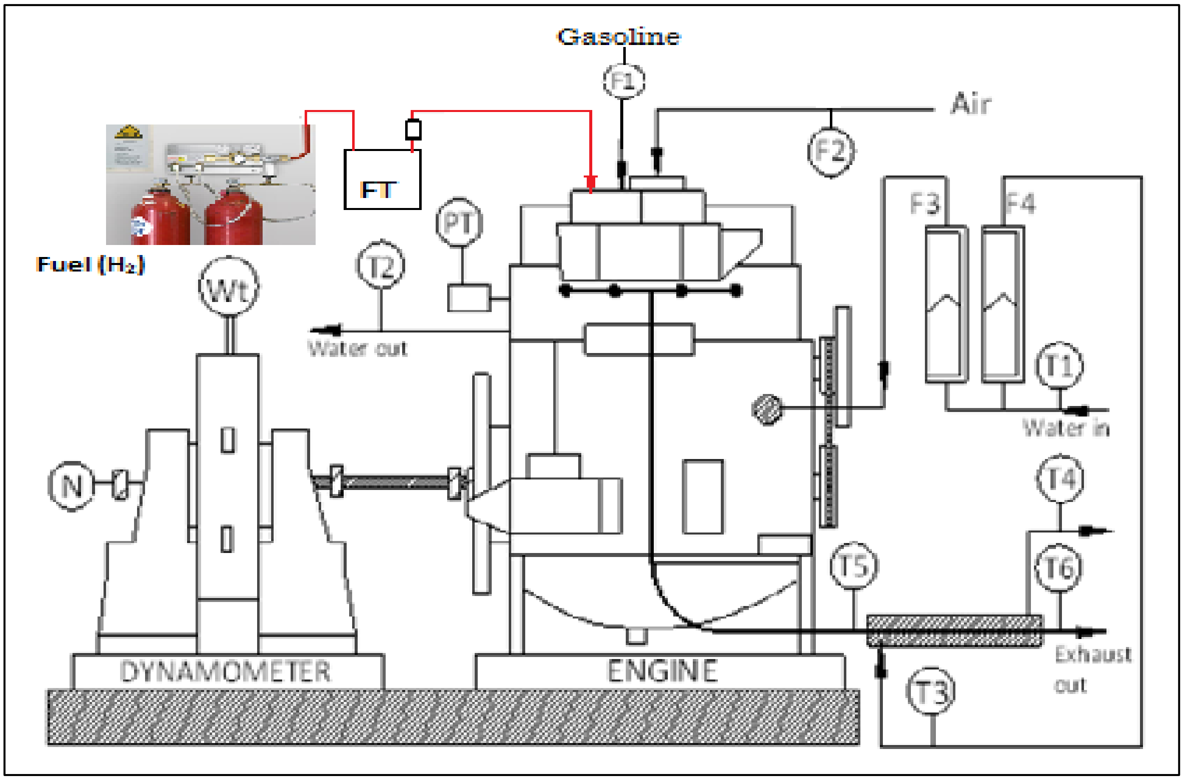


Fig. 4.1 Schematic Diagram of the Experimental Setup.

F1- Differential pressure unit for fuel flow

F2- Air Intake DP unit

F3- Rotameter (Engine)

F4- Rotameter (Calorimeter)

N – RPM decoder

Wt – Load on Dynamometer

T1- Engine Cooling water inlet temperature

T2- Engine Cooling water outlet temperature

T3- Calorimeter water inlet temperature

T4- Calorimeter water outlet temperature

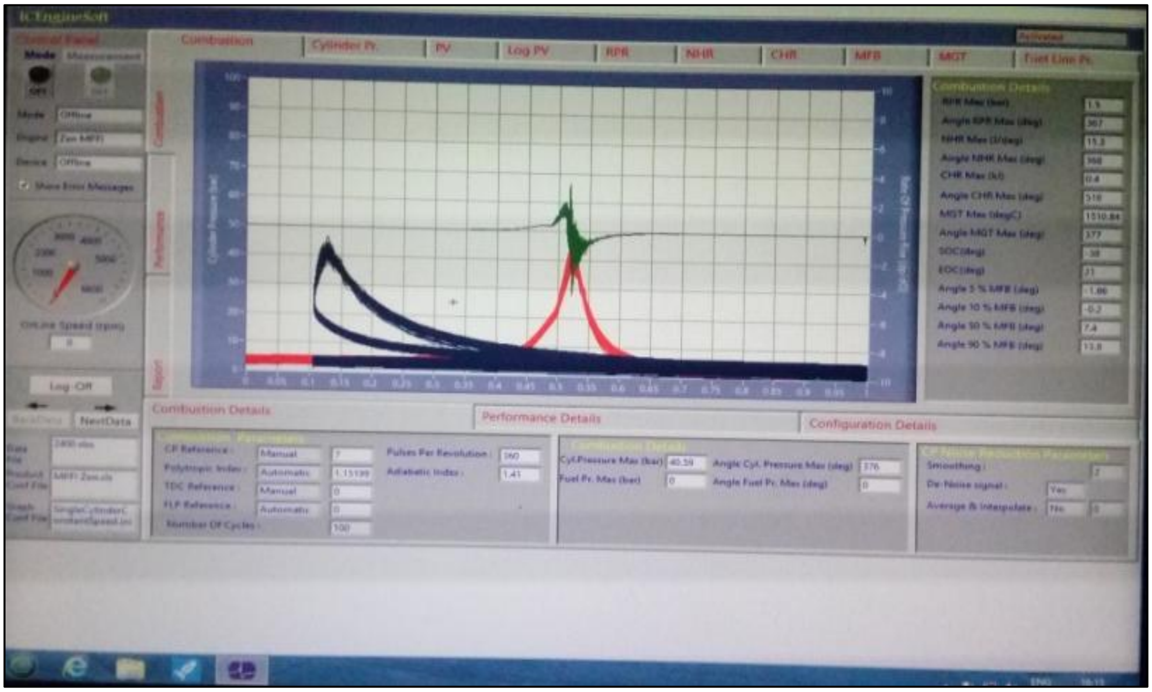
T5- Exhaust gas inlet temperature to calorimeter

T6- Exhaust gas outlet temperature to calorimeter

Fig. 4.2 Photographic View of the Experimental Test Engine

The arrangement facilitates study of engine performance like brake power, indicated power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, volumetric efficiency, specific fuel consumption etc.

National Instruments (NI) based USB-6210 data acquisition system, engine combustion and performance analysis software ‘IC Engine Soft’ is provided by the supplier of the test rig M/s Apex Innovation Pvt. Ltd. Sangli, India for on-line performance evaluation. The software also evaluate the combustion parameters for Heat Release Rate, Mass fraction Burned, In-cylinder pressure- volume, Rate of pressure rise and Mean gas temperature for each crank angle deg. The complete specifications of the gasoline engine and other instrumentation mounted on the test-rig are given as Appendix I and II respectively. The test rig is also compatible to supply gaseous fuels through gas ECU software system using solenoid injectors mounted on it. The software is used to record and modulate the gaseous fuel supply as required for the engine. Spread sheet of IC Engine Soft and gas ECU is shown in Figure 4.3 and figure 4.4 respectively.



Mode: Offline
Engine: Zen MPFI
Device: Offline

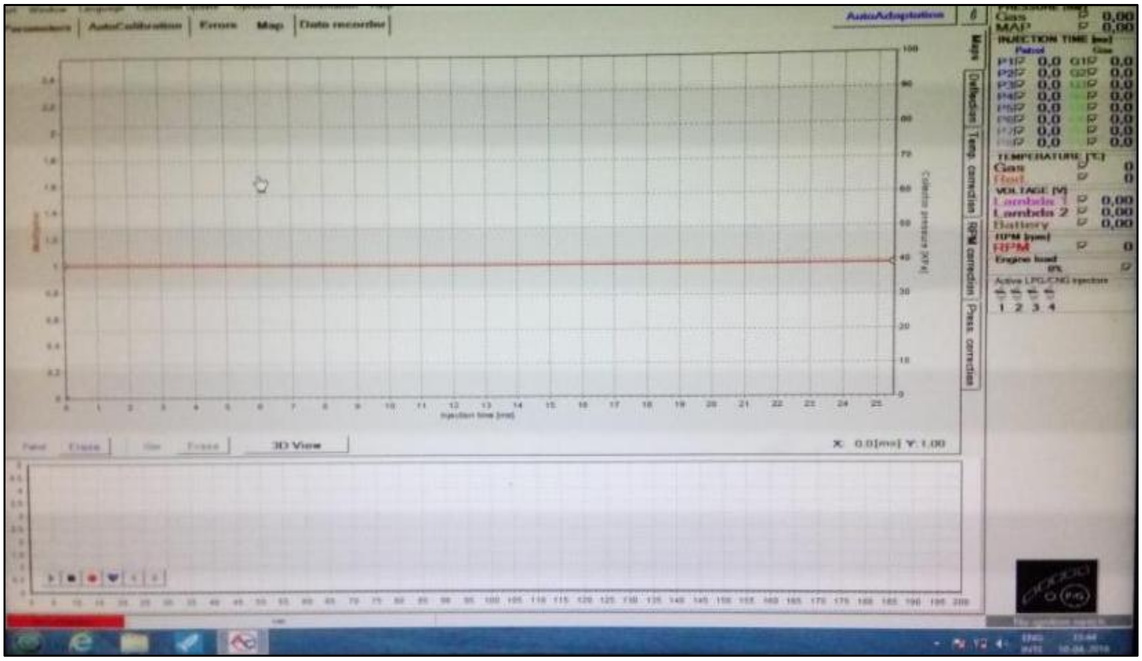
Combustion Details
RPR Max (bar): 1.5
Angle RPR Max (deg): 367
NHR Max (J/deg): 15.3
Angle NHR Max (deg): 368
CHR Max (kJ): 0.4
Angle CHR Max (deg): 518
MGT Max (degC): 1510.84
Angle MGT Max (deg): 377
SOC(deg): -38
EOC(deg): 21
Angle 5 % MFB (deg): -1.86
Angle 10 % MFB (deg): -0.2
Angle 50 % MFB (deg): 7.4
Angle 90 % MFB (deg): 13.8

CP Reference: Manual 7
Polytropic Index: Automatic 1.15139
TDC Reference: Manual 0
FLP Reference: Automatic 0
Number Of Cycles: 100
Pulses Per Revolution: 360
Adiabatic Index: 1.41

Cyl.Pressure Max (bar): 40.59
Angle Cyl. Pressure Max (deg): 376
Fuel Pr. Max (bar): 0
Angle Fuel Pr. Max (deg): 0

Smoothing: 2
De-Noise signal: Yes
Average & Interpolate: No 0

Fig. 4.3 Spread Sheet of IC Engine Soft



Gas 0,00
MAP 0,00
INJECTION TIME [ms]
P1 0,0 G1 0,0
P2 0,0 G2 0,0
P3 0,0 0,0
P4 0,0 0,0
P5 0,0 0,0
P6 0,0 0,0
P7 0,0 0,0
P8 0,0 0,0
TEMPERATURE [°C]
Gas 0
Red 0
VOLTAGE [V]
Lambda 1 0,00
Lambda 2 0,00
Battery 0,00
RPM [rpm]
RPM 0
Engine load 0%
Active LPG/CNG injectors
1 2 3 4

X: 0.0[ms] Y: 1.00

Fig. 4.4 Spread Sheet of gas ECU Software

4.2 MODIFICATION OF THE ENGINE SET UP FOR HYDROGEN OPERATION

The engine is modified to operate with hydrogen fuel. Four separate gas injectors are fixed to the inlet manifold near to inlet port of each cylinder for injecting hydrogen. The gas injectors are functioned by solenoid valves driven by 12V DC power supply. A set of available nozzles (Standard size of 1.7 mm) were purchased from market and modified to test for injection till 2.5 mm; some of the nozzles were prepared (For 1.2 – 1.5 mm diameter) from raw material. These different diameter nozzles from 1.2 mm to 2.5 mm were tested for the injection of the hydrogen into the engine for optimizing the size for hydrogen operation based on the power output and for trouble free operation per cylinder. Then nozzle diameter of 2.2 mm is finalized after confirming fine results for hydrogen operation. A distinct gas ECU system is used for driving the solenoid valves and the signals from the gas ECU was controlling the activation period of the gas injectors. The after-market LPG injection system manufactured by M/s Europe gas (Auto gas v 3.1 LPG) is used for hydrogen feeding. The block diagram of the hydrogen injection system is shown in the Fig. 4.5

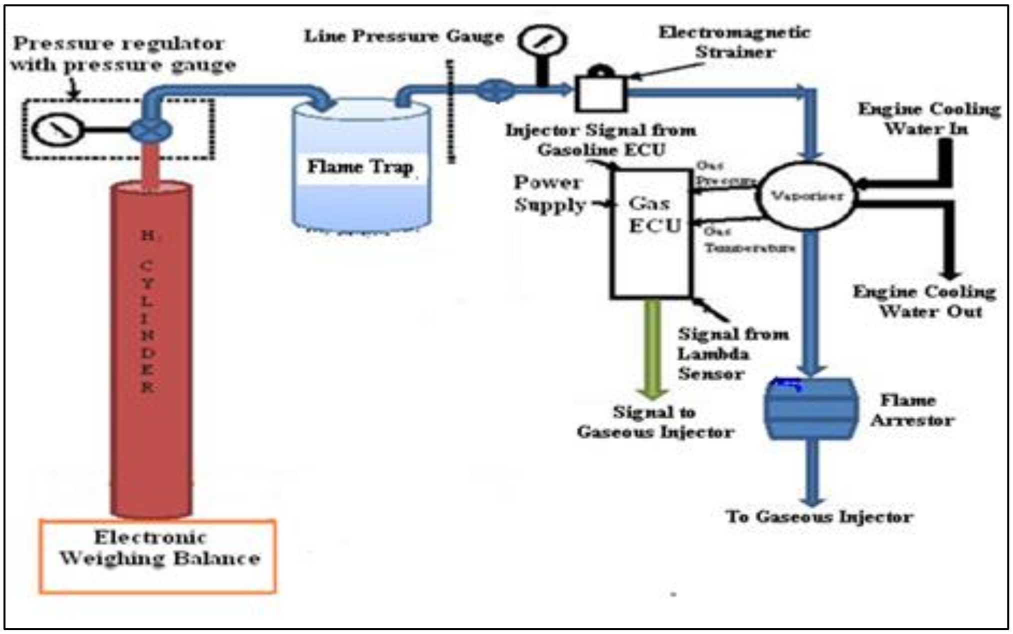


Fig.4.5 Block Diagram of Hydrogen Injection System

A copper pipe is used to supply the hydrogen from flame trap to the engine cylinder. A switch is mounted on the control panel assembly that permits immediate switching from gasoline to hydrogen. This switch controls the actuation of solenoid valves on the gasoline and hydrogen line without stopping the engine between two fuels.

Grade-III quality (99.985% Pure) hydrogen gas (about 230 bar pressure) is used for the test. Compressed hydrogen is contained in a steel cylinder with two stage regulator mounted on it so that hydrogen flow can be controlled and supply pressure of hydrogen can be maintained. The hydrogen flow control system consists of two stage regulator with pressure gauges, one indicate cylinder pressure and other indicate line pressure. Compressed hydrogen at 230 bars was released down to 3-5 bars in the first stage regulator. The second stage regulator deliveries the gaseous hydrogen to the flame trap and then to engine according to the inlet manifold pressure. The fuel line consists of a copper tube connected to a hydrogen flow meter and engine.

The flame trap and flame arrestor are used as a safety measures and mounted amid of hydrogen cylinder and engine. Flame trap consist of pressure indicator, safety valve and flow regulating control valve. The hydrogen from the cylinder first flows to the flame trap and then supplies to the engine via control valve of flame trap and flame arrestor at a required pressure. Engine line pressure can be further regulated with the help of pressure reducer/control valve if required. AVL's exhaust gas analyzer is used to verify the major engine exhaust emissions by placing in the way of engine exhaust system.

4.2.1 Hydrogen Engine Control Unit (Gas ECU)

The purpose of the gas ECU is to regulate the gas injector at right time to control the duration of injection. Master slave theory working concept is used for bi-fuel gas ECU application (Khatri et al. 2009). A sequential gas injector controller of IV generation OSCAR-N OBD CAN is used. The opening signal pulse for gasoline injector from the pre-installed Gasoline ECU is fed to gas ECU as an input. The gas ECU uses a correction factor and adjusts the gasoline pulse width and sends it to gas injectors.

This correction factor is calculated based on the density of liquid gasoline and gaseous hydrogen. It also considers the signals from the other sensors such as exhaust lambda sensor and inlet manifold absolute pressure sensor indicating the engine load. When the engine is running with hydrogen, the emulator system in the gas ECU cuts off gasoline injection signals and provides the emulated signal to the gasoline ECU so that it doesn't give a fault signal. A switch provided in the control panel to use it to switch between hydrogen and gasoline fuel operation. The specifications of the gas ECU is given as Appendix III.

4.2.2 Turbocharging System

The schematic diagram of turbocharged MPFI engine is shown in figure 4.6. Turbocharger consists of turbine and compressor. Exhaust gas energy is used to run the turbine. A waste gate regulates the exhaust gas flow that enters the exhaust-side driving turbine and therefore the air intake into the manifold and the degree of boosting.

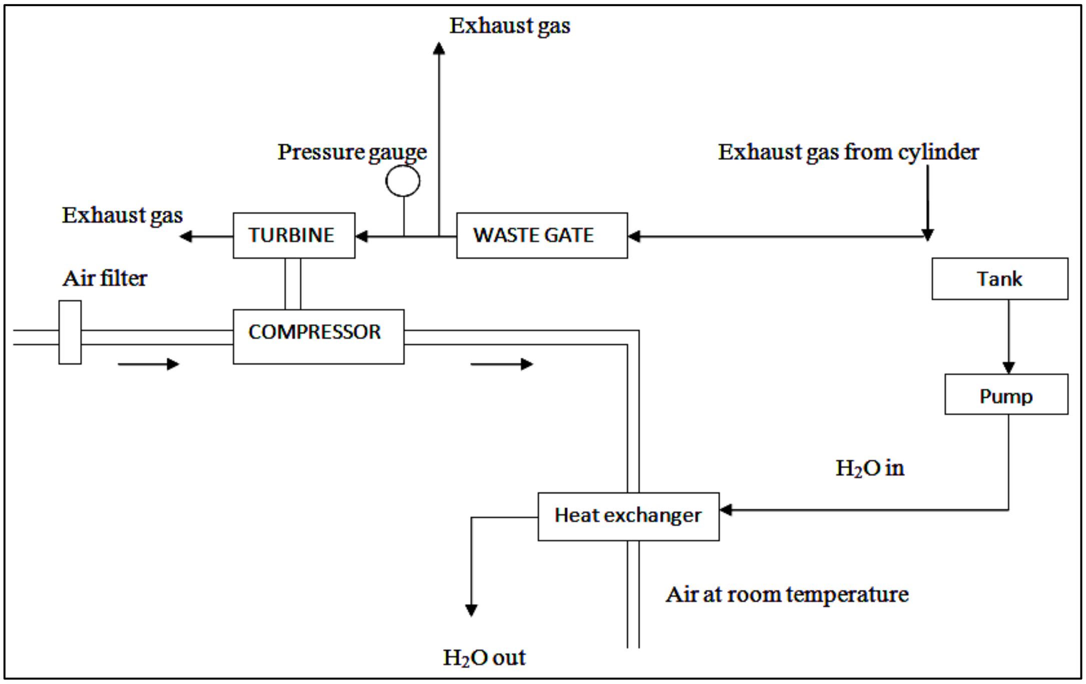


Fig. 4.6 Schematic Diagram of Turbocharger Setup for Engine

Depending upon the required output pressure the compressor, exhaust gas energy is used through waste gate. Excess exhaust gas will let into the exhaust line. Intake air pressure is measured in terms of pressure gauge. The boost pressure is maintained around 0.25 bar. The compressed air temperature is more than room temperature, so intercooler (heat exchanger) is used to bring down the temperature of the compressed air.

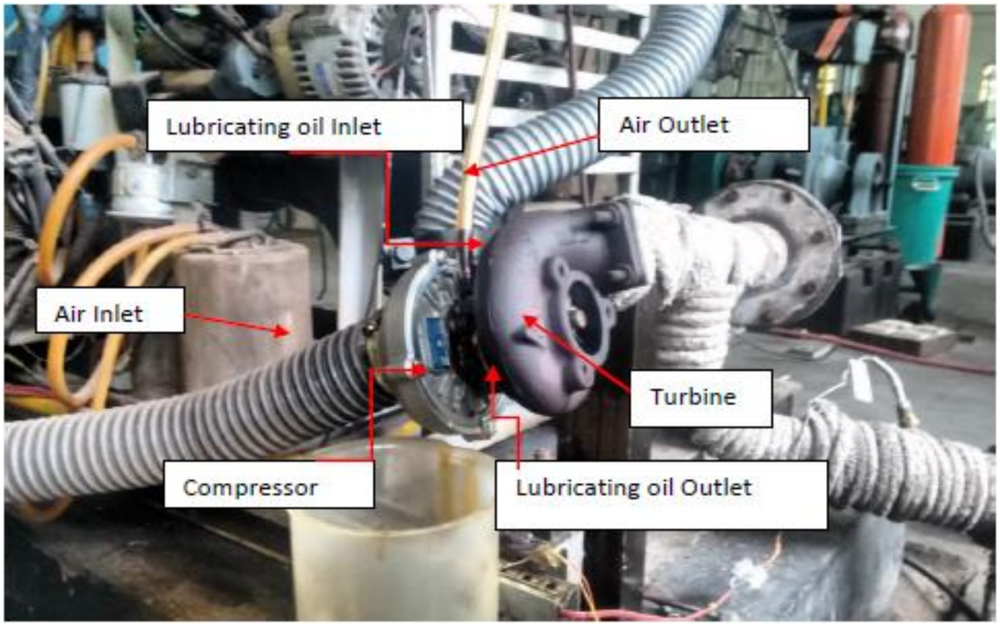


Fig. 4.7 Turbocharger Setup

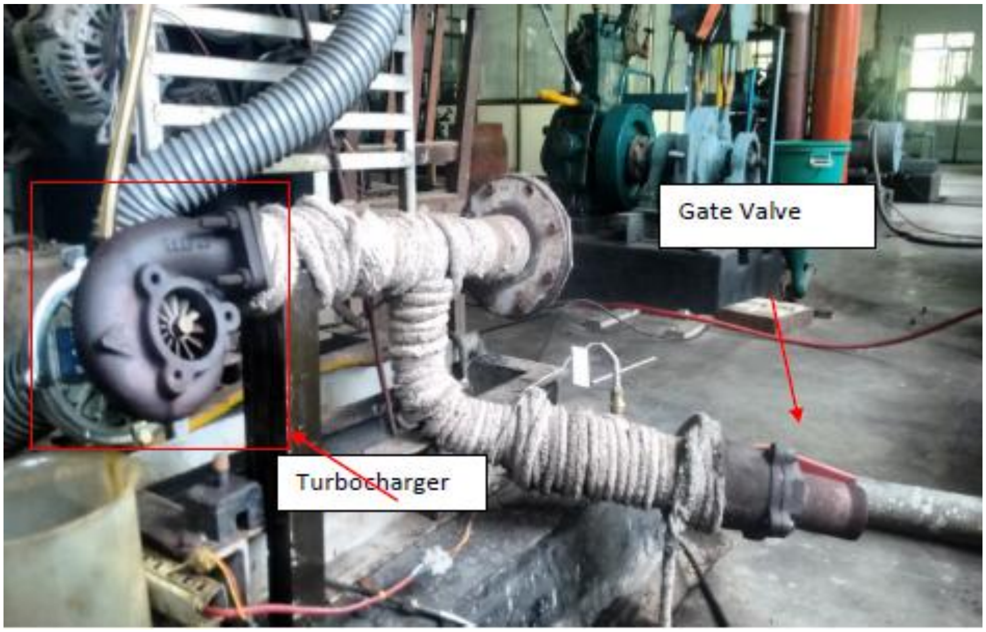


Fig. 4.8 Turbocharger Setup with Gate Valve

As cooling of intake air will make air denser and hence more oxygen available for combustion which increases volumetric efficiency. The pressure ratio is maintained as 1.25. The pressure difference between the intake manifold and atmosphere is measured in terms of mercury U-tube manometer. Through waste gate, the intake pressure is controlled. Figure 4.7 & 4.8 shows the turbocharger setup in an engine.

4.2.3 Vaporized Water-Methanol Injection System Development

Hydrogen combustion in SI engine results in higher emissions of harmful NO_x even though the emissions of CO and HC are reduced substantially. Use of after treatment devices may reduce the NO_x emissions. In this section a method of reduction of NO_x in the engine itself is described. Among several in cylinder NO_x reduction techniques, the method of vaporized water-methanol injection with intake air is used by developing a device to supply vaporized water-methanol at various proportions. The vaporized water-methanol is produced with the help of heat of engine exhaust gases, which is otherwise lost to the surroundings.

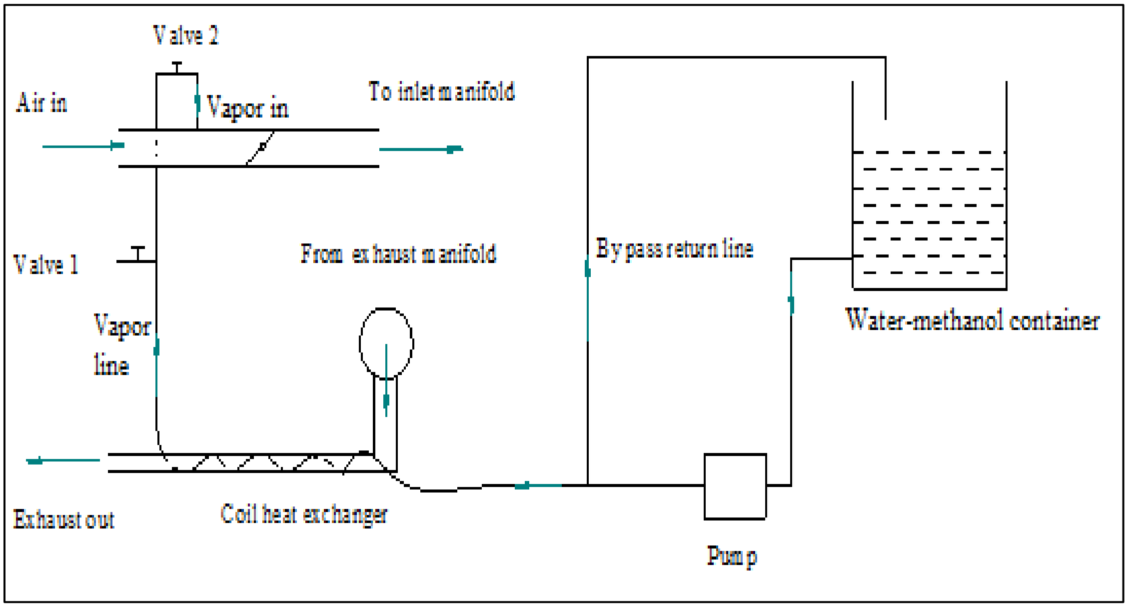


Fig. 4.9 Block Diagram of Vaporized Water-Methanol Injection System

Figure 4.9 shows the block diagram of water-methanol injection system. De-ionized water along with methanol in the proportion of 60:40 is stored in a container and a low power pump is used to pass the water through a copper tube of 1/4th inch size. The copper tube is coiled around the engine exhaust pipe such that the water-methanol mixture and exhaust gases pass in a counter flow way so as to maximize the heat transfer between the two fluids. Since the flow rate of the available pump was higher than the required water flow rate (max. 3 liters per hour), a bypass system is provided after pump so that the excess water returns back to the sump.

Fig. 4.10 Photographs of Vaporized Water-Methanol Injection System

Fig. 4.11 Heat Exchanger for Production of Vapor of Water-Methanol.

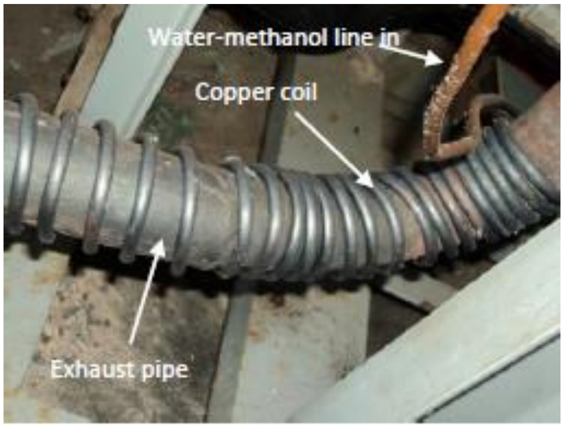


Fig. 4.12 Copper Coils to the Exhaust Pipe for the Production of Vaporized Water-Methanol.

Sufficient length of copper coiling is provided so that the water-methanol will be completely vaporized and vapor is injected in to the engine manifold. The amount of vaporized water-methanol to be inducted is decided based on the hydrogen fuel flow rate at each operating condition. Before admitting vaporized water-methanol in to the engine manifold at each operating condition with a specific vaporized water-methanol flow rate, it is ensured that liquid form is completely converted into vapor form.

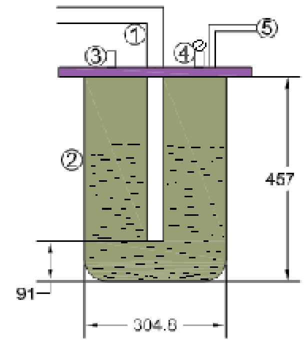
Vaporized water-methanol to hydrogen fuel mass ratios of 0.1 is used for operating condition. A provision is made in the inlet manifold just before the throttle valve to inject vapor continuously to confirm good mixing of vaporized water-methanol with the intake air. The water-methanol flow rate is measured and controlled manually by a rotameter of range 0.1 LPH (litres per hour) to 10 LPH with a least count of 0.1 LPH. Figures 4.10, 4.11 and 4.12 detail the entire vaporized water methanol injection system with copper coil and intake manifold.

4.3 SAFETY MEASURES

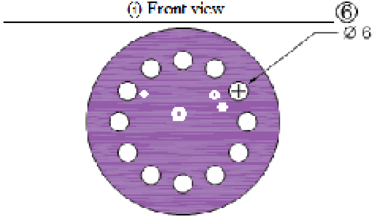
Gaseous fuels are always difficult to handle compared to liquid fuels and thus they are considered to be more dangerous than liquid fuels. So care should be exercised while handling the gaseous fuels. Hydrogen has very low ignition energy, low density and high diffusion coefficient so the contingencies of leakage, auto ignition and thus explosion are rather more here. Also flames may propagate back into the pipeline which may trigger the fuel in the gas cylinder to explode (back fire). To avoid any such misfortune to occur, following safety measures have been taken while conducting the experiments:

4.3.1 Flame Trap

Flame trap is a safety device which is intended to prevent fire or explosion in case of back fire. This is connected in series of fuel supply line. With a flame trap, if flames or sparks from the system start to make their way back into fuel supply area, such as the supply line, they hit the flame trap first. Flame trap extinguishes the fire, ensuring that it does not come into contact with the raw fuel supply. Flame trap is made up of stainless steel. As shown in Figure 4.13, flame trap mainly consists of inlet, outlet, pressure indicator and safety valve. The flame trap assembled with control valve and flow meter, outlet of which is connected to the engine manifold.



(i) Front view



(ii) Top view

Figure 4.13 Flame Trap

1.Hydrogen Gas In

2.Flame Trap Cylinder

3. Safety Valve

4. Pressure Indicator

5. Hydrogen Gas Out

6.Bolts for Assembly

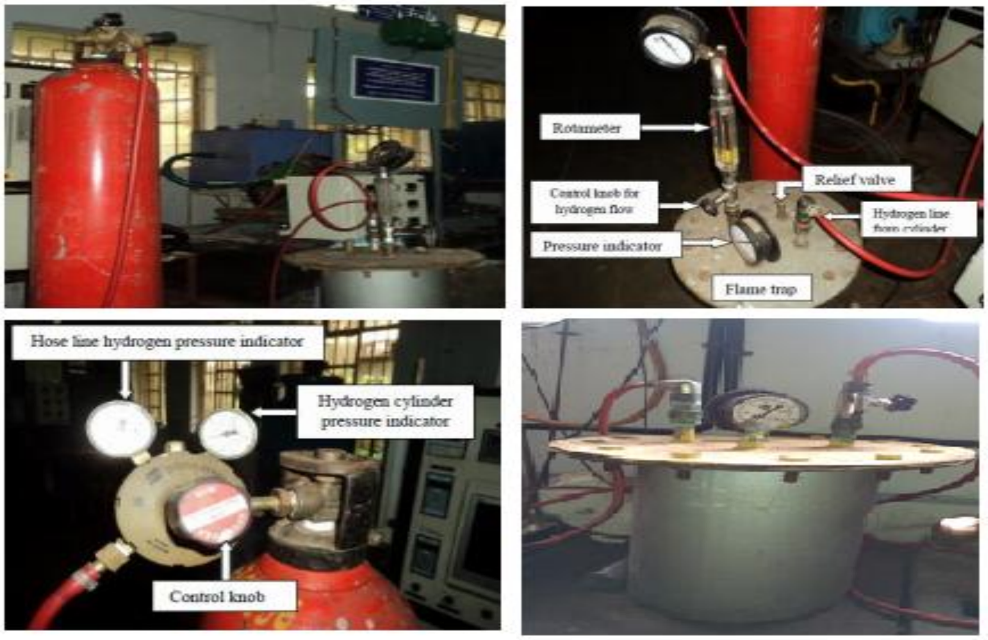


Figure 4.14 Photographic View of the Fuel Injection System with Flame Trap and Hydrogen Cylinder

The hose from the hydrogen cylinder is connected to the inlet of the flame trap. Flame trap is approximately 3/4 filled with water and the outlet hose is placed approximately 100 mm above the base level. The pressure indicator ranging 1 to 10 bars and safety valve are fitted to the top of the flame trap. The stem of the pressure indicator is attached by means of an adopter. In case of fire, the hydrogen flows backwards and quenches in water. If pressure exceeds 10 bars, then the safety valve will release the hydrogen out without any danger. The photographic view of fuel injection system with flame trap and hydrogen cylinder is shown in Figure 4.14.

4.3.2 Flame Arrestor

Figure 4.15 shows the photograph of flame arrestor. Flame arrestor is the equipment which quenches flames that are propagating back to the supply line of cylinder. These are connected in series in the fuel supply line. Flame arrestors are passive device with no moving parts. They prevent the propagation of flame from the exposed side of the unit to the protected side by the use of wound crimped metal ribbon type flame cell element called as Honeycomb.

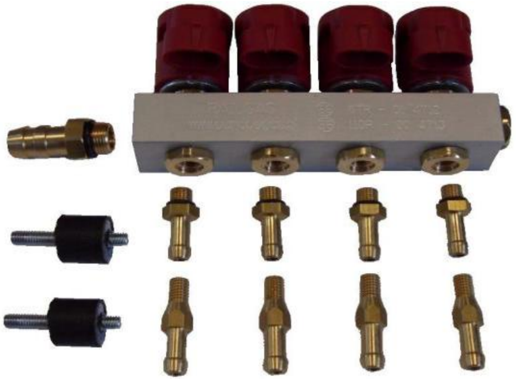


Fig.4.15 Gas Injectors

Fig. 4.16 Flame Arrestor

This assembly produces a matrix of uniform openings that are carefully built to quench the flame by absorbing the heat of the flame. This provides a quenching barrier on the ignited vapor mixture. Under usual operating conditions the flame arrestor permits a relatively free flow of gas or vapor through the piping system. If the mixture is ignited and flame begins to travel back through the piping, the arrestor will prohibit the flame from moving back to the gas source. Figures 4.15 and 4.16 respectively show the gas injectors and the flame arrestor used in the system.

4.3.3 Measures Taken to Avoid Leakage

The leakage in hydrogen pipeline can happen as it is too lighter fuel. This may happen in two ways, one such chance is through the injector connected to the cylinder and other one is through any leaks in the pipeline. The safety measure to avoid this leakage is done by conducting the periodic leak checking of both the injector and the pipelines. The new injector may not have any leakage problems but as the time progress due wear and tear of the parts, the injectors may be subjected to some leakage problems. These leakages may be of very small quantity but are sufficient enough to get auto ignited.

Use of ordinary pipes increases the chances of leakage of gases to the atmosphere which may enhance the chances for hydrogen to mix with the air and cause fire. This may even led to hazardous explosions. Hence seamless copper pipes are used to avoid the chances of leakage of gas through the pipes to the atmosphere.

4.4 MEASUREMENT SYSTEM

The experimental set up is fully instrumented to measure the different parameters during the experiments on the engine. A detailed description of the different measurement systems used for evaluating the engine performance and emission is given in this section.

4.4.1 Cylinder Pressure Measurement

A piezo-electric pressure transducer for cylinder pressure recording is used which uses number of consecutive cycles for combustion variability studies. A PCB Piziotronics Inc, built piezoelectric pressure transducer is installed in the engine cylinder head of 1st cylinder. The sensor is flush mounted and it measures the pressure trace in the cylinder with 1degree crank-angle resolution. The pressure crank-angle data is acquired on a digital computer operating on windows 8.1 system through National Instrument (NI) based data logger NI USB 3210. ‘IC Engine Soft’ software is installed to get required data from different sensors through NI USB 3210 data logger. The software provided is capable of data logging a maximum of 100 consecutive combustion cycles. The sensor body is continuously circulated with cooling water so as to maintain the sensor at a constant temperature. A rotary encoder is fixed on the engine output shaft for receiving crank angle signal. Both signals are concurrently scanned by an engine indicator (electronic unit) and sent to computer. The software in the computer draws pressure crank-angle and pressure volume plots and further computes performance and other combustion properties for the engine.

4.4.2 Measurement of Air Consumption:

In IC engines, for satisfactory measurement of air consumption an air box of suitable volume is fitted with orifice. The air box is used for damping out the pulsations as the air flow is pulsating. The differential pressure across the orifice is measured by manometer and pressure transmitter. The flow across the orifice is connected via a parallel section to the U- tube manometer and the air intake differential pressure (DP) unit. The DP unit senses the pressure difference across the orifice, which is sent to the transducer. The transducer gives a proportional output as DC voltage (analog signal), which is converted into digital signal through NI data acquisition system which will be in turn processed by the computer software program to get the air flow rate in mm of water column and kg/h.

4.4.3 Measurement of Fuel Consumption:

The fuel consumed by the engine is measured by determining the volume flow rate of the fuel in a given time interval or specific time taken for fixed amount of fuel and multiplying it by the density of the fuel. A glass burette having graduations in milliliters is used for volume flow measurement. Time taken by the engine to consume this volume is measured by stopwatch manually. Alternatively a differential pressure transmitter working on hydrostatic head principles is also used for fuel consumption measurement. The fuel tank is linked to a burette for physical fuel flow measurement and to a fuel flow DP transmitter unit. The fuel line is connected to a two-way fuel cock which can be kept either in tank position or measuring position. When kept in measuring position, the fuel to the engine goes from the burette. The pressure head difference is sensed by the fuel DP transmitter. It gives proportional analog signal, which through the NI USB 3210 hardware goes to the ‘IC Engine soft’ which calculates the fuel flow rate in kg/h. It is essential to enter the values of density and the lower calorific value of each test fuel to the software ‘IC Engine soft’ before operating with that test fuel.

To minimize the error in measurement while operating the system under varying pressures, flow rate of hydrogen is measured on mass basis. An electronic weighing balance with a maximum capacity of 100 kg and least count of ten gram (10g) has been used which serves the purpose of measuring the flow rate of gas. A hydrogen cylinder with a maximum capacity of 65 kg is placed over the weighing balance. Time duration for consumption of specified amount of hydrogen is measured using stop watch.

4.4.4 Speed Measurement

Engine speed is sensed and shown by an inductive pickup sensor in conjunction with a digital rpm indicator, which is a part of the eddy-current dynamometer controlling unit. The dynamometer shaft spinning close to inductive pickup rotary encoder directs voltage pulse whose frequency is converted to rpm and displayed by digital indicator in the control panel, which is calibrated to indicate the speed directly in number of revolution per minute (rpm). The ECU is linked to crank position sensor which also notices the speed of the engine.

4.4.5 Load Measurements

The load is measured by an eddy current dynamometer. It consists of a stator with a number of electromagnets fitted on it and a rotor disc attached to the output shaft of the engine. Eddy currents are produced in the stator when rotor rotates inside it due to the magnetic flux set up by the passage of field current in the electromagnets. These eddy currents oppose the rotor motion, thus loading the engine. These eddy currents are dissipated in producing heat so that this type of dynamometer needs cooling arrangement. Regulating the current in electromagnets controls the load. A moment arm measures the torque with the help of a strain gauge kind load cell mounted underneath the dynamometer arm. The analog load cell signal through the ADC card is fed to the computer to give load in kg. The dynamometer is loaded by the loading unit located in the control panel.

4.4.6 Temperature Measurements

Six Chromel -Alumel thermocouples of K type are placed in different position to measure the following temperature: Jacket water inlet temperature (T_1), Jacket water outlet temperature (T_2), calorimeter inlet water temperature (T_3), calorimeter outlet water temperature (T_4), exhaust gas temperature before calorimeter (T_5) and exhaust gas temperature after calorimeter (T_6). All thermocouples sense the temperature of respective location and give the digital signal to control panel and these are also interfaced to the computer through NI hardware.

4.4.7 Static Ignition Timing Measurements

The device used to measure the static ignition timing is ignition timing gun. This ignition timing illuminates the light when engine is running and keep the light on the flywheel which is having the scale for the measurement of ignition timing. The flywheel has the scale of 10 divisions with least count 2 deg. bTDC. To change the static ignition timing, the ignition distributor assembly is loosened and is rotated slightly in the direction of rotation of flywheel to retard the timing and in the direction opposite of rotation of flywheel to advance the timing.

4.4.8 Brake Power (BP) Measurement:

The brake power is measured by an eddy current dynamometer: It consists of a stator with a number of electromagnets fitted on it and a rotor disc attached to the output shaft of the engine. Eddy currents are produced in the stator when rotor rotates inside it due to the magnetic flux set up by the passage of field current in the electromagnets. These eddy currents oppose the rotor motion, thus loading the engine. These eddy currents are dissipated in producing heat so that this type of dynamometer needs cooling arrangement. Regulating the current in electromagnets controls the load. A moment arm measures the torque with the help of a strain gauge type load cell. The analog load cell signal through

NI data acquisition system is fed to the computer and also displayed on the display. Basically three types of loading i.e., constant speed, variable speed and a combination of these are possible. Then brake power is computed having the data of load/torque and speed. The dynamometer is loaded by its loading unit mounted in the control panel.

4.4.9 Indicated Power (IP) Measurement:

A dynamic pressure sensor (piezo sensor) is fitted in the cylinder head to sense combustion pressure. A rotary encoder is fitted on the engine shaft for crank angle signal. Both signals are concurrently scanned by an engine indicator (electronic unit) and linked to computer. The software in the computer draws pressure crank-angle and pressure volume plots and computes indicated power of the engine. By knowing the IP, BP and fuel consumption thermal efficiency can be found out.

4.4.10 Exhaust Emission Measurements

An AVL Digas 444 exhaust gas analyzer is used to measure the exhaust gas emissions of CO (% volume), CO_2 (% volume), HC (ppm), oxygen (O_2, % volume), NO_X (ppm) and relative air-fuel ratio (λ). The five gas analyzer is calibrated by the supplier AVL prior to the use and necessary precautions are taken to see the proper working of it by regular checkup. Leakage test, zero adjustments, cleanliness of filters and probes are done regularly before starting the experiments. The engine has no after treatment devices and thus emission readings are taken are raw emissions, without being treated. The specifications of the exhaust gas analyzer are given as Appendix IV.

4.4.11Calibration of Instruments:

All instruments are calibrated prior to their use in the tests. The dynamometer, exhaust gas analyzer and pressure sensor are calibrated by the suppliers. The temperature sensors are calibrated with reference to standard thermometers. Rotameters are calibrated by manual measurement of the liquid flow through a known time.

4.5 RESEARCH METHODOLOGY

This section presents the methodology used to carryout comprehensive experiments in four strokes, four cylinder SI engine using neat hydrogen and gasoline.

4.5.1 Scheme of Engine Experimental Studies

The engine experimental study involves five distinct stages. The scheme of experiments is carefully planned in a manner to fulfill the objectives framed under present research. The first set of tests involves evaluation of base gasoline fuel for engine combustion, performance and emission characteristics at static ignition timing 5 bTDC. Based on the load values at wide open throttle condition (WOT), load is varied from 25% to 100% in step of 25% and speed is varied from 1500 to 3000 rpm in step of 300 rpm.

The second set of tests involved with neat hydrogen for above mentioned load, speed and static ignition conditions. The engine was initially started with the base fuel and allowed to stabilize. Neat hydrogen was allowed to enter the engine cylinder by cylinder instead once at a time as it would have created serious problem for the engine (sudden fall in speed and load). The engine was set to predetermined throttle and speed condition by allowing the neat hydrogen to enter all four cylinders by the way of altering the multiplier provided in the gas ECU software. For changing the fuel mode, faulty signal were given to gasoline injector so that it will switch off and switch ON the hydrogen injector, so that cylinder will work in hydrogen mode of operation. The recorded pressure-crank angle data for 100 consecutive cycles are used for calculating the combustion and performance parameters. Analysis of the obtained data is performed and results are plotted.

The third set of tests involved in studying the effect of spark timing variation on engine performance, combustion and emission characteristics with neat hydrogen operation. Two spark timings were used for tests (i.e., 8 bTDC and 2 bTDC; advancing and retarding the spark timing by 3 bTDC from static spark timing).To check the ignition timing, an “ignition timing gun” (timing light) is used. It is connected to the battery positive and negative terminals. Another probe of the timing gun is hooked to the cable connected to the spark plug of the first cylinder. The engine is started and kept at static condition for 2-3 minutes. Now the timing gun is used to illuminate the pulley connected to the engine flywheel and the static ignition timing can be read on a scale with the help of timing gun light.

The fourth set of tests involved with studying the effect of turbocharging for neat hydrogen for combustion, performance and emission evaluation at optimized ignition timing for full load (100%) and maximum speed condition. In this stage of experiment, a turbocharger is selected based on the exhaust mass energy, and fitted into the engine with necessary modification in the exhaust and intake manifold. In the last stage of engine testing, study of the effect of turbocharging and water-methanol injection for neat hydrogen is performed for optimized ignition timing for full load (100%) and maximum speed condition. Vapor of water-methanol mixture is produced from using waste heat from exhaust gases. Precisely measured water at rates of 10% by mass of hydrogen is converted in to vapor form and is injected in to the intake air stream.

While conducting the experiments due care is taken to check the repeatability of readings. At each test point the engine is allowed to reach steady state operating condition by allowing it to run for sufficient time. Average of at least three readings at each test point is taken to minimize the experimental error. For all testing conditions, brake specific energy consumption (BSEC) is maintained constant and the observations for 100 consecutive cycles were recorded at each crank angle and analyzed through “IC engine soft” to obtain profiles of cylinder pressure against crank angle, net heat release rate at mean value. Regulated exhaust emissions namely CO, HC and NO_x were recorded with the help of AVL digas 444 exhaust analyzer. Performance parameters are calculated by conventional way analytically.

4.6 COMBUSTION ANALYSIS

In-cylinder combustion pressure data is very useful information, which could be used to quantify the combustion behavior of the fuel inside the engine.

4.6.1 Heat Release Rate Analysis

Rate of heat release analysis shows the estimated rate of heat release during the combustion process. The results provide a quantified assessment of combustion rate and the means to diagnose combustion process (Catania et al. 2003). Heat release analysis is usually applied to compression ignition (C I) engines, though there is no reason why it cannot be used for spark ignition applications. Heat release analysis calculates how much heat would have been added to the cylinder contents, in order to produce the observed pressure variations.

4.7 ERROR AND UNCERTAINTY ANALYSIS

Error is related with various key experimental measurements and the calculations of performance parameters. Errors and uncertainties in the experiments can rise because of instrument choice, condition, standardization, environment, observation, reading and test planning. Uncertainty analysis is desirable to prove the accuracy of the experiments. The uncertainty in any measured parameter is estimated based on Gaussian distribution method with confidence limit of ±2σ (95.45% of measure data lie within the limits of ± 2σ of mean). Thus uncertainty of any measured parameter is given by:

$$W_i = \frac{2\,\sigma_i}{\ddot{x}} 100 \tag{4.1}$$

Experiments are conducted to obtain the mean ($\ddot{x}$) and standard deviation (σ_i) of any measured parameter (x_i) for a number of readings. This is done for speed, load, time for a specified amount of air and fuel flow etc. For the analysis, 20 sets of readings are taken at the same operating condition. The uncertainty values for speed, torque, air flow rate, fuel flow rate, exhaust gas temperature and emission of CO, HC, and NO_x are calculated using equation (4.1).

A scheme of estimating uncertainty in experimental results has been presented by Kline and McClintock (1953). This method is based on careful specifications of the uncertainties in the different primary experimental measurements. Suppose a set of measurements are made and the uncertainty in each measurement may be expressed with the same odds, then these measurements are used to calculate some desired results of the experiments. The uncertainty in the calculated result can be estimated on the basis of the uncertainties in the primary measurements.

If an estimated quantity R depends on 'n' independent measured parameters x_1, x_2, x_3, x_4…, x_n. Then R is given by

$$R = R\ (x_1, x_2, x_3, x_4 \ldots\ldots x_n) \qquad (4.2)$$

Let w_R be the uncertainty in the result and w_1, w_2…w_n be the uncertainties in the independent measured parameters. R is the computed result function of the independent measured parameters x_1, x_2, x_3….x_n as per the relation $x_1 \pm w_1$, $x_2 \pm w_2$,…. $x_n \pm w_n$. If the uncertainties in the independent variables are given with the same odds, then the uncertainty in the result having these odds is given as (Adnan et al. 2012):

$$W_R = \left(\left[\frac{\partial R}{\partial x1} w_1 \right]^2 + \left[\frac{\partial R}{\partial x2} w_2 \right]^2 + \ldots\ldots.. + \left[\frac{\partial R}{\partial xn}\ n \right]^2 \right)^{1/2} \qquad (4.3)$$

Using the equation (4.3) for a given operating condition, the uncertainties in the computed quantities such as mass flow rates of air and fuel, brake power, brake thermal efficiency are estimated. The estimated uncertainty values at a typical operating condition are given in the Table 4.1.

Table 4.1 Uncertainty of Various Parameters

Parameter	**Uncertainty (%)**	**Parameter**	**Uncertainty (%)**
Speed	± 0.25	HC Emission	± 5.50
Torque	± 0.32	CO Emission	± 3.77
Air Flow Rate	± 1.05	Brake Power	± 0.3
Fuel Flow Rate	± 0.81	Brake Thermal Efficiency	± 0.1
Exhaust Gas Temperature	± 0.50	Volumetric Efficiency	± 0.4
NO_x Emission	± 5.91		

CHAPTER 5

RESULTS AND DISCUSSION

This chapter provides the experimental results of investigations on engine performance, emission and combustion characteristics of a multi cylinder SI engine fueled with gasoline and neat hydrogen at various operating conditions. A four stroke, four cylinders multipoint fuel injection SI engine has been modified to work on hydrogen injection system. The exhaustive experiments has been done on the engine operating at four load condition, six engine speeds and three spark timings. Turbocharging and water-methanol injection method is further used for neat hydrogen operation for evaluating and comparing performance, combustion and emission characteristics at optimized condition.

This chapter is divided into five segments. The first segment deals with the investigation of neat hydrogen fuel on engine performance, combustion and emission features by different loads and speeds at static ignition timing of 5 bTDC. It also provides comparative study of neat hydrogen with base gasoline fuel for the same conditions. An engine performance, combustion and emission characteristic with different load and different speeds by two spark timings (retarded and advanced) for neat hydrogen have been discussed in the second segment including comparison with static ignition timing.

The third segment reports on the investigation of neat hydrogen fuel with turbocharging on the engine performance, combustion and emission characteristics at optimized condition of 8 bTDC for full load. It also includes comparison with previous work for the aforesaid conditions. The fourth segment deals with the investigation of engine characteristics with neat hydrogen fuel with turbocharging and water-methanol injection. The last segment provides the comparative study on engine combustion and emission characteristics at idle condition for 1500 rpm.

5.1 INVESTIGATION OF NEAT HYDROGEN FUEL FOR VARIOUS LOAD AND SPEED CONDITIONS AT STATIC IGNITION TIMING

This section provides the results of the experiments which have been conducted to investigate the effect of neat hydrogen to appraise performance, combustion and emission characteristics by various load and different speed conditions at static ignition timing of 5 bTDC. Experiments are carried out for 25 - 100% load in step of 25% and for speed range of 1500 - 3000 rpm in step of 300 rpm. Results are summarized as follows:

5.1.1 Combustion Characteristics

Combustion characteristics like pressure- crank angle, net heat release rate at various load and different speed conditions at static ignition timing are discussed in this section.

5.1.1.1 Pressure- Crank Angle (P-θ)

Figure 5.1 shows the variation of cylinder pressure with crank angle for gasoline and neat hydrogen operation by various loads (i.e., 25%, 50%, 75% and Full load) and by different engine speeds at 5bTDC condition. The graphs show the peak pressure and corresponding crank position at which maximum pressure reached by hydrogen and gasoline fuel. As shown in the graphs, cylinder pressure is distinctly raised with hydrogen fuel compared to gasoline operation for all speeds and loads. Maximum rise in pressure of 30.93, 31.7, 37.81 and 44.76 bar at 366, 369, 373 and 369 deg.CA is observed for 25, 50, 75% and full load respectively at an engine speed of 3000 rpm for hydrogen. This indicates that, combustion took place at relatively high temperature and pressure due to high adiabatic flame temperature and high flame speed of hydrogen which improves the combustion process with shorter combustion duration (Subramanian et al. 2007).

It also observed that peak pressure in hydrogen operation started occurring at around 6 degree crank angle after top dead center, which is earlier than that of gasoline engine operation. This was due to higher burning velocity of hydrogen, which shortens the combustion duration implying rise in rate of pressure during hydrogen engine operation. At 3000 rpm, the increase in peak pressure is 77.96, 21.13, 3.53 and 34.41% for 25, 50, 75% and full load hydrogen operation compared to respective gasoline operations. This increase in peak pressure will indicate that hydrogen has better combustion properties compared to that of gasoline.

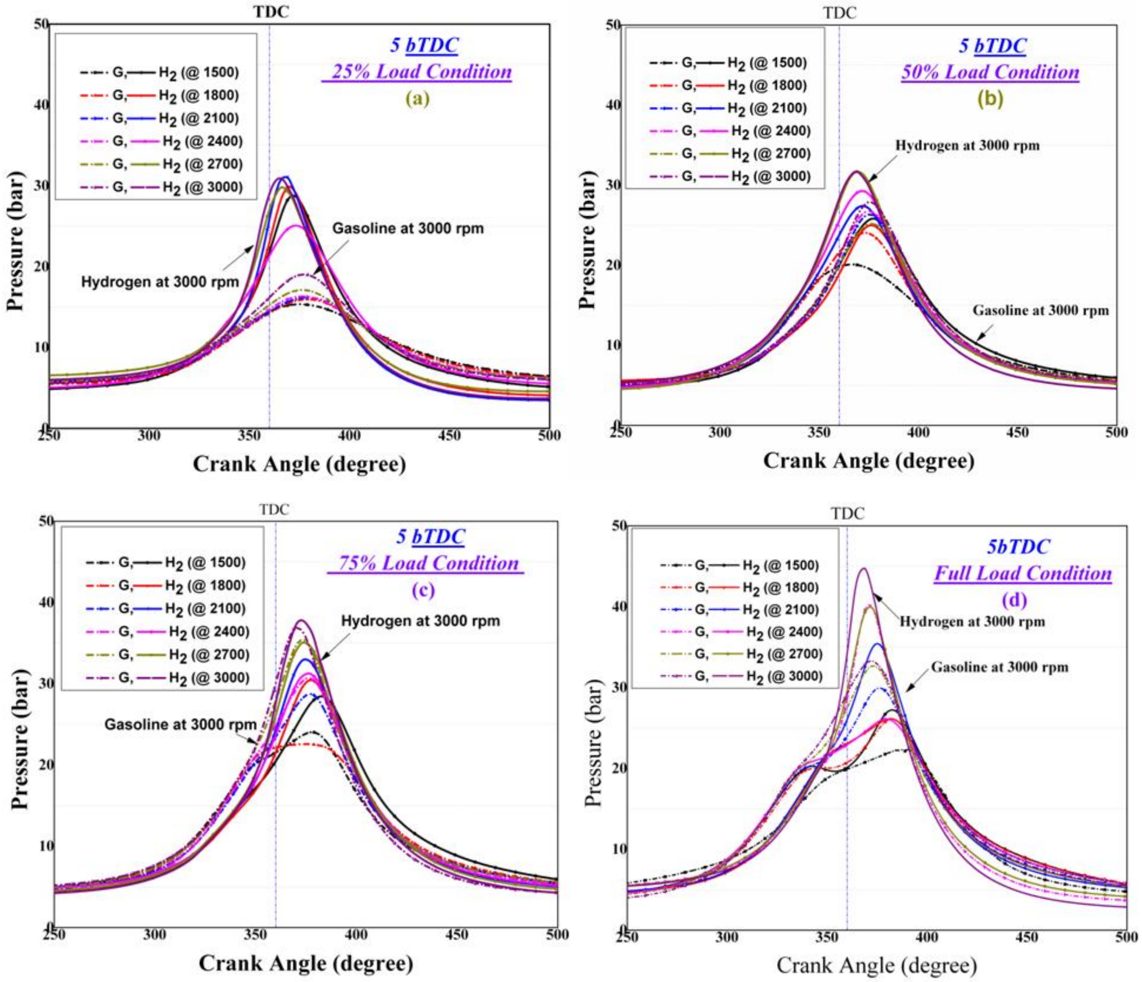


Fig.5.1 Pressure-Crank Diagram for Various Loads at 5 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.1.1.2 Net Heat Release Rate (NHR)

Net heat release rate is an effort to get information about the combustion process in an engine. Heat release rate is used both in engine performance and combustion which influence numerous operating conditions and same engine performances under the equal conditions. Moreover, physical and chemical properties of the fuel used in internal combustion engines are one of the main parameters which affect the heat release rate.

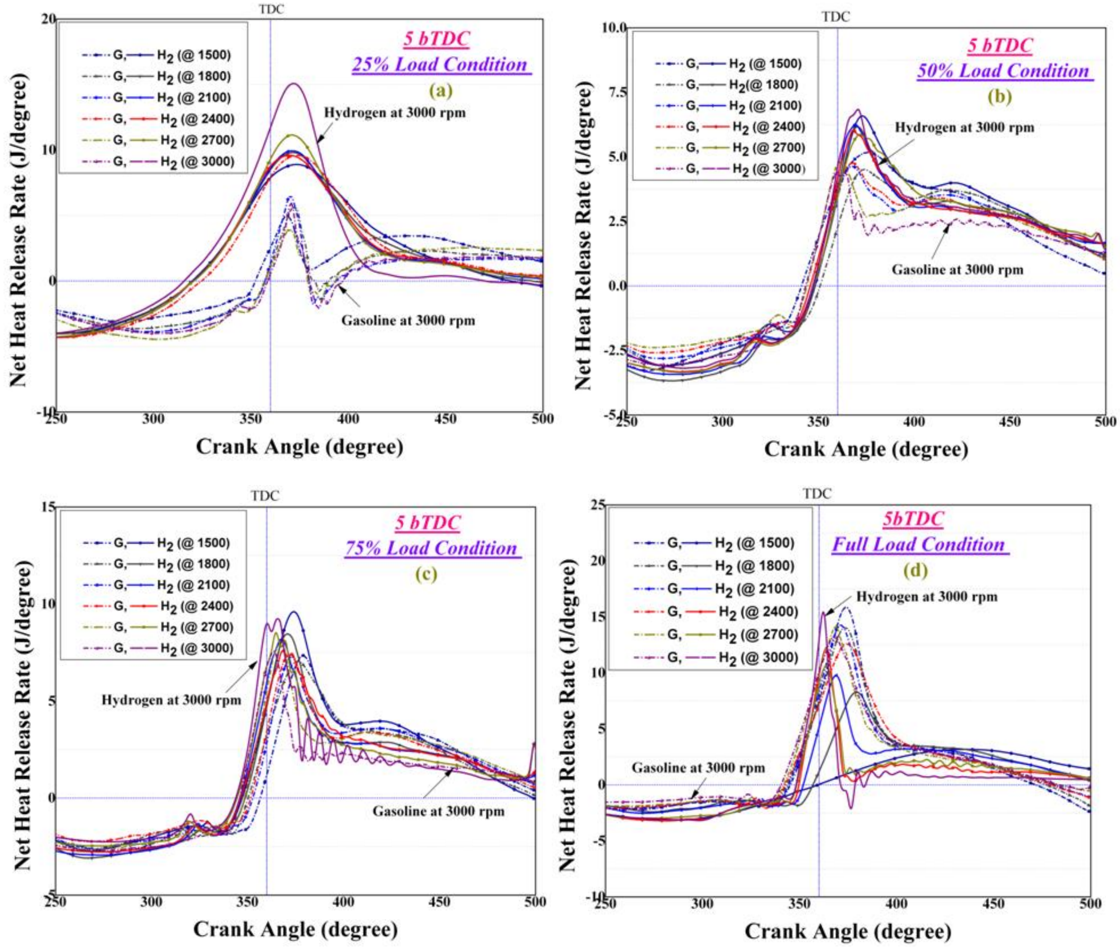


Fig.5.2 Net Heat Release Rate for Various Loads at 5 bTDC Condition.

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

Figure 5.2 shows the disparity of net heat release rate versus crank angle for gasoline and hydrogen operation by various loads (i.e., 25, 50, 75 and Full load) and by different engine speeds at 5 bTDC condition.

From the plots, it can be revealed that rate of heat release is increased with hydrogen for all loads and engine speeds. This is mainly owing to quicker flame propagation of the hydrogen and high rate of combustion. The maximum rate of heat release of 15.08, 6.86, 9.25 and 15.62 J/degree is observed for 25, 50, 75% and Full load condition at 3000 rpm compared to other engine speeds.

As seen in the figures, the heat release rate began to rise earlier than that of gasoline for hydrogen fuel at all load and speed conditions. This may be due to the fact that hydrogen will work in lean combustion and this contributes combustion chamber to contain oxygen which improves combustion and burning takes place close to TDC (Ji and Wang 2010). For all load conditions of hydrogen operation heat release rate took place nearer to TDC with the increasing speed.

5.1.2 Performance Characteristics

This section includes the engines performance results such as brake power, brake thermal efficiency and volumetric efficiency for gasoline and hydrogen operation by various load and speed conditions at static ignition timing.

5.1.2.1 Brake Power

Figure 5.3 depicts the variation of brake power with engine speed for gasoline and hydrogen operation by different loads (i.e., 25, 50, 75% and Full Load) and by six different engine speeds at static spark condition. As observed from graph brake power increases linearly with engine speeds for hydrogen and gasoline. But because of displacement of the air by low density hydrogen leading to improper combustion, brake power dropped for hydrogen operation in comparison with gasoline [Subramanian et al. 2007, Rahaman et al. 2009]. Maximum brake power of 5.08, 8.12, 12.16 and 17.13 kW is observed for neat hydrogen at 3000 rpm condition which in average 19-20% lower compared to gasoline.

As the speed increases, torque and mean effective pressure decreases more rapidly at low load condition. This may be endorsed to the reduced air flow in to the cylinder as the throttle area is reduced. The pumping component of total friction also increases as the engine is throttled thus lowering the mechanical efficiency. In addition the influx of fuel is less in part load conditions compared to full load, this results in the lower power generation during lower load condition for both the fuels (Heywood 1998).

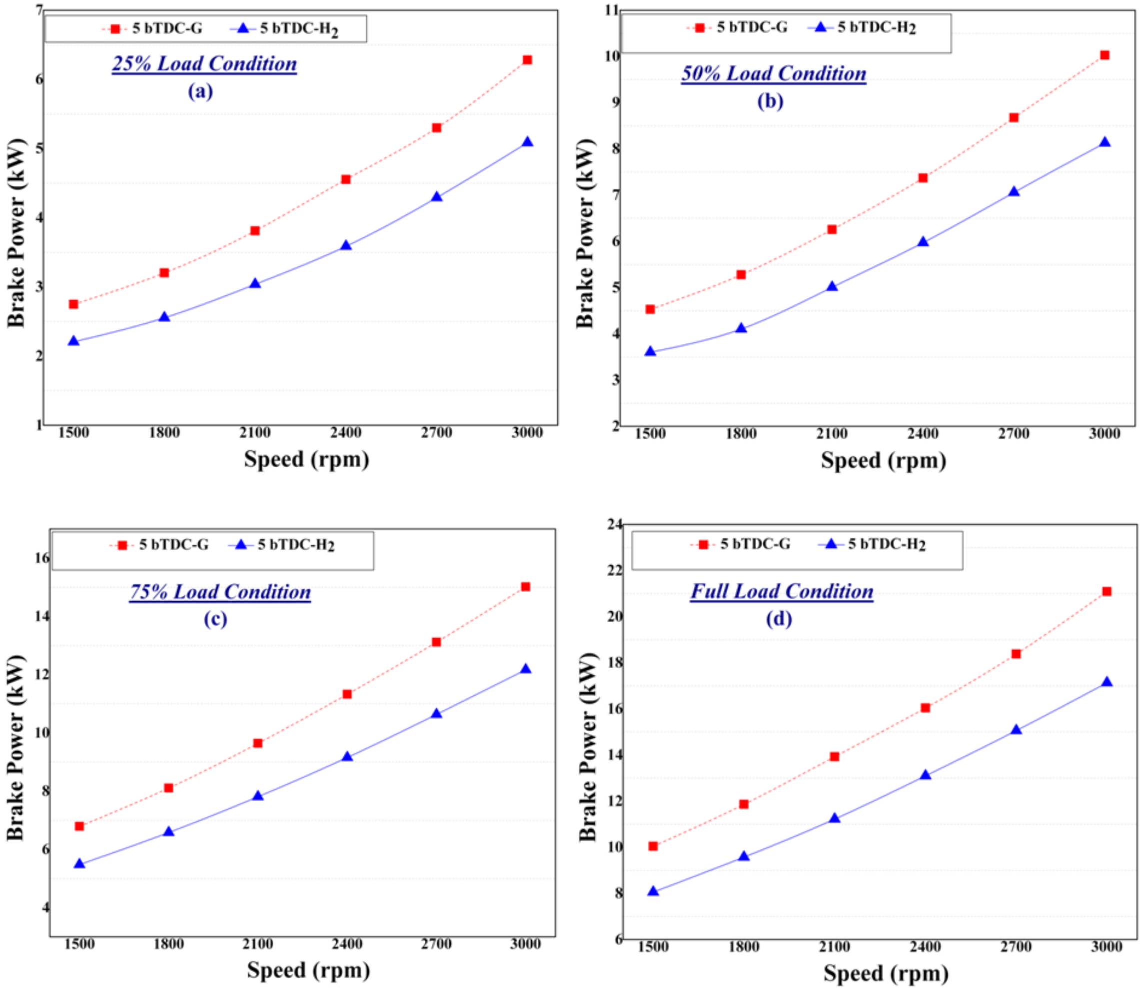


Fig.5.3 Brake Power for Various Loads at 5 bTDC Conditions

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.1.2.2 Brake Thermal Efficiency

Engine thermal efficiency is vital parameter on assessing the engine economic and overall performance. Efficiency can be upgraded by either optimizing the combustion system or fuel properties. Engine brake thermal efficiency counter to various engine speeds for gasoline and hydrogen operation at different loads (i.e., 25, 50, 75% and Full load) by six different engine speeds and at static spark condition is shown in Figure 5.4.The characteristic of these curves displays that brake thermal efficiency is higher for hydrogen than gasoline at all engine operating conditions.

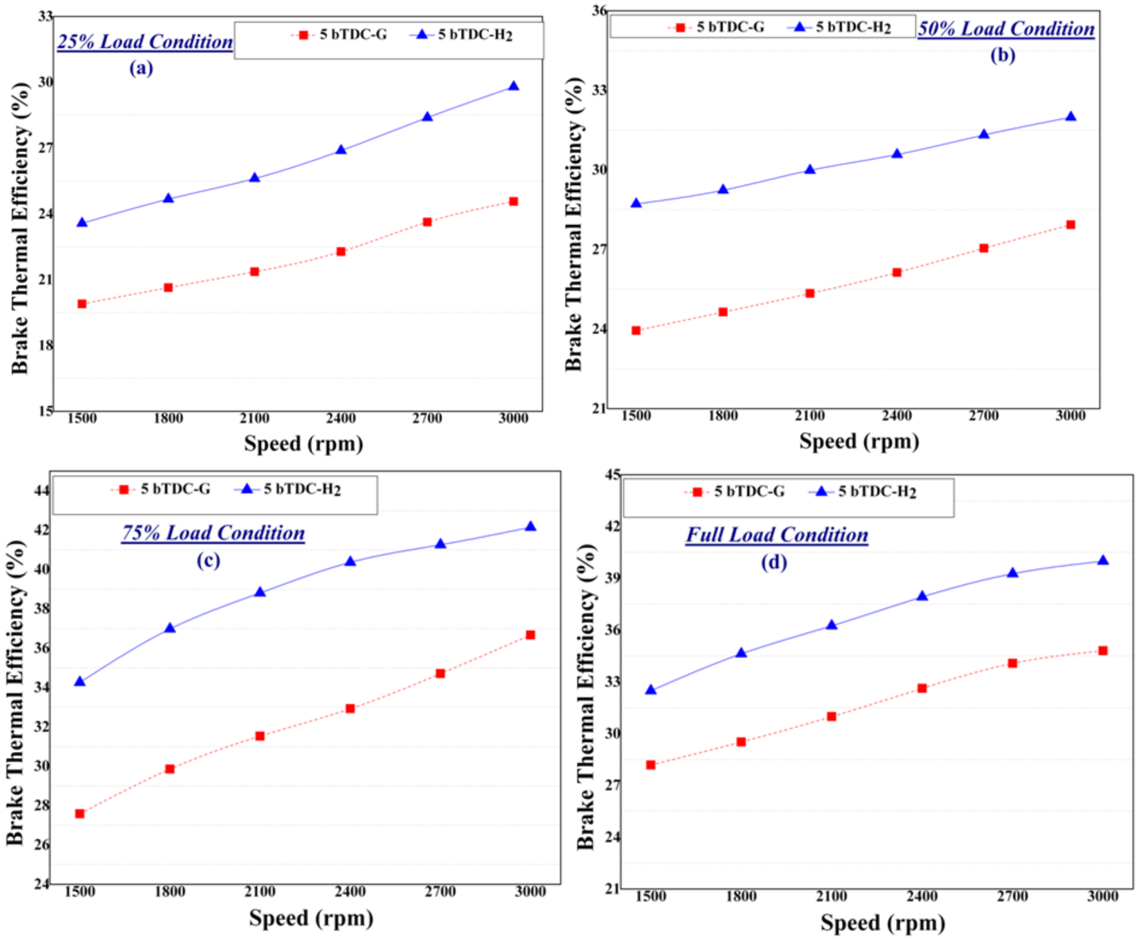


Fig.5.4 Brake Thermal Efficiency for Various Load at 5 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

As it is observed from figure 5.4, brake thermal efficiencies of the hydrogen are higher than the gasoline operation at all engine speeds and loads at static ignition. Peak brake thermal efficiency under the test conditions revealed 29,78%, 31.98%, 42.14% and 39.99% at 25, 50, 75%and full load conditions which is 21.25%, 14.5%, 14.95% and 14.91% higher as compared to gasoline operation.

Since the flame speed of hydrogen is five times larger and flammability range is much wider than the gasoline, it can achieve shorter burning length and more complete burning. Therefore, hydrogen leads to higher degree of constant volume combustion, meaning that the engine operates much closer to the ideal cycle and gains a higher brake thermal efficiency than gasoline at all the operating engine speeds (Ma et al. 2010).

5.1.2.3 Volumetric Efficiency:

Volumetric efficiency is the ratio of the actual mass of air in the combustion chamber to the mass of air that the displacement volume could hold if the air is at ambient condition. The quantity of air taken inside the cylinder is dependent on this efficiency and hence puts a limit on the amount of fuel which can be efficiently burned.

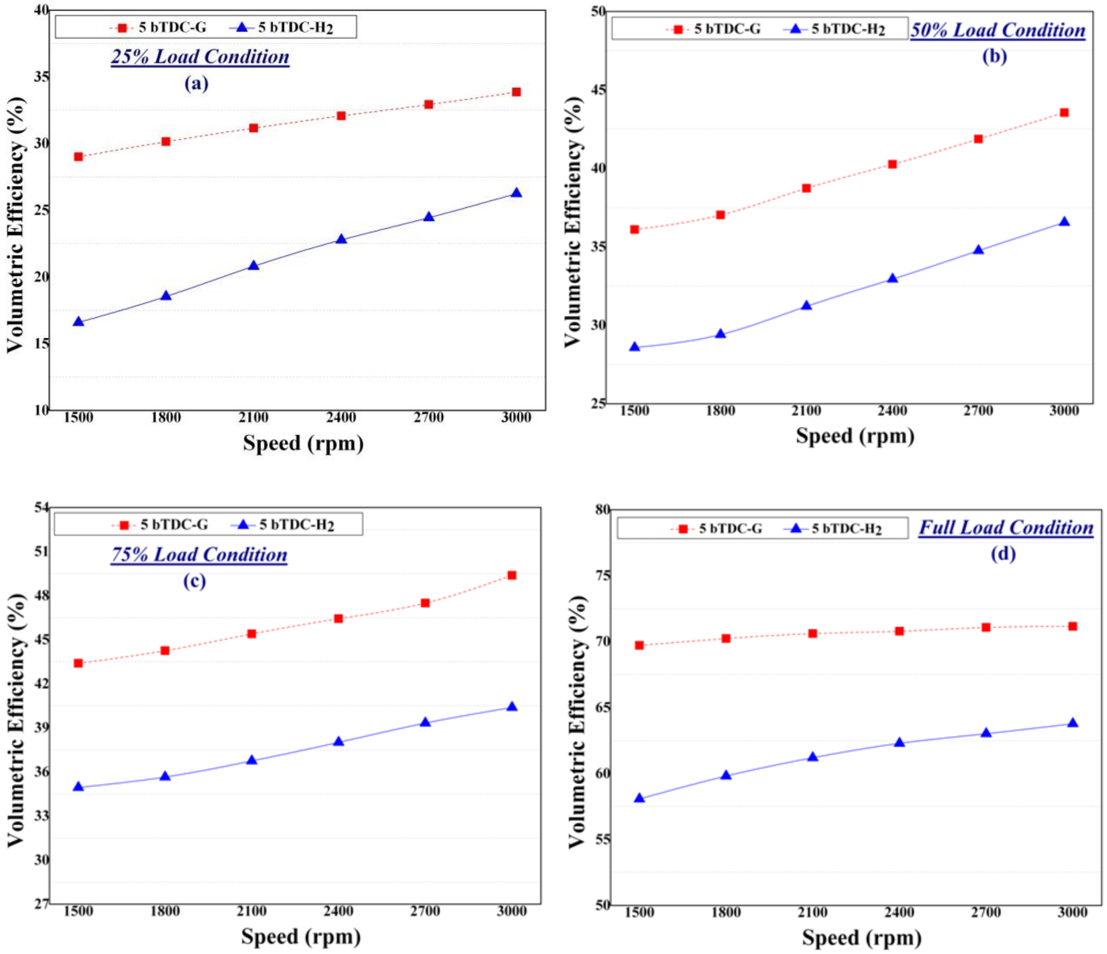


Fig.5.5 Volumetric Efficiency for Various Loads at 5 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

Figure 5.5 indicates the variation of volumetric efficiency with speed for hydrogen and gasoline operation by four loads (i.e., 25, 50, 75% and Full load) and six different engine speeds at static spark condition. In general as speed increases, there is increase in volumetric efficiency due to reduction in pumping losses and more air is drawn into the cylinder (Das 2002).

It is observed that volumetric efficiency for the hydrogen drops due to density difference between air and hydrogen. Maximum volumetric efficiency observed for hydrogen is 26.26%, 36.55%, 40.39% and 47.07% for 25, 50, 75% and full load conditions at 3000 rpm which is 33.08%, 42.71%, 48.56% and 49.07% lower compared to gasoline operation. As the load increases the volumetric efficiency increases for both the fuels in all speed conditions.

Volumetric efficiency is affected by the fuel being burned in the engine. Liquid fuel takes up very little space in the intake port and combustion chamber, but as hydrogen is vapor can take considerably more space, leaving less volume for the air being pumped into the cylinder. This causes less amount of mixture density at the inlet of the engine in turn reduction in volumetric efficiency (Rahaman et al. 2009).

5.1.3 Emission Characteristics:

This section provides the emission results for hydrogen and gasoline by various load and speed conditions, at static spark timing. Emission results include carbon monoxide (CO), hydrocarbons (HC) and oxides of Nitrogen (NO_x). Detailed exhaust emission plots is shown in Figures 5.6 to 5.8 which compares toxic emissions of hydrogen with gasoline fuel at above specified conditions.

5.1.3.1 Carbon Monoxide (CO)

Figure 5.6 shows the CO emissions for hydrogen and gasoline by various load and speeds at static spark timing. Hydrogen is non-carbon content fuel and have higher flame propagation speed which enhances combustion, therefore it can be inferred that CO emission is far less for hydrogen compared to gasoline at all load conditions. CO emissions found to be greater for hydrogen at 25% load condition compared to other load conditions due to more pumping losses and incomplete combustion.

Hydrogen also helps the formation of O and OH radicals which benefit for the combustion completeness (Wang et al 2014). Least value of 0.01 at 1800 rpm, 0.01 at 2400 rpm, 0.01 at 1500 & 3000 rpm and 0.24 at 1500 rpm is observed at 25, 50, 75% and at full load conditions.

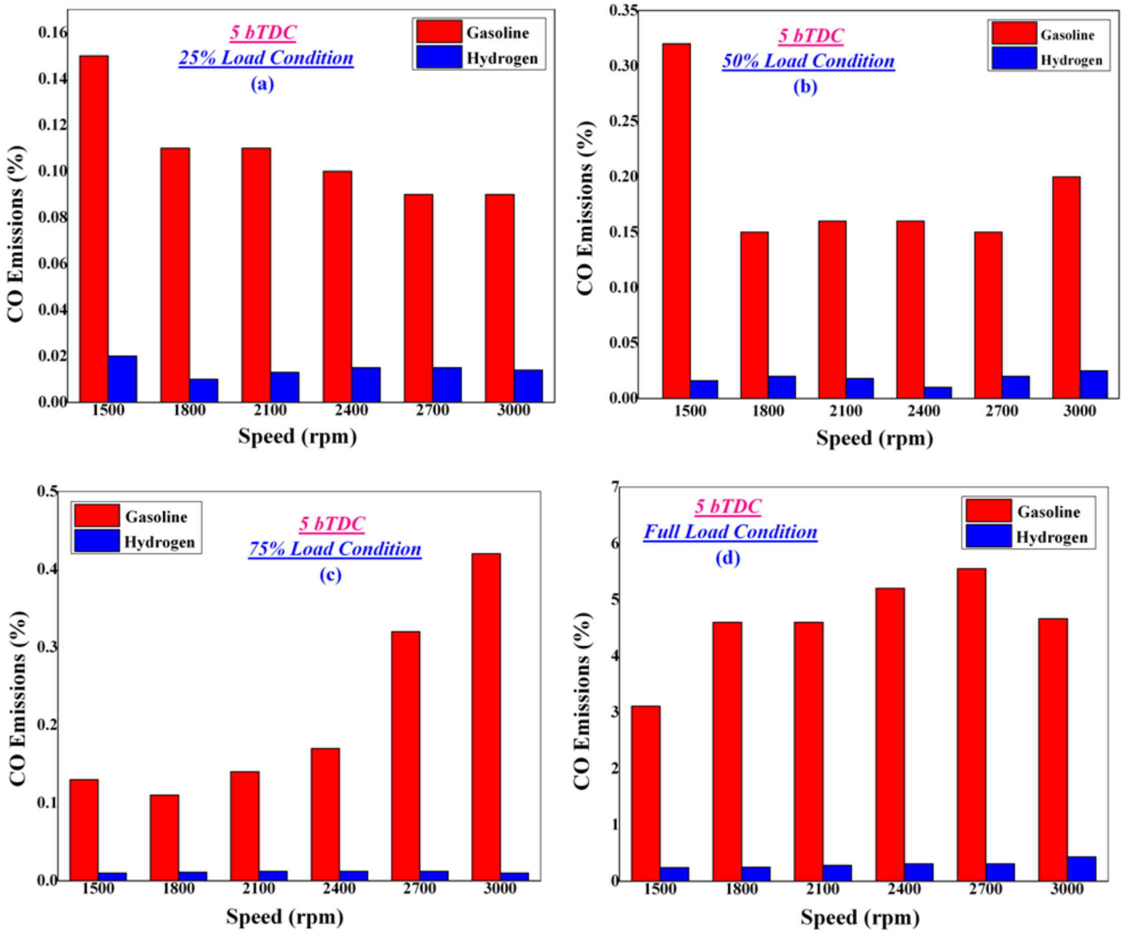


Fig.5.6 Carbon Monoxide Emission for Various Loads at 5 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.1.3.2 Hydrocarbon (HC)

Figure 5.7 shows the Hydrocarbon (HC) emissions for hydrogen and gasoline by various loads and different speeds at static spark timing. Hydrocarbon emissions are results of traces of oil present or trapping of unburned fuel air mixture within the cylinder. Figure 5.7 shows that HC emissions stood low for hydrogen compared to gasoline because hydrogen accelerates the formation rate of OH radical and since gasoline works in richer region.

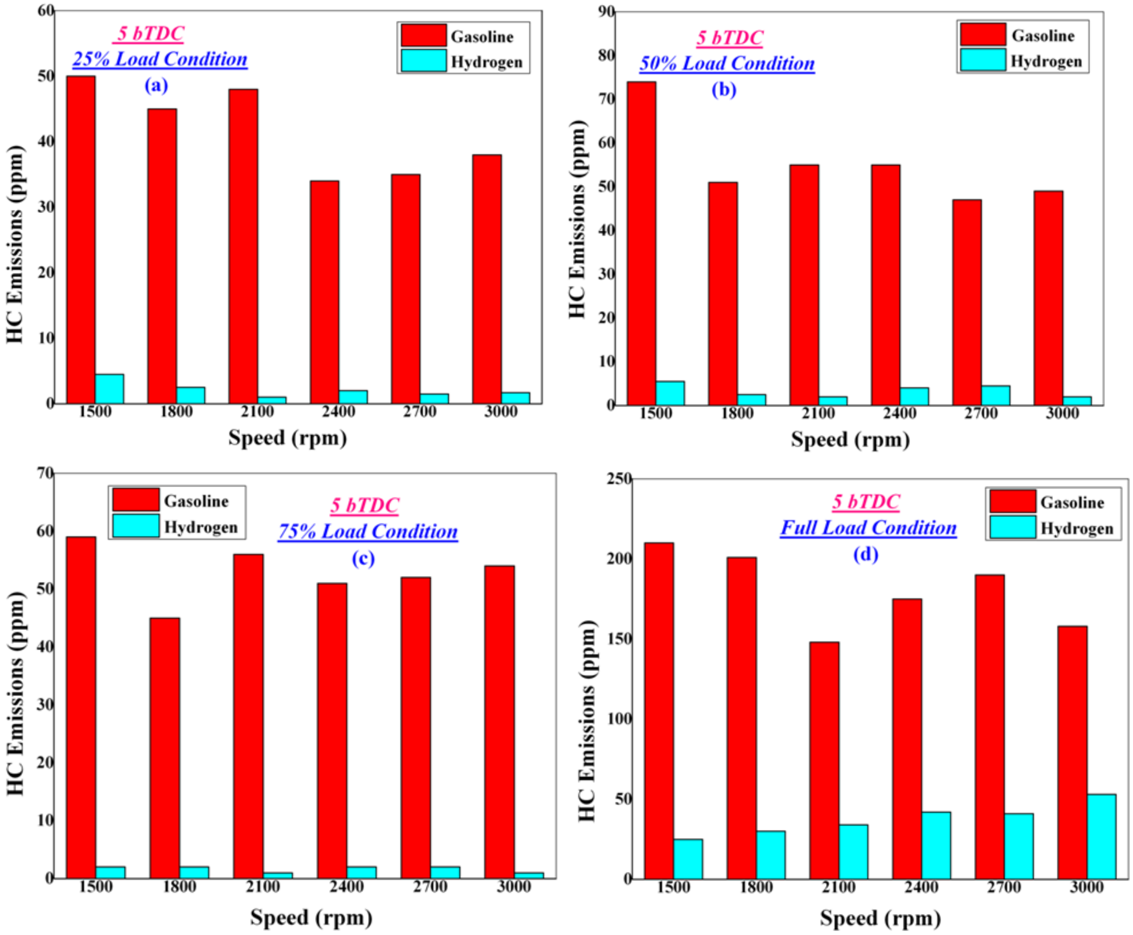


Fig.5.7 Hydrocarbon (HC) Emission for Various Loads at 5 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.1.3.3 Oxides of Nitrogen (NO_x)

Figure 5.8 shows the oxides of nitrogen **(**NO_x) emissions for hydrogen and gasoline by various loads, different speeds and at static spark timing. One of the most important engine variables that effect NO_x emission is the combustion temperature. Due to accurate mixing of gaseous fuels with air grounds an increase in the burning rate of the fuel and thus results in complete combustion thence the cylinder pressures and combustion temperatures increases which make NO_x to increase (Wang et al. 2014).

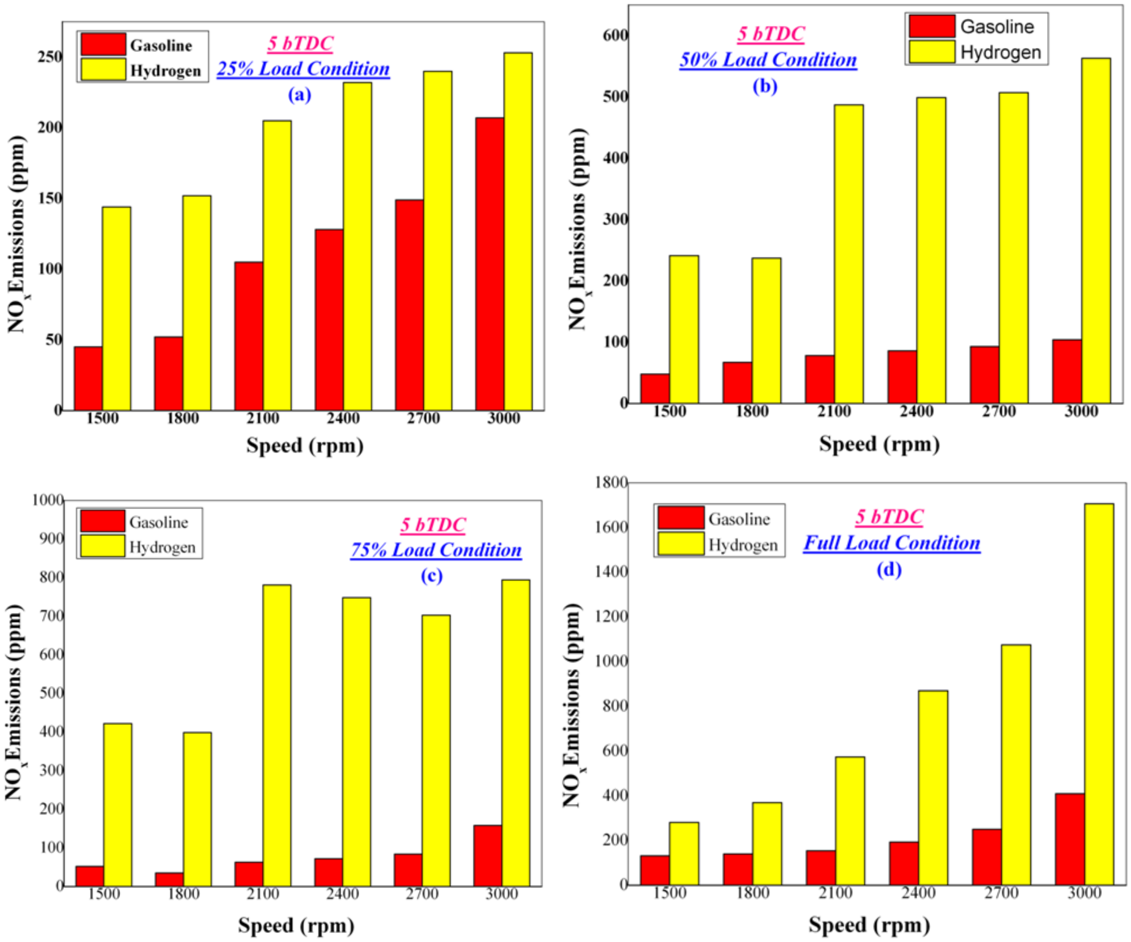


Fig.5.8 Oxides of Nitrogen (NO_x) Emission for Various Loads at 5 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load.

As observed from plots, at all conditions, NO_x emissions are found to be higher for hydrogen compared gasoline more or less for all speeds. This is due to high energy content, wide range of flammability of hydrogen and high combustion temperature attainment. In addition, if there is an excess of oxygen that can combine with the nitrogen to form various oxides. There is a maximum amount of 253, 563, 794 and 1706 ppm is observed for 25, 50, 75% and full load condition respectively. All these maximum values were observed at 3000 rpm speed. This trend of NO_x increment was observed for all load conditions.

5.1.4 Concluding Remarks on Static Timing:

Exhaustive experiments with hydrogen for evaluating performance, combustion and emission characteristics on four cylinders, four strokes MPFI SI engine at static ignition timing of 5 bTDC condition delivered the results as follows:

1. Cylinder pressure increased for hydrogen operation in comparison with gasoline for all load and speed conditions.
2. Cylinder pressure shifted towards the top dead centre (TDC) for hydrogen with all speed and load conditions.
3. Net heat release rate is increased in most of the cases for hydrogen with all speed and load conditions.
4. Brake power is reduced for hydrogen operation in comparison with gasoline for all load conditions.
5. Brake thermal efficiency is increased for hydrogen operation in comparison with gasoline for all load conditions.
6. Volumetric efficiency for hydrogen operation is reduced considerably in comparison with gasoline for all load conditions.
7. Carbon monoxide (CO) emissions reduced drastically for hydrogen operation in comparison with gasoline for all load conditions.
8. Hydrocarbon (HC) emissions reduced considerably for hydrogen operation in comparison with gasoline for all load conditions.
9. Oxides of Nitrogen (NO_x) emissions increased dramatically for hydrogen operation in comparison with gasoline for all load conditions.
10. Abnormal combustion anomalies not observed.

5.2 INVESTIGATION OF NEAT HYDROGEN FUEL FOR VARIOUS LOAD AND SPEED FOR TWO SPARK TIMING CONDITIONS

This section provides the results of the experiments which have been conducted to investigate the effect of neat hydrogen to evaluate performance, combustion and emission characteristics by various loads and different speed conditions at 2 bTDC and 8 bTDC spark timings. Experiments are carried out for 25 - 100% load in step of 25% and for speed range of 1500 – 3000 rpm in step of 300 rpm at 2, and 8 bTDC spark conditions. Results are summarized as follows:

5.2.1 ANALYSIS OF NEAT HYDROGEN FUEL AT 2 bTDC SPARK CONDITION

5.2.1.1 Combustion Characteristics:

Combustion characteristics like pressure- crank angle, net heat release rate at various load and different speed conditions at 2 bTDC spark timing is discussed in this section.

5.2.1.1.1 Pressure- Crank Angle (P-θ):

Figure 5.9 shows the variation of cylinder pressure with crank angle for gasoline and hydrogen operation by different loads (i.e., 25 - 100% in step of 25%) and by different engine speeds for 2 bTDC condition. As shown in the plots, cylinder pressure is noticeably raised with hydrogen compared to gasoline fuel operation at all speeds. Maximum rise in pressure of 25.35, 28.87, 34.41 and 30.27 bar at 369, 371, 370 and 369 deg.CA is observed for 25, 50, 75% and full load condition respectively at an engine speed of 3000 rpm for hydrogen. This indicates that, combustion occurred at relatively high temperature and pressure owing to high adiabatic flame temperature and high flame speed of hydrogen which progress the combustion process with shorter combustion duration (Subramanian et al. 2007). Also peak pressure of hydrogen fuel was shifted towards the TDC position in comparison with its counter fuel (Ji et.al. 2010a).

It is also observed that peak pressure in hydrogen operation occurred at around 9 crank angle degrees after top dead center, which is earlier than the gasoline engine operation. At 3000 rpm, the increase in peak pressure is 34.41%, 12.37%, 5.9% and 2.15% for 25, 50, 75% and full load hydrogen operation when compared to gasoline operation respectively. This increase in peak pressure will indicate that neat hydrogen has better combustion properties compared to that of gasoline.

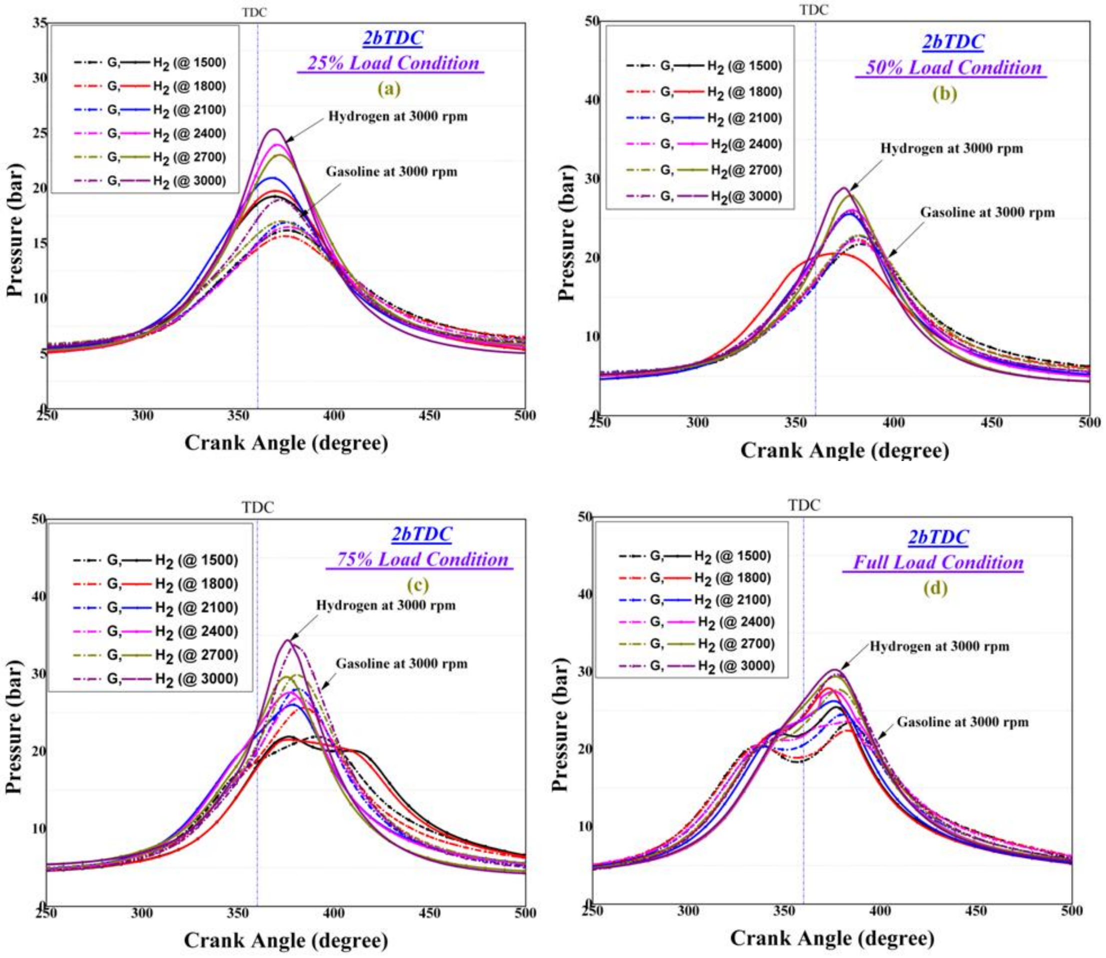


Fig.5.9 Pressure-Crank Angle Diagram for Various Loads at 2 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.2.1.1.2 Net Heat Release Rate (NHR)

Net heat release rate is an effort to get information about the combustion process in an engine. Moreover, physical and chemical properties of the fuel used in internal combustion engines are one of the main parameters which affect the heat release rate.

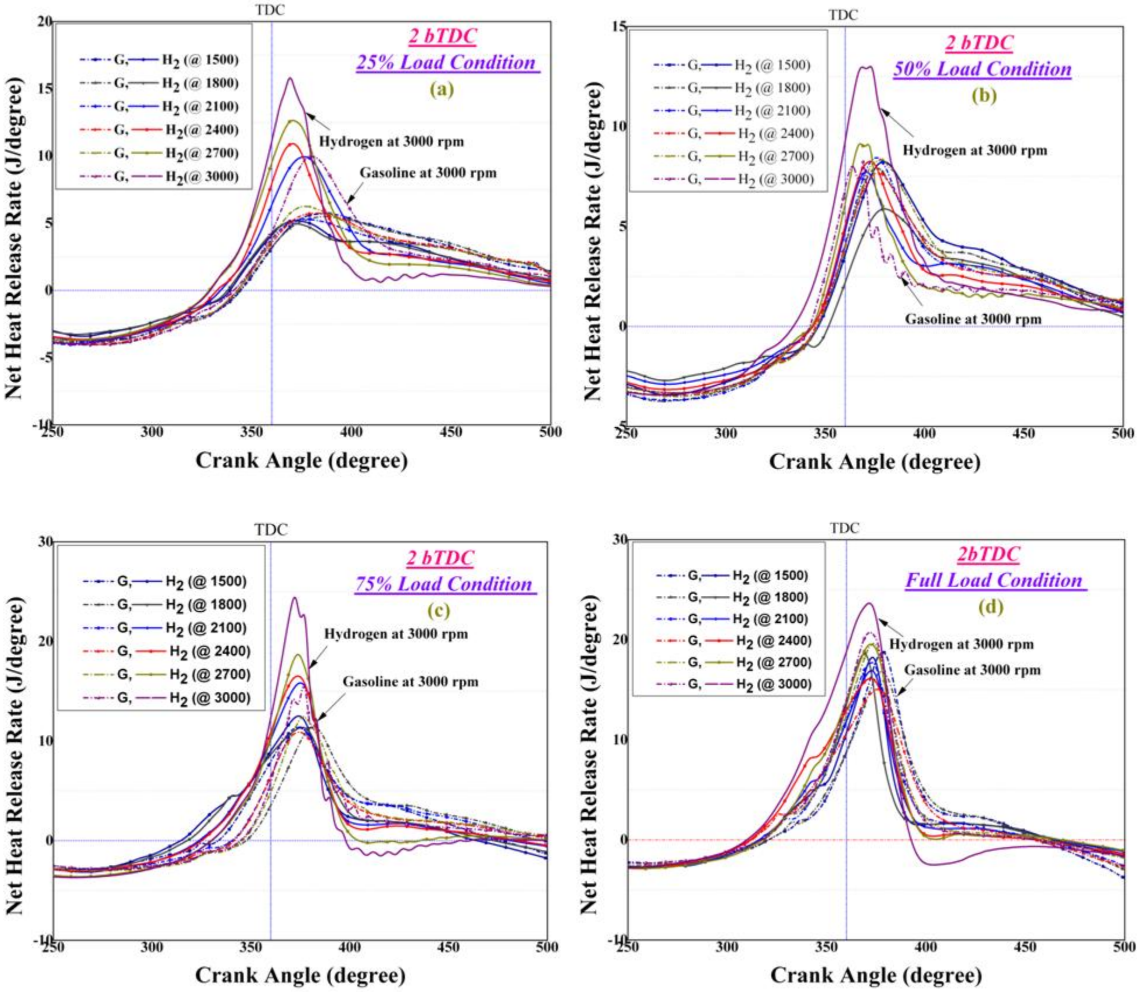


Fig.5.10 Net Heat Release Rate for Various Loads at 2bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

Variation of net heat release rate versus crank angle for gasoline and hydrogen operation by different loads (i.e., 25 - 100% in step of 25%) and for different engine speeds at 2 bTDC is shown in figure 5.10. From the plots, it can be revealed that rate of heat release is increased with engine speeds for hydrogen. This is mainly owing to quicker flame front propagation speed of the hydrogen and great rate of combustion within shorter period. This quality of hydrogen leads to reach higher value of net heat release rate and nearer to TDC while reducing cyclic variations (Wang and Ji 2012).The maximum rate of heat release of 15.85, 13.03, 24.55 and 23.64 J/degree is observed for 25, 50, 75% and full load conditions at 3000 rpm for neat hydrogen compared to other engine speeds.

5.2.1.2 Performance Characteristics:

This section includes the engines performance results such as brake power, brake thermal efficiency and volumetric efficiency for various loads and speeds at 2 bTDC condition.

5.2.1.2.1 Brake Power:

Figure 5.11 shows the variation of brake power versus engine speeds for all loads (i.e., 25 - 100% in step of 25%) for gasoline and hydrogen operation at 2 bTDC spark condition.

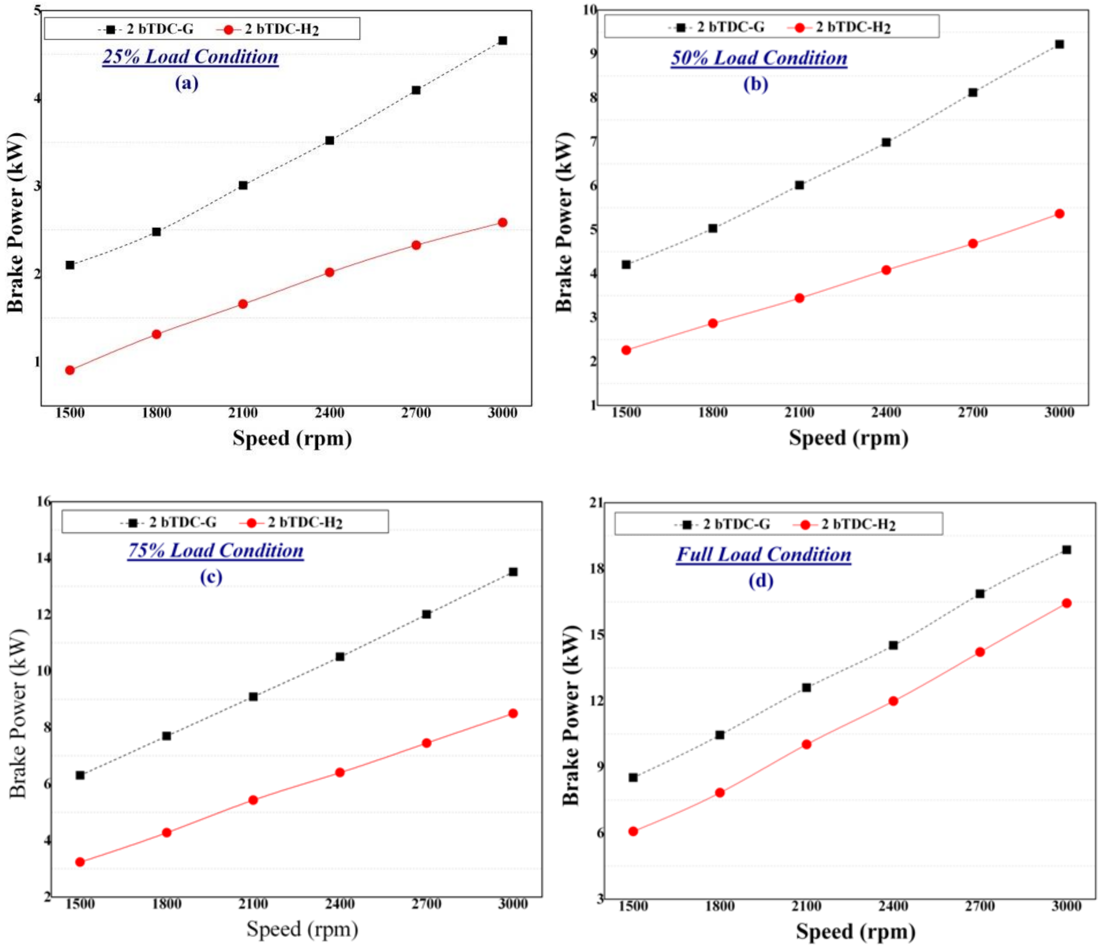


Fig.5.11Brake Power for Various Loads at 2 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

From the graphs it can be revealed that, as the speed increased brake power of both the fuel increased almost linearly. This is due to higher flame propagation speed and higher adiabatic flame temperature of hydrogen than gasoline (Rahaman et al. 2009).

But brake power for hydrogen operation dropped in comparison with gasoline because of high displacement of the air by low density hydrogen thus leading to improper combustion. The influx of fuel is less in part load conditions compared to full load, this results in the lesser power generation in the lower load condition for both the fuels [Heywood 1998]. Maximum brake power of 2.58, 5.36, 8.49 and 16.43 kW is observed for hydrogen at 3000 rpm speed.

5.2.1.2.2 Brake Thermal Efficiency

Engine thermal efficiency is vital parameter on assessing the engine economic and overall performance. Efficiency can be upgraded by either optimizing the combustion system or fuel properties. Engine brake thermal efficiency counter to various engine speeds for gasoline and neat hydrogen operation at different loads (i.e., 25%, 50%, 75% and Full load) for 2 bTDC sparks conditions is shown in Figure 5.12. The characteristic of these curves displays that brake thermal efficiency is higher for hydrogen than gasoline at all engine operating conditions.

As it is observed from figure 5.12, brake thermal efficiency is linearly increasing for both the fuels at all engine speeds. Peak brake thermal efficiency under the test conditions revealed 21.47%, 26.73%, 34.63% and 31.75% at 25%, 50%, 75% and full load condition.

Since the flame speed of hydrogen is five times larger than the gasoline and the flammability range of hydrogen is much wider than gasoline. The hydrogen will have a faster burning velocity and an extended flame limit than gasoline, which can achieve shorter burning duration and more complete burning. Therefore, hydrogen leads to higher degree of constant volume combustion, meaning that the engine operates much closer to the ideal cycle, and gains a higher brake thermal efficiency than gasoline at all the operating engine speeds (Ma et al. 2010).

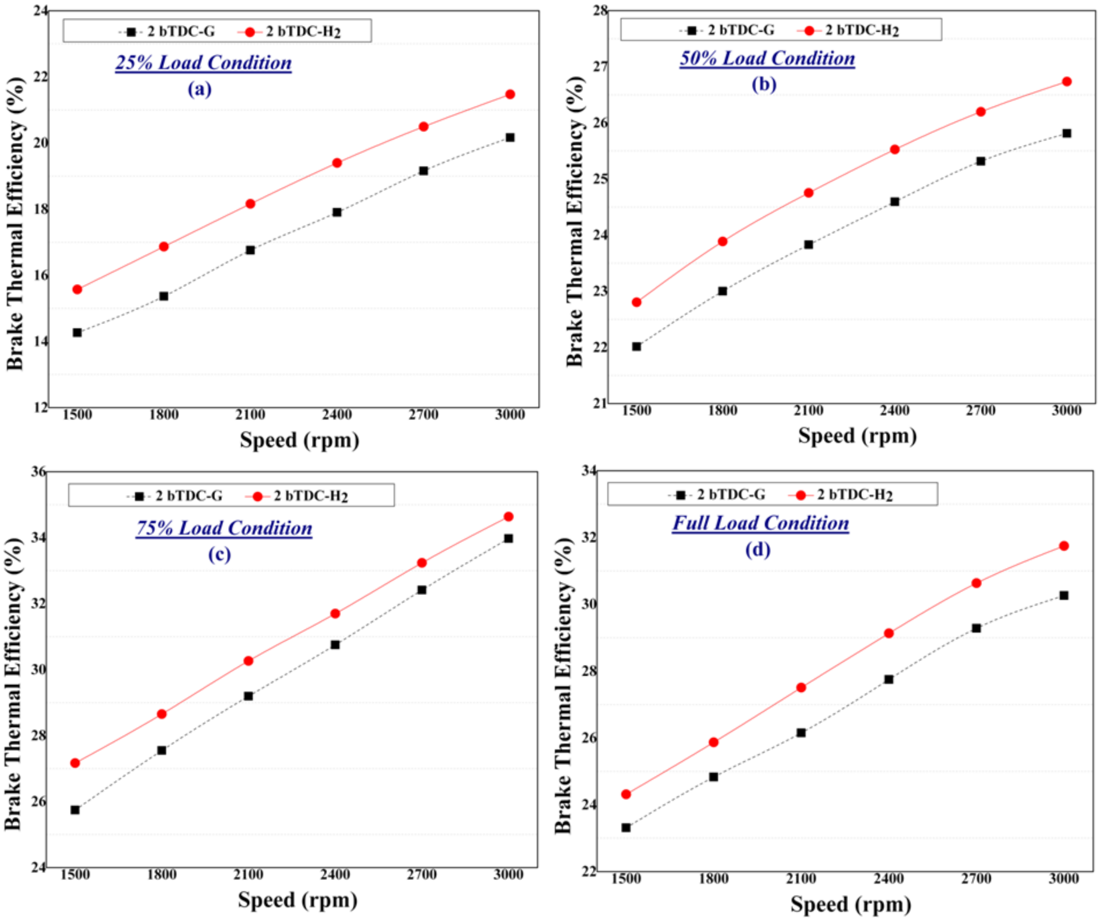


Fig.5.12 Brake Thermal Efficiency for Various Loads at 2 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.2.1.2.3 Volumetric Efficiency:

Figure 5.13 indicates the variation of volumetric efficiency with engine speed for gasoline and hydrogen operation at all loads (i.e., 25%, 50%, 75% and full load) and 2 bTDC spark condition.

For the hydrogen operation drop in volumetric efficiency is observed which is due to density difference between air and hydrogen. But as the load and speed increases the volumetric efficiency also increases for both the fuel due to reduction in pumping losses. Maximum volumetric efficiency of 24.84%, 35.85%, 44.95% and 61.68% is attained for hydrogen at 25%, 50%, 75% and full load condition respectively for 3000 rpm speed, which is 23.96%,12.24%, 4.8% and 12.47% lower compared to gasoline operation.

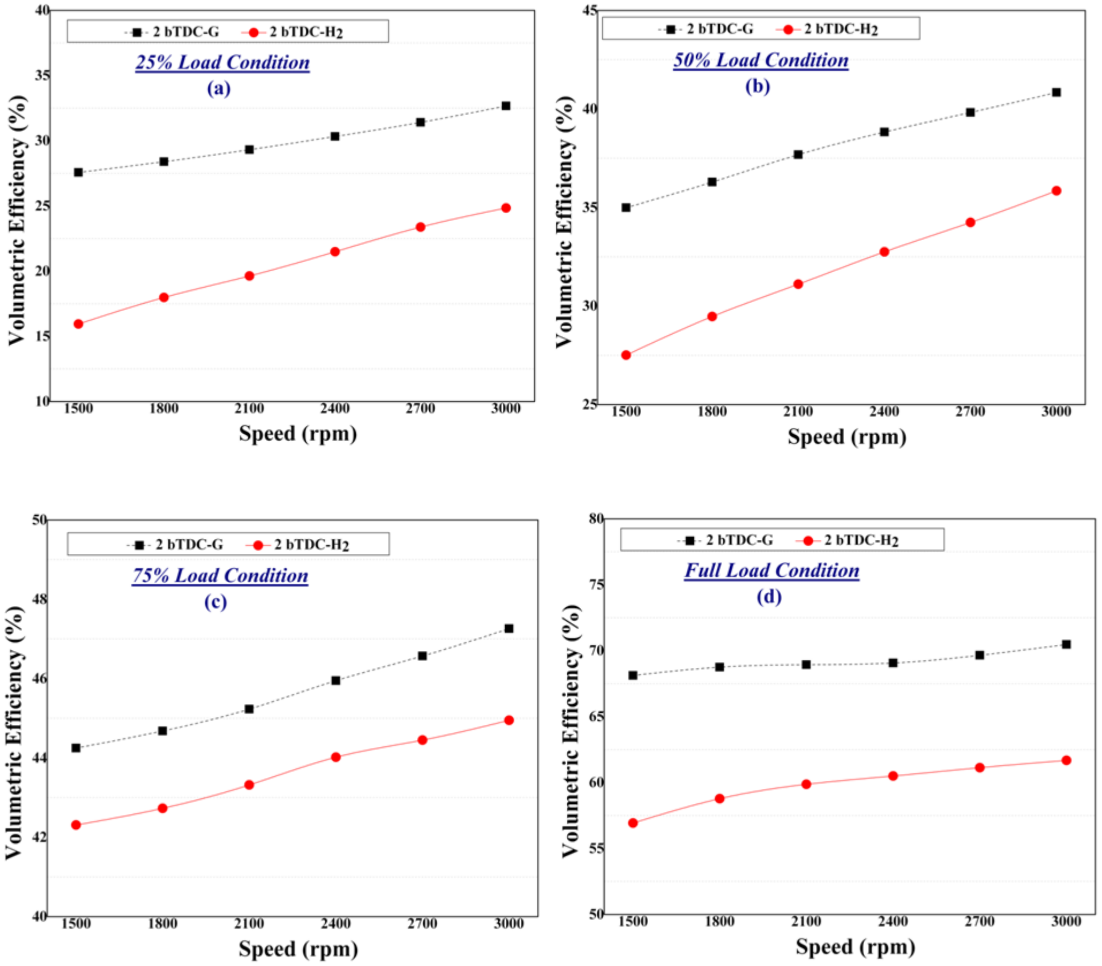


Fig.5.13 Volumetric Efficiency for Various Loads at 2 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

Volumetric efficiency is affected by the fuel being burned in the engine. Liquid fuel takes up very little space in the intake port and combustion chamber, but as hydrogen is vapor can take considerably more space, leaving less volume for the air being pumped into the cylinder. This causes less amount of mixture density at the inlet of the engine in turn reduction in volumetric efficiency (Rahaman et al. 2009).

5.2.1.3 Emission Characteristics:

This section provides the emission results of experiments conducted by neat hydrogen and gasoline for different load and speed condition at 2 bTDC spark timing for non-regulated emissions. Detailed exhaust emission plots were made in Figure 5.14 to 5.16.

5.2.1.3.1 Carbon Monoxide (CO)

Figure 5.14 shows the CO emissions for hydrogen and gasoline by different load and speeds at 2 bTDC spark timing.

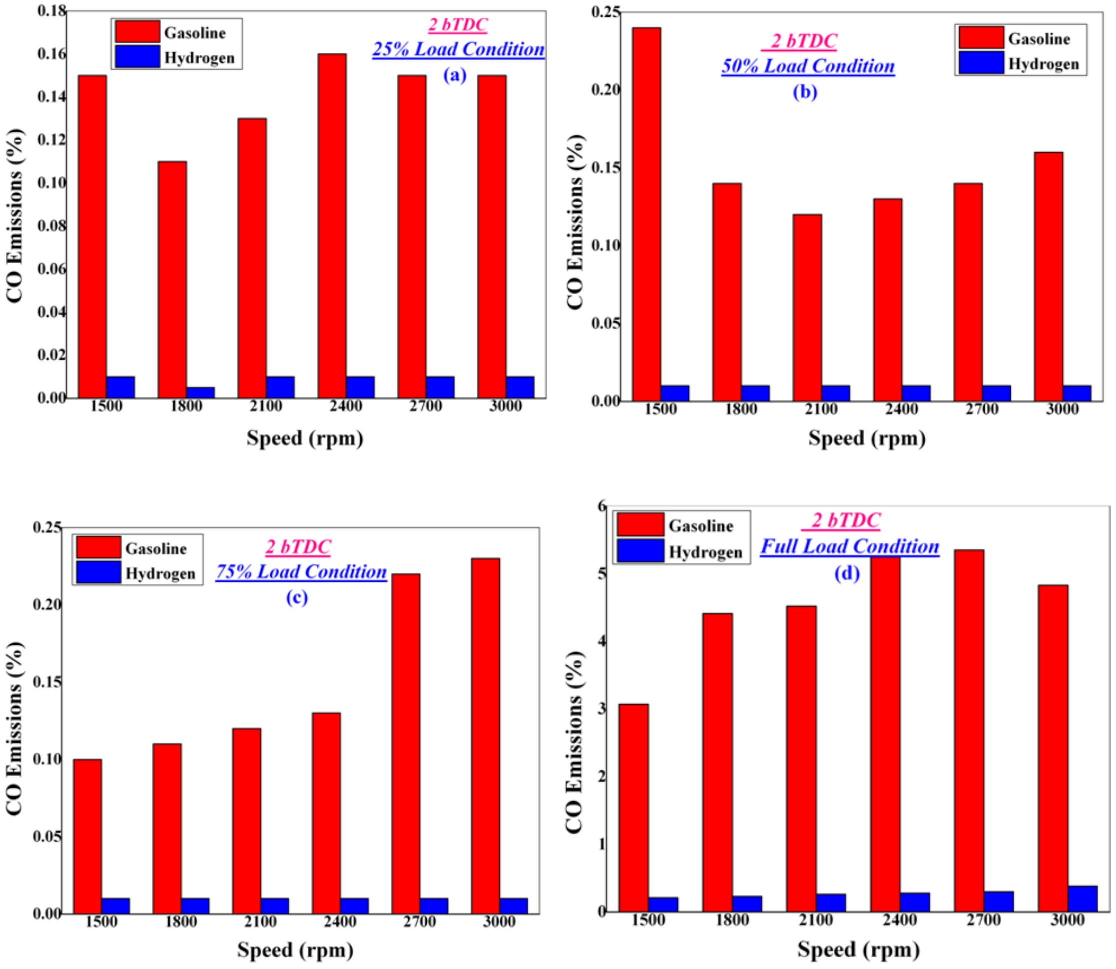


Fig.5.14 Carbon Monoxide Emissions for Various Loads at 2 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

Hydrogen is non-carbon content fuel and have higher flame propagation speed which enhances combustion, therefore it can be inferred that CO emission is far less for hydrogen compared to gasoline at all load conditions.

Hydrogen also helps the formation of O and OH radicals which benefit for the combustion completeness (Wang et al. 2014). Least value of 0 .01 at almost all speeds for 25%, 50% and 75% load, and 0.38% at 3000 rpm for full load is observed for hydrogen. These are merely result of presence of residual oil/gas fraction.

5.2.1.3.2 Hydrocarbon (HC)

Figure 5.15 shows the hydrocarbon (HC) emissions for hydrogen and gasoline by various loads, different speeds and at 2 bTDC sparks timing. Hydrocarbon (HC) emissions are results of traces of lubricating oil present or trapping of unburned fuel air mixture within the cylinder. Figure shows that HC emissions were low with hydrogen compared to gasoline because hydrogen speeds up the formation rate of OH radical.

Shorter quenching distance, high flame speed and high diffusivity of hydrogen allows the combustion flame to travel closer to the cylinder wall facilitating complete combustion which helps in substantial reduction of HC emissions by increasing formation rate of OH radicals (Ji and Wang 2009b). Additionally, the high flame speed of hydrogen reduces the combustion duration and decreases the probability of occurrence of slow-burning and incomplete combustion cycles. Due to these factors, hydrogen can be fully burnt and emits less HC emissions than gasoline (Ceviz et al. 2011).There is a least decrement of 4 ppm at 25% and 50% load, 2 ppm at 75% load and maximum of 34 ppm at full load is observed with hydrogen fuel. This reduction in HC emissions not only helps in controlling harmful emissions, but also adds up to the thermal efficiency of the engine.

5.2.1.3.3 Oxides of Nitrogen (NO_x)

Oxides of Nitrogen (NO_x) are prime emissions when hydrogen is used in IC engines. Figure 5.16 shows the NO_x emissions for hydrogen and gasoline for various loads, different speeds and at 2 bTDC spark timing. One of the most important engine variables that effect NO_x emission is the combustion temperature. Due to proper mixing of gaseous fuels with air imparts an increase in the burning rate of the fuel and thus complete combustion thence the cylinder pressures and combustion temperatures increases which make NO_x to increase (Wang et al. 2014).

As observed from plots, for all load conditions NO_x emissions are higher for hydrogen compared with gasoline more or less for all speeds. At Full load condition NO_x emission is more for hydrogen compared to other load and gasoline.

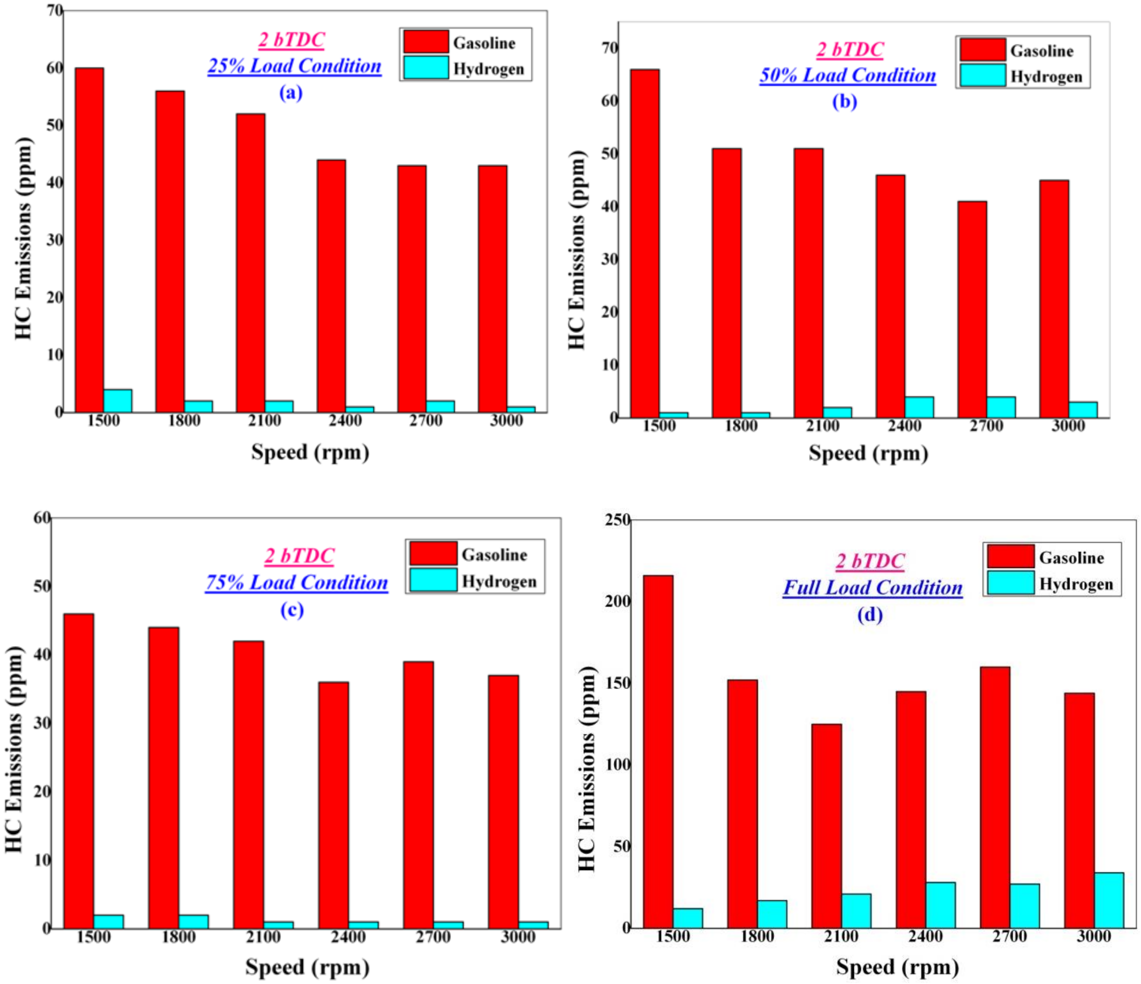


Fig.5.15 Hydrocarbon Emissions for Various Loads at 2 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

This is due to high energy content, wide range of flammability of hydrogen and high combustion temperature attainment. In addition, if there is an excess of oxygen that can combine with the nitrogen to form various oxides. There is a maximum amount of 170, 422, 530 and 1343 ppm NO_x emissions is observed at 3000 rpm speed for at 25%, 50%, 75% and full load condition respectively. This trend of NO_x increment was observed for all speed conditions.

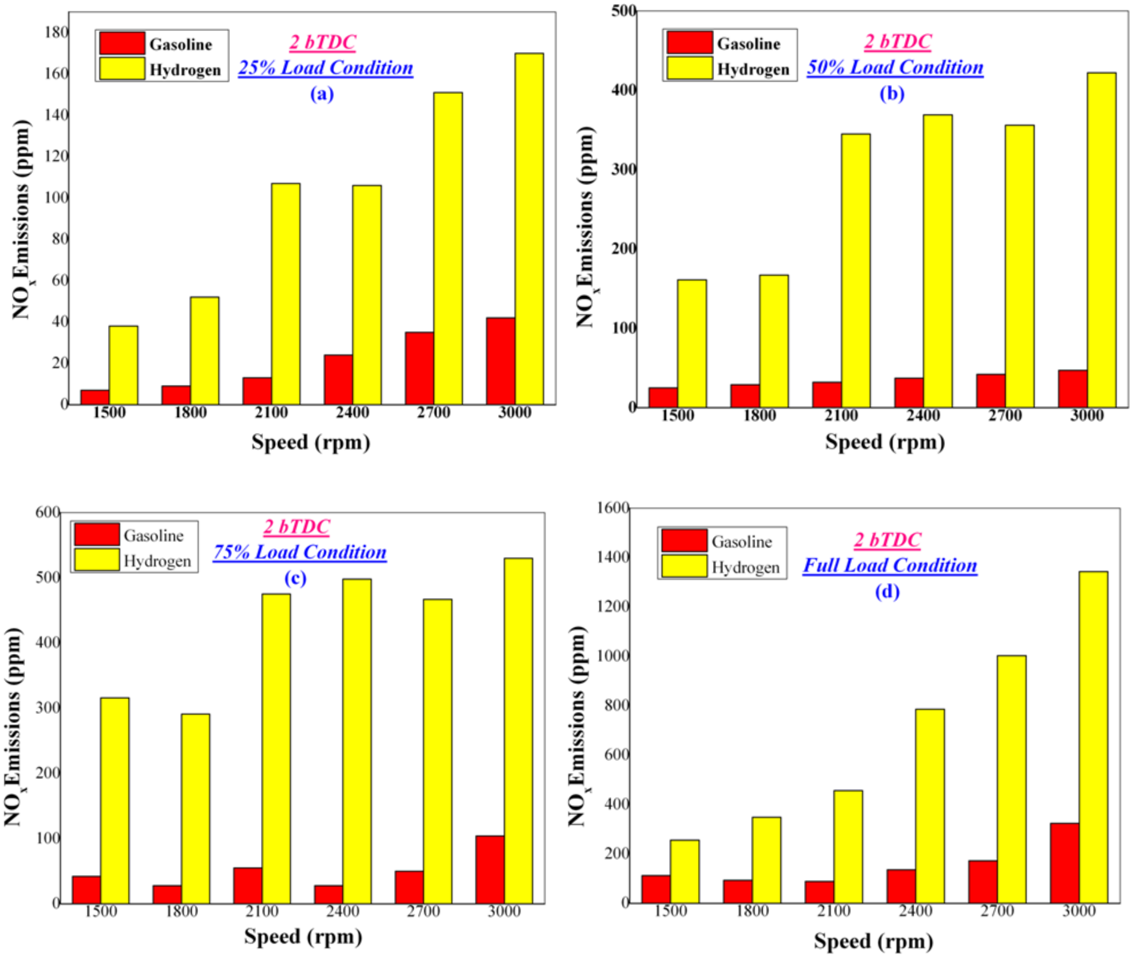


Fig.5.16 Oxides of Nitrogen Emissions for Various Loads at 2 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.2.2 ANALYSIS OF NEAT HYDROGEN FUEL FOR 8 bTDC SPARK CONDITION

5.2.2.1Combustion Characteristics:

Combustion characteristics like pressure- crank angle, net heat release rate by various load and different speed conditions at 8 bTDC spark timing is discussed in this section.

5.2.2.1.1 Pressure- Crank Angle (P-θ)

Figure 5.17 shows the variation of cylinder pressure with crank angle for hydrogen and gasoline operation at various loads (i.e., 25%, 50%, 75% and Full load) and for different engine speeds at 8 bTDC spark conditions.

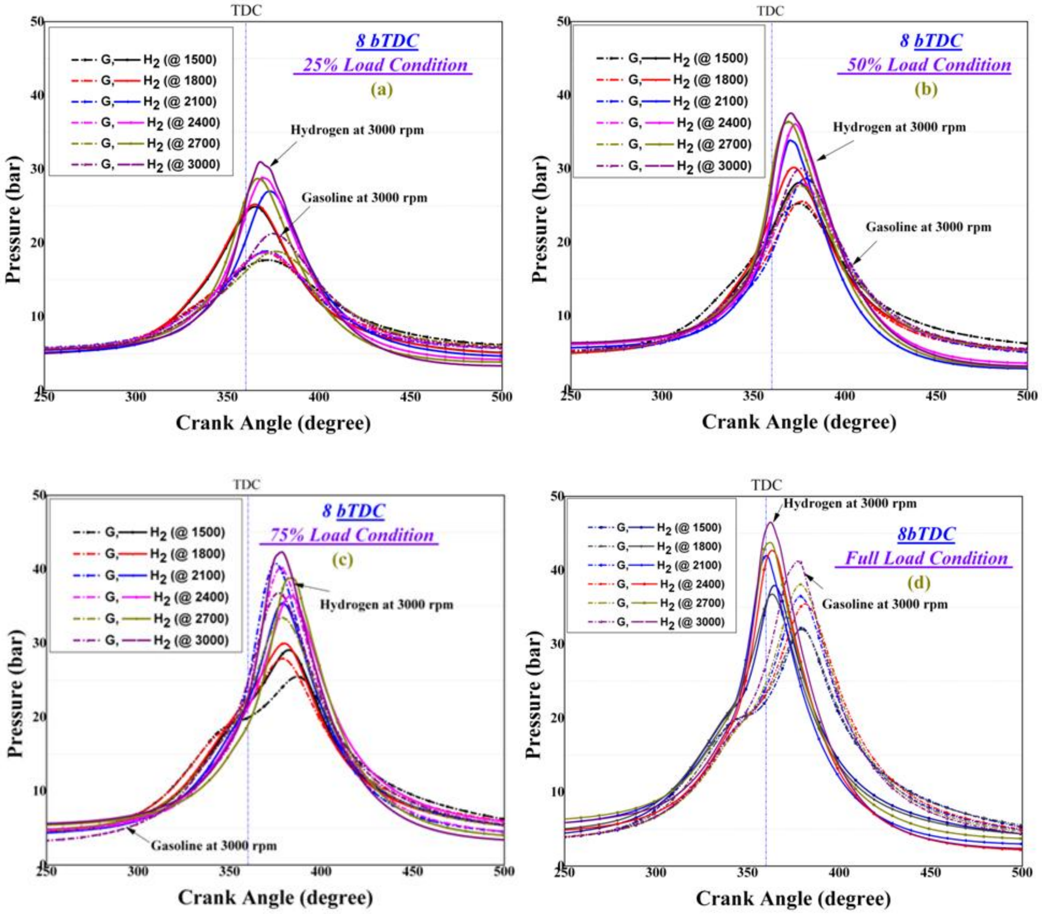


Fig.5.17 Pressure-Crank Angle Diagram for Various Loads at 8 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

As shown in the plots, cylinder pressure is distinctly raised with hydrogen compared to gasoline engine operation for all speeds. Maximum rise in pressure of 31.02, 37.55, 42.34 and 46.51 bar at 368, 370, 372 and 363 deg.CA is observed for 25, 50, 75% and full load condition respectively at an engine speed of 3000 rpm for neat hydrogen. This owed to high adiabatic flame temperature and high flame speed of hydrogen which improve the combustion process with shorter combustion duration (Subramanian et al. 2007). Also peak pressure of hydrogen fuel was shifted towards the TDC position in comparison with its counter fuel (Ji and Wang 2010). It is also observed that peak pressure in hydrogen operation occurred at around 3 crank angle degrees after top dead center, which is earlier than the crank angle of gasoline engine operation. At 3000 rpm, the increase in peak pressure is 45.77%, 25.00%, 15.08% and 12.64% for 25, 50, 75% and full load hydrogen operation when compared to respective gasoline operation. This increase in peak pressure will indicate that neat hydrogen has better combustion properties compared to that of gasoline.

5.2.2.1.2 Net Heat Release Rate (NHR)

Variation of net heat release rate versus crank angle for hydrogen and gasoline operation by various loads (i.e., 25 - 100% in step of 25%) and at different engine speeds at 8 bTDC is shown in Figure 5.18. From the plots, it can be revealed that rate of heat release is increased with engine speeds for hydrogen. This is mainly payable to faster flame speed of the hydrogen and high rate of combustion in shorter period. This quality of hydrogen leads to reach higher value of net heat release rate and nearer to TDC while reducing cyclic variations (Wang et al. 2012).The maximum rate of heat release of 11.82, 16.39, 17.2 and 29.31 J/degree is observed for 25, 50, 75% and full load conditions at 3000 rpm for hydrogen compared to other engine speeds.

5.2.2.2 Performance Characteristics:

This section includes the engines performance results such as brake power, brake thermal efficiency and volumetric efficiency for neat hydrogen and gasoline by various load and speed conditions at 8 bTDC ignition timing.

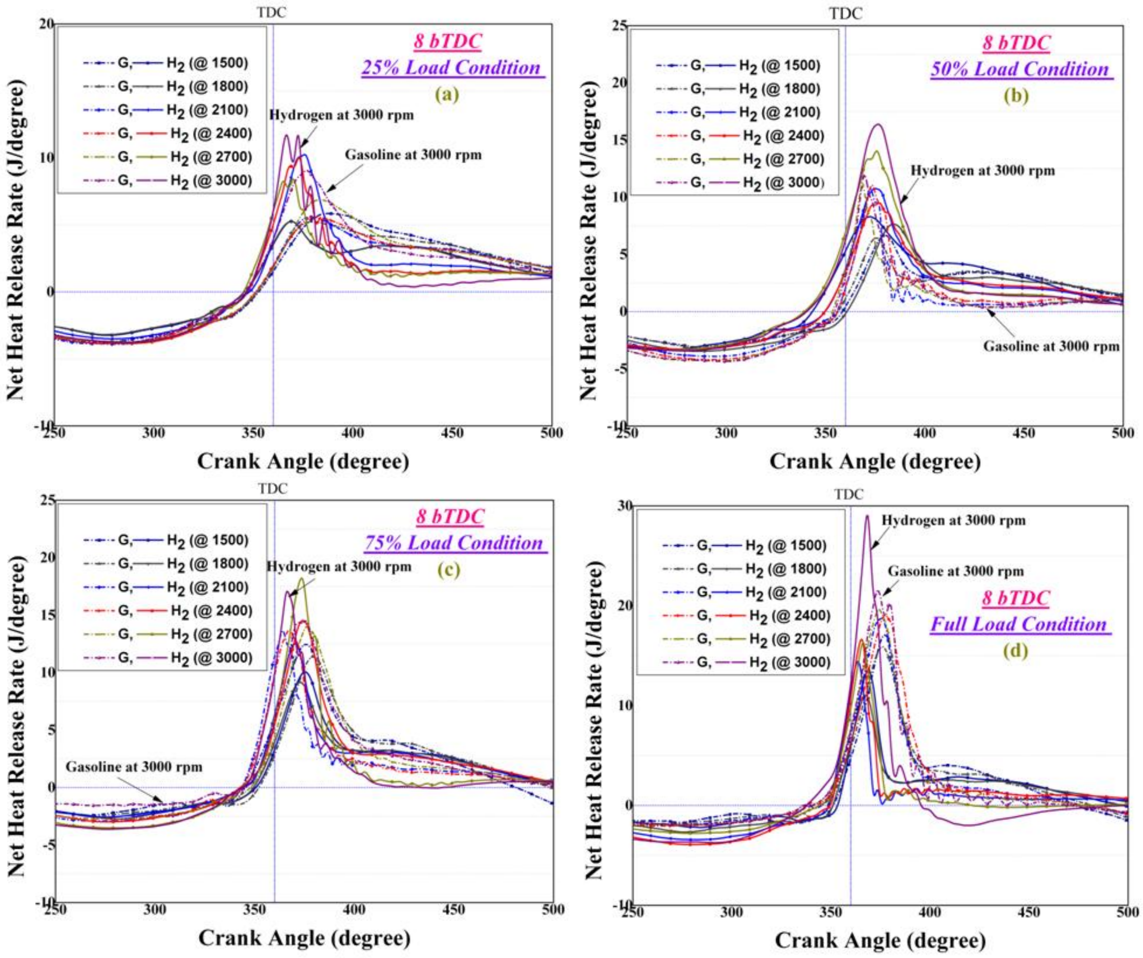


Fig.5.18 Net Heat Release Rate for Various Loads at 8 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.2.2.2.1 Brake Power:

Figure 5.19 shows the variation of brake power with different engine speeds and for various loads (i.e., 25 - 100% in step of 25%) for hydrogen and gasoline operation at 8 bTDC spark condition. From the graphs it can be revealed that as the speed increase brake power of hydrogen increases almost linearly. This is due to wider flammable range, higher flame propagation speed and higher adiabatic flame temperature of hydrogen than gasoline (Rahaman et al. 2009).

But brake power dropped for hydrogen operation in comparison with gasoline because of high displacement of the air by low density hydrogen thus leading to improper combustion. The influx of fuel is less in part load conditions compared to full load this results in the lower power generation in the lower load condition for both the fuels (Heywood 1998). Maximum brake power of 3.6, 6.78, 10.99 and 19.01 kW is observed for neat hydrogen at 3000 rpm speed.

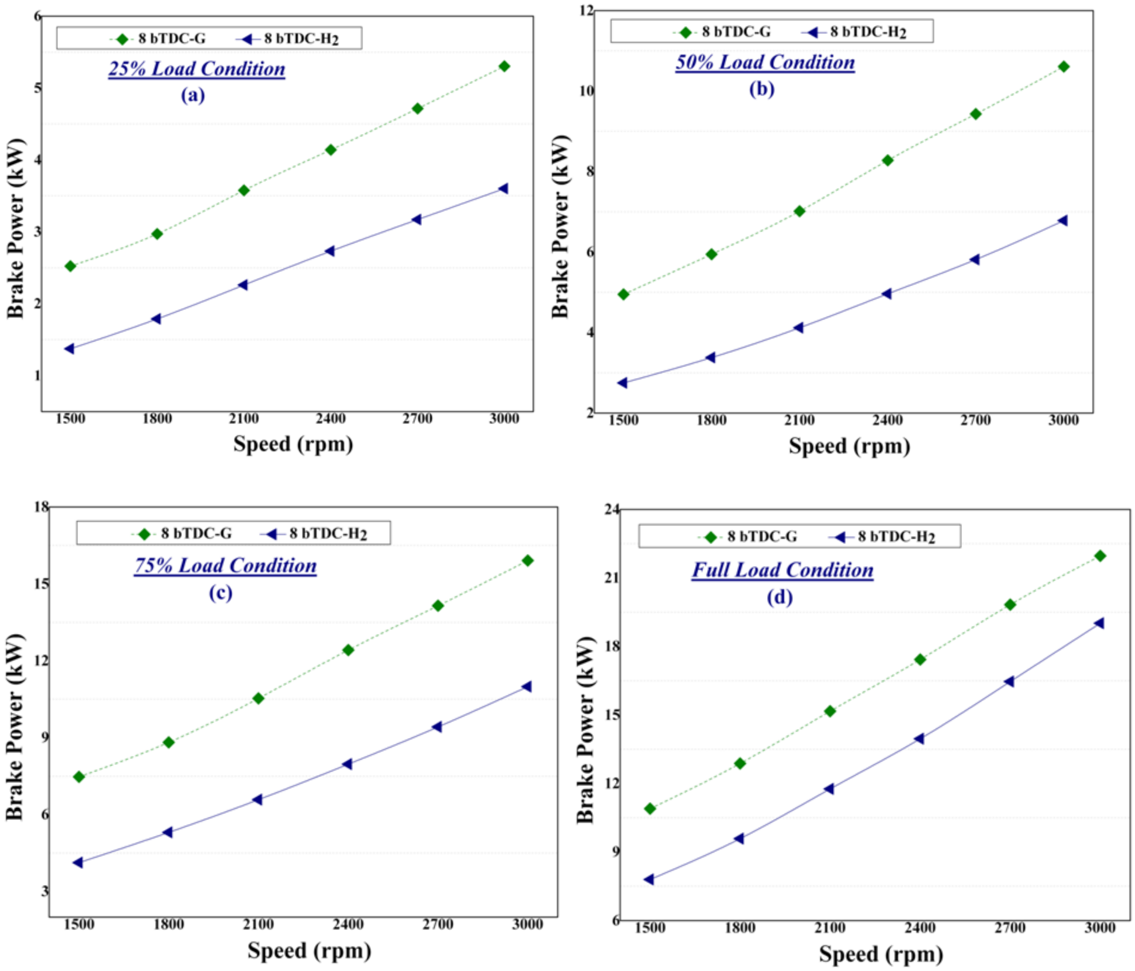


Fig.5.19 Brake Power for Various Loads at 8 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.2.2.2.2 Brake Thermal Efficiency

Engine brake thermal efficiency against various engine speeds for hydrogen and gasoline operation at various loads (i.e., 25 - 100% in step of 25%) for 8 bTDC spark conditions is shown in Figure 5.20. The characteristic of these curves depicts that brake thermal efficiency is higher for neat hydrogen than gasoline at all engine operating conditions. As it is observed from figure 5.20, brake thermal efficiency is linearly increasing for both the fuels at all engine speeds. Peak brake thermal efficiency for the test conditions revealed 33.28%, 30.10%, 39.97% and 37.04% at 25%, 50%, 75% and full load condition.

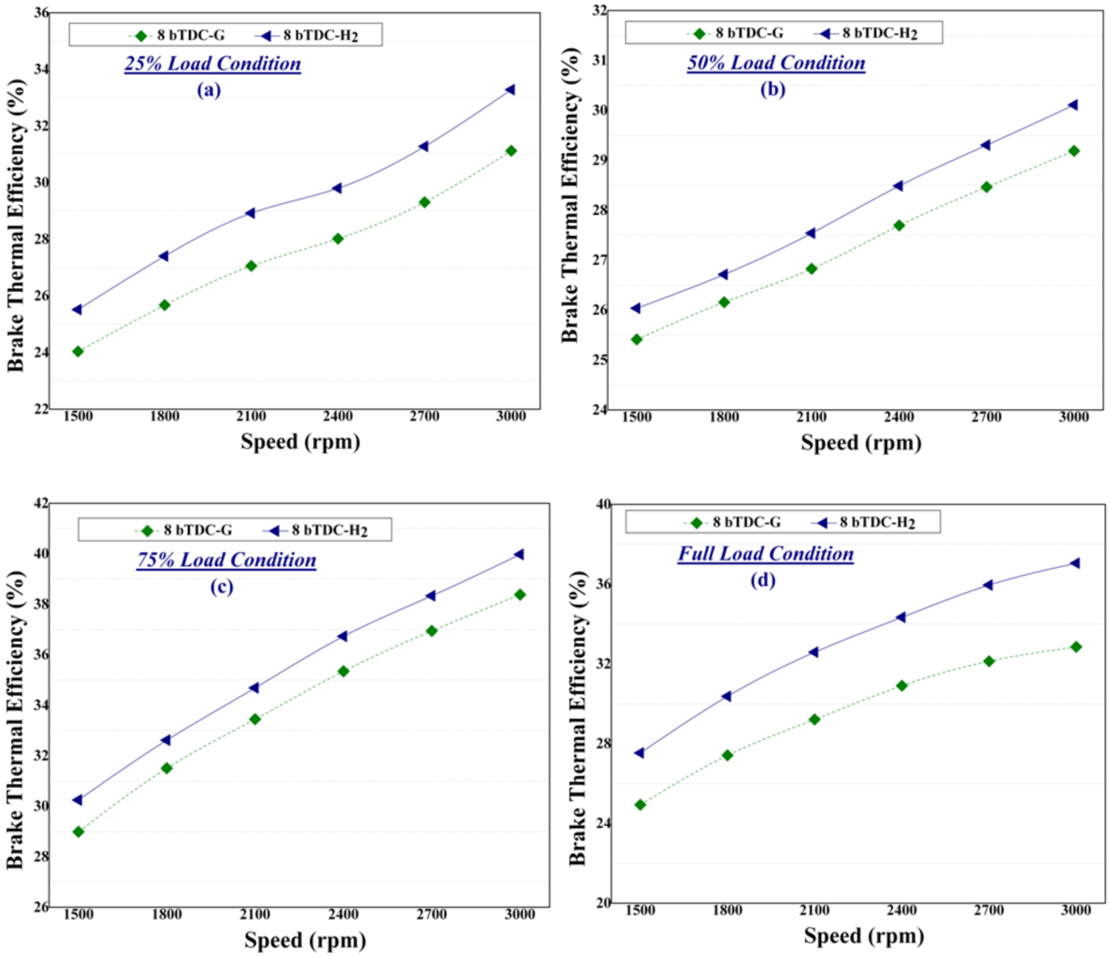


Fig.5.20 Brake Thermal Efficiency for Various Loads at 8 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

Since the flame speed of hydrogen is five times larger than the gasoline and the flammability range of hydrogen is much wider than gasoline. The hydrogen will have a faster burning velocity and an extended flame limit than gasoline, which can achieve shorter burning duration and more complete burning. Therefore, hydrogen leads to higher degree of constant volume combustion, meaning that the engine operates much closer to the ideal cycle and gains a higher brake thermal efficiency than gasoline at all the operating engine speeds (Ma et al. 2010).

5.2.2.2.3 Volumetric Efficiency:

Figure 5.21 indicates the variation of volumetric efficiency with engine speed for hydrogen and gasoline operation at all loads (i.e., 25%, 50%, 75% and full load) and 8 bTDC spark condition.

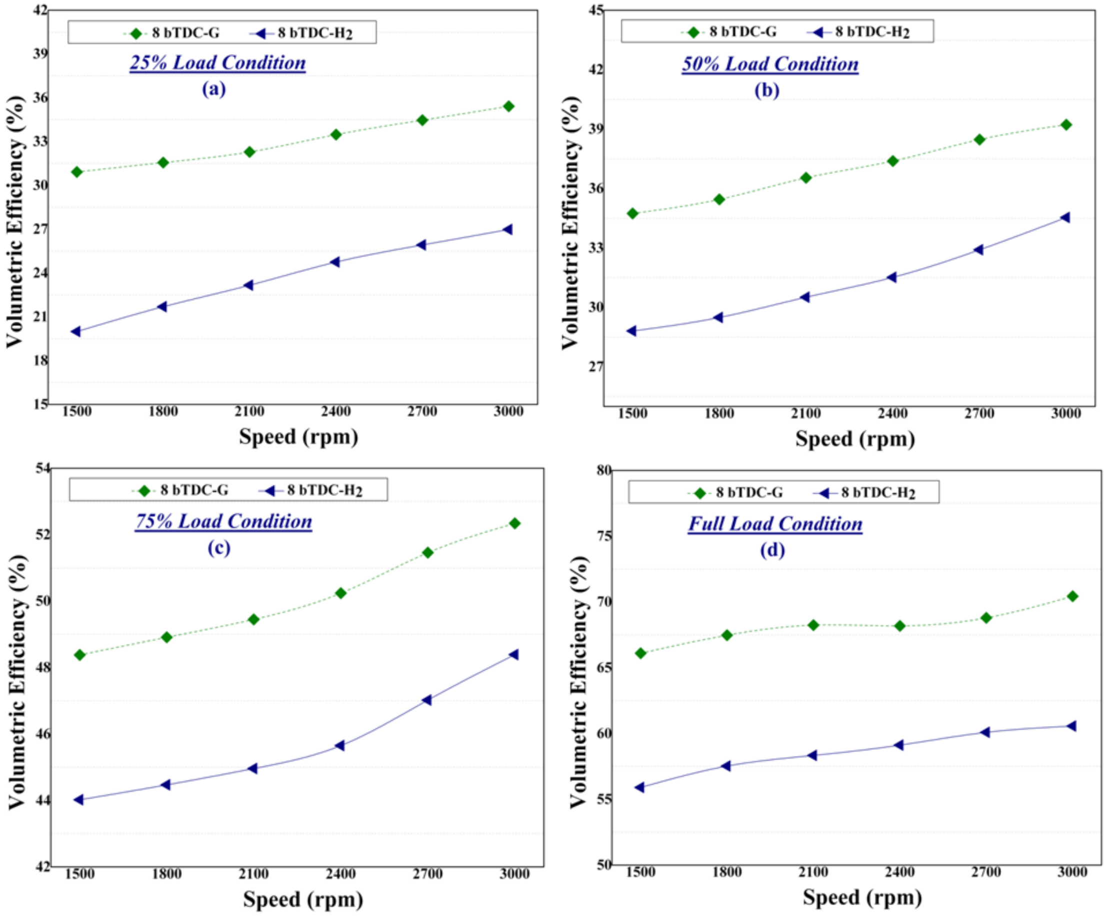


Fig.5.21 Volumetric Efficiency for Various Loads at 8 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

Hydrogen operation has shown drop in volumetric efficiency due to density difference between air and hydrogen. But as the load and speed increases the volumetric efficiency also increases for both the fuel due to reduction in pumping losses. Maximum volumetric efficiency achieved for hydrogen is 26.98%, 34.54%, 48.39% and 60.57% for 25, 50, 75% and full load condition at 3000 rpm which is 23.82%, 11.93%, 7.5% and 14.01% lower compared to gasoline operation.

5.2.2.3 Emission Characteristics:

This section includes the emission results of experiments conducted with hydrogen and gasoline by various load and speed conditions, at 8 bTDC spark timing for carbon monoxide (CO), hydrocarbons (HC) and oxides of Nitrogen (NO_x). Detailed exhaust emission graphs were made in Figure 5.22 to 5.24 which compare toxic emissions of hydrogen with gasoline fuel at above specified conditions.

5.2.2.3.1 Carbon Monoxide (CO)

Figure 5.22 shows the CO emissions for hydrogen and gasoline by different load and speeds at 8 bTDC spark timing condition. As hydrogen is non-carbon content fuel and have higher flame propagation speed hence enhances combustion, therefore CO emission is far less compared to gasoline at all load conditions. At 25% load condition emission of CO is higher compared to other load conditions due to more pumping losses and incomplete combustion.

Least value of 0.01 at almost all speeds for 25%, 50% and 75% load and 0.15% at 3000 rpm for full load is observed for neat hydrogen. These are merely result of presence of residual oil/gas fraction.

5.2.2.3.2 Hydrocarbon (HC)

Figure 5.23 shows the HC emissions for hydrogen and gasoline at different loads, various speeds at 8 bTDC spark timing. These are results of traces of lubricating oil present or trapping of unburned fuel air mixture within the cylinder. Figure shows that HC emissions were low with neat hydrogen compared to gasoline because hydrogen accelerates the formation rate of OH radical.

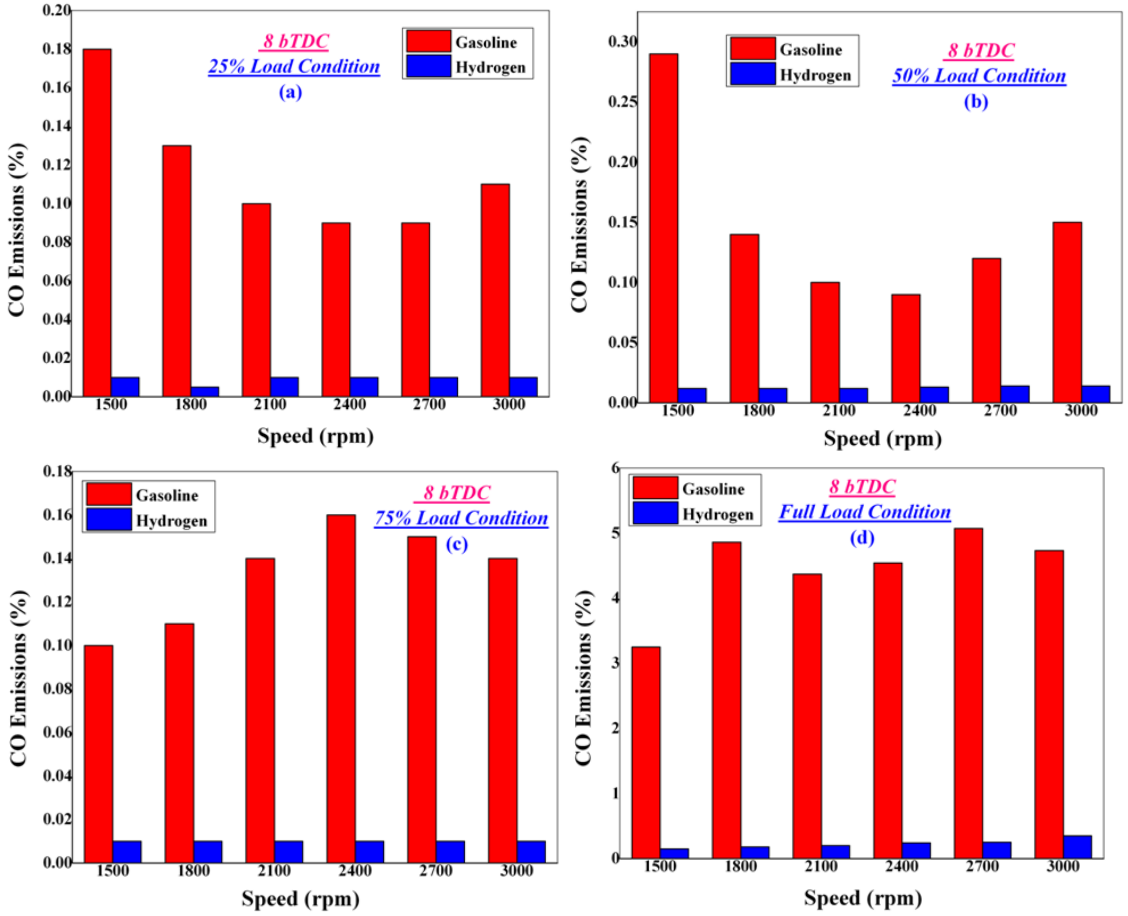


Fig.5.22 Carbon Monoxide Emissions for Various Loads at 8 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

High flame speed, high diffusivity and shorter quenching distance, of hydrogen facilitates complete combustion which helps in substantial reduction of HC emissions by increasing formation rate of OH radicals (Ji and Wang 2009a). Additionally, the high flame speed of hydrogen reduces the combustion duration thus decreasing the probability of occurrence of slow-burning and incomplete combustion cycles. Due to these factors, hydrogen can be fully burnt and emits less HC emissions than gasoline (Ceviz et al. 2011).There is a least decrement of 1 ppm at 25%, 2 ppm at 50%, 8 ppm at 75% load and maximum of 27 ppm at full load is observed with hydrogen fuel.

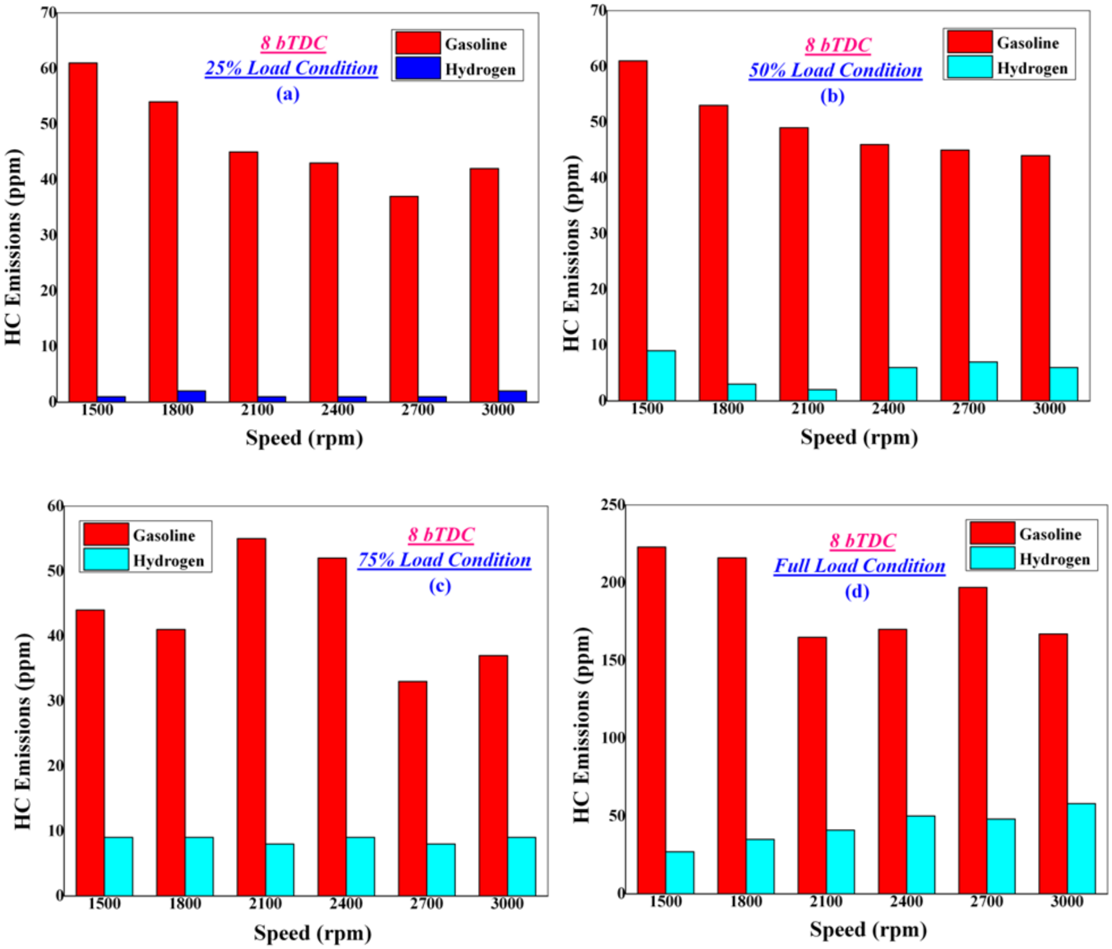


Fig.5.23 Hydrocarbon Emissions for Various Loads at 8 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

5.2.2.3.3 Oxides of Nitrogen (NO_x)

Oxides of Nitrogen (NO_x) are prime emissions when hydrogen is used in IC engines. Figure 5.24 shows the NO_x emissions for neat hydrogen and gasoline at different load, various speeds and at 8 bTDC spark timing. One of the most important engine variables that effect NO_x emission is the combustion temperature. Due to proper mixing of gaseous fuels with air imparts an increase in the burning rate of the fuel and thus complete combustion thence the cylinder pressures and combustion temperatures increases which make NO_x to increase (Wang et al. 2014).

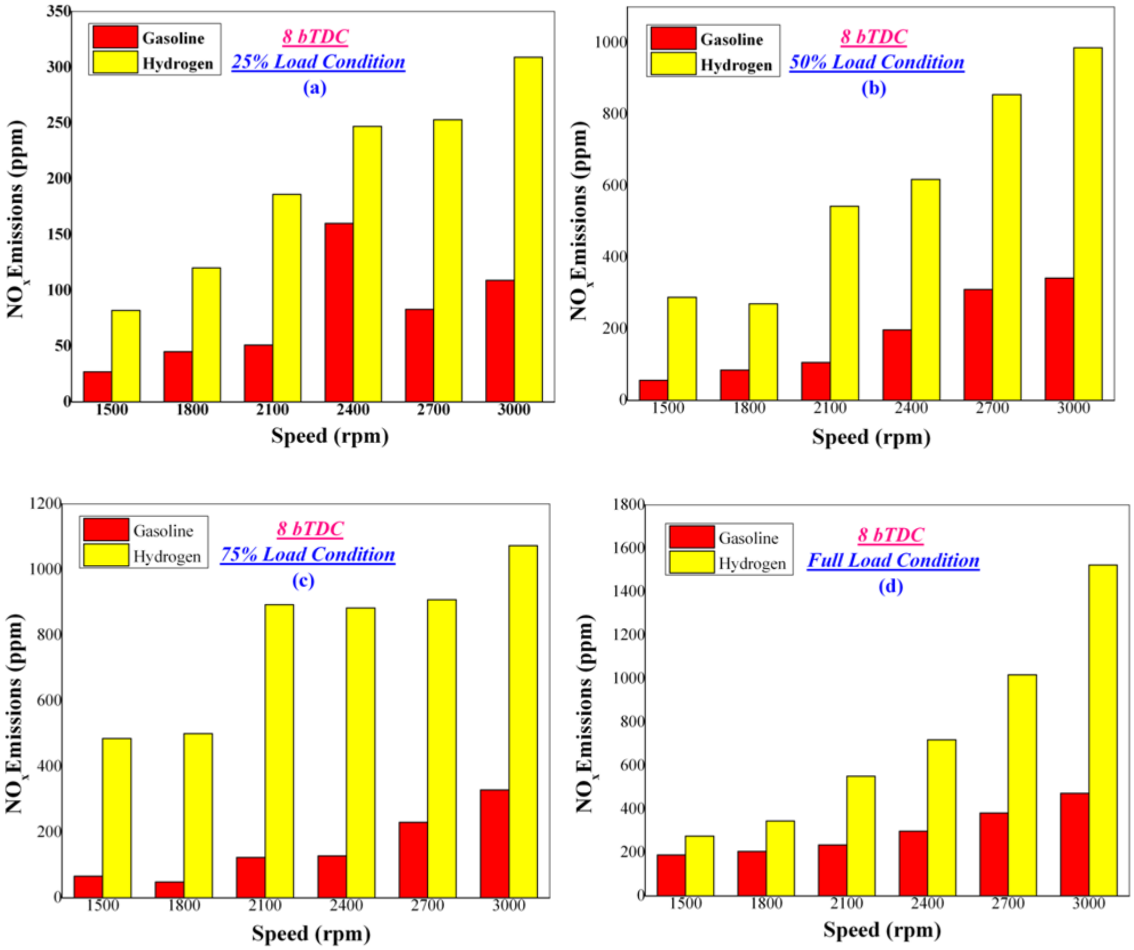


Fig.5.24 Oxides of Nitrogen Emissions for Various Loads at 8 bTDC Condition

(a) 25% Load (b) 50% Load (c) 75% Load (d) Full Load

As observed from graphs, NO_x emissions are higher for hydrogen compared with gasoline for all loads and more or less for all speeds. At Full load condition, NO_x emission is higher for hydrogen compared to other load and gasoline. This is due to high energy content and high combustion temperature attainment by hydrogen. Added to this, if there is surplus of oxygen that can combine with the nitrogen to form various oxides. Maximum amount of 309, 986, 1073 and 1523 ppm NO_x emissions is observed at 3000 rpm speed for at 25%, 50%, 75% and full load condition respectively.

5.2.3 COMPARISON OF NEAT HYDROGEN FOR DIFFERENT SPARK TIMINGS AT FULL LOAD CONDITION

This section provides the comparison of the neat hydrogen and gasoline for three spark timings to evaluate performance, combustion and emission characteristics at full load condition. Results are summarized as follows:

5.2.3.1 Combustion Characteristics:

Combustion characteristics like pressure- crank angle, net heat release rate for full load and 3000 rpm speed and for three spark timings is discussed in this section.

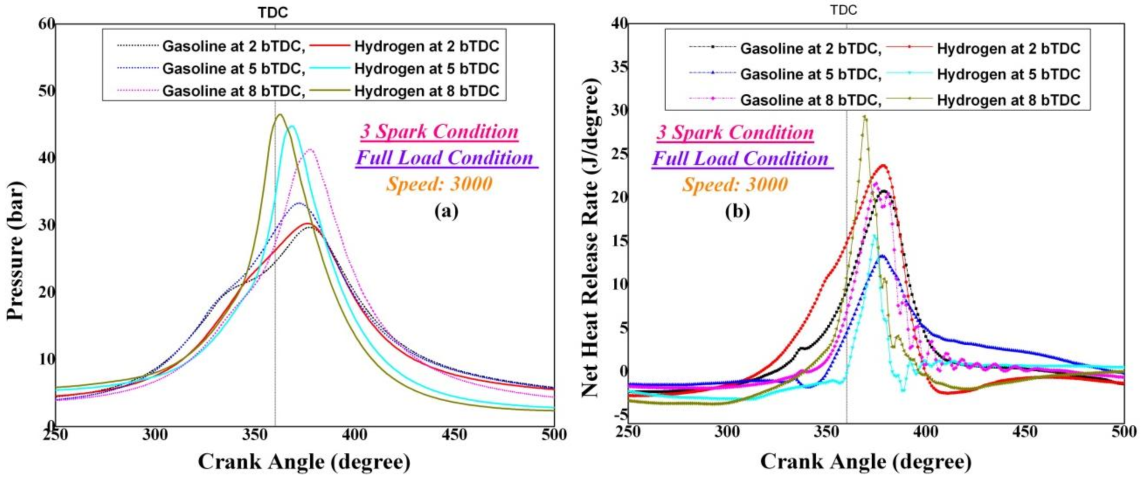


Fig.5.25 Comparison of Combustion Characteristics for Three Sparks Timings

(a) Pressure - Crank angle (P-Theta)   (b) Net Heat Release Rate

5.2.3.1.1 P-θ Diagram:

The pressure-crank angle diagram for gasoline and neat hydrogen for three spark timings is shown in Figure 5.25 (a). As depicted in figure, the cylinder pressure is significantly elevated with neat hydrogen in comparison with gasoline. This is attributed to high adiabatic temperature and high flame speed of hydrogen which improved the combustion and relatively raised pressure and temperature (Subramanian et al. 2007). Also peak pressure of hydrogen fuel was shifted towards the TDC position in comparison with its counter fuel (Ji et al. 2010a, Shivaprasad et al. 2016). Maximum raise in pressure of 30.27, 44.76 and 46.51 bar for 2, 5 and 8 bTDC respectively observed for neat hydrogen compared against 29.69, 33.3 and 41.29 bars at respective spark timings with gasoline operation.

5.2.3.1.2 Net Heat Release Rate:

The variation of the net heat release rate against the crank angle for both the fuels at all spark timings is shown in Figure 5.25 (b). From the graph it can be revealed that rate of heat release is improved with neat hydrogen compared to gasoline. This is mainly because of hydrogen’s faster flame front propagation and high rate of combustion within shorter period. This quality of hydrogen leads to reach higher value of net heat release rate and nearer to TDC while reducing cyclic variations (Wang et al. 2012, Shivaprasad et al. 2016). The maximum net heat release rate of 23.64, 15.62 and 29.31 J/degree is observed for 2, 5 and 8 bTDC respectively for neat hydrogen compared against 20.73, 13.27 and 21.61 J/degree at respective spark timings to gasoline operation.

5.2.3.2 Performance Characteristics

5.2.3.2.1 Brake Power:

Figure 5.26 (a) shows the variations of brake power with the engine speed for different spark timings and at full load condition. From the graph it can be revealed that, as the speed and spark timings increased brake power of hydrogen increased almost linearly but not in appreciable amount. However due to density difference the power obtained by hydrogen operation is lower by 19-23% compared with gasoline operation (Rahaman et al. 2009).

5.2.3.2.2 Brake Thermal Efficiency (BTE):

Figure5.26 (b) shows the variations of brake thermal efficiency with three spark timing at different engine speeds and at full load condition. From the plot, it is found that brake thermal efficiency has improved for spark advancement whereas decreased for retard condition. This is also supported by Alasfour (1998) and Shivaprasad et al. (2015). As shown in plot, brake thermal efficiency is 4.1% higher at 8 bTDC and 0.6% lower at 2 bTDC than static ignition operation for hydrogen compared with gasoline operation.

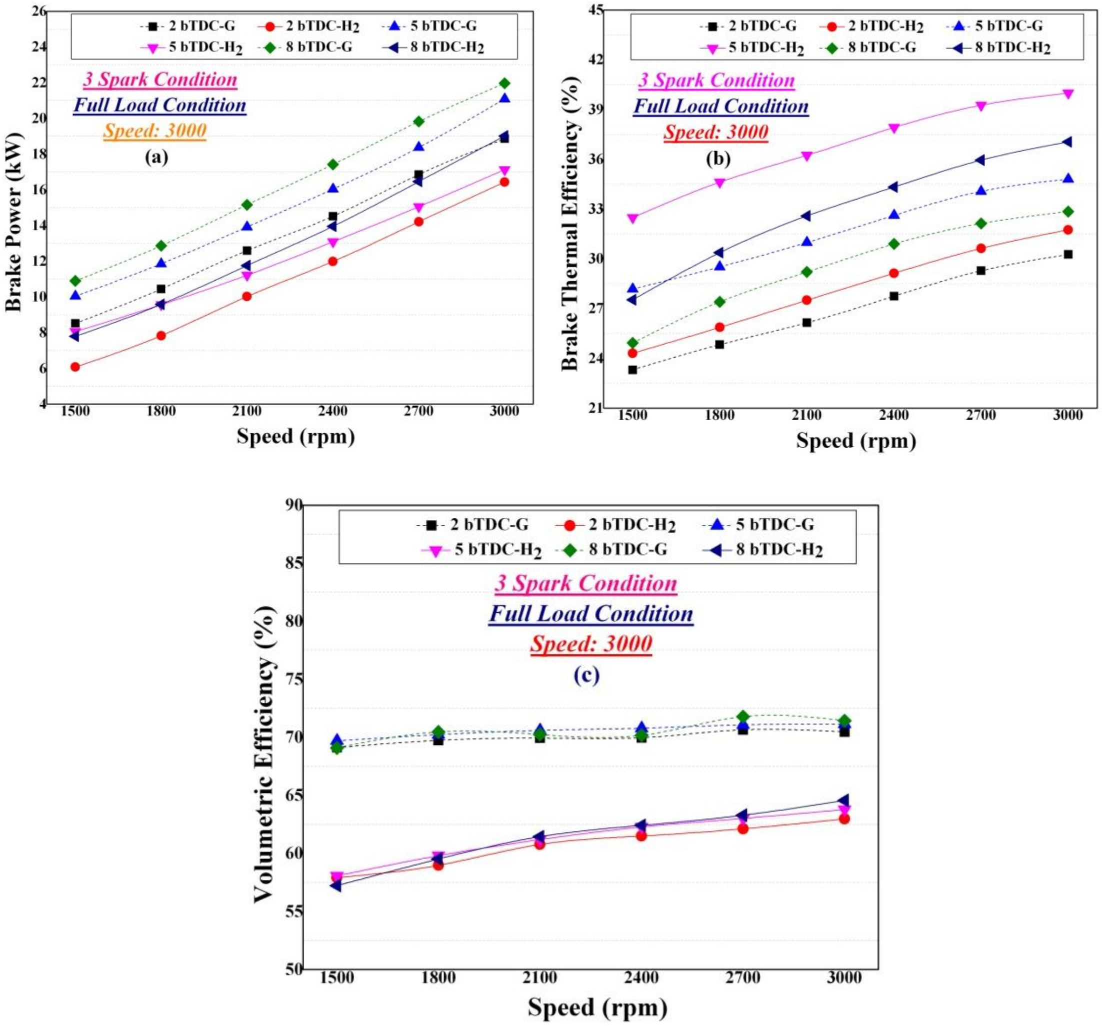


Fig.5.26 Performance Characteristics for Three Spark Timings

(a) Brake Power (b) Brake Thermal Efficiency (c) Volumetric Efficiency

5.2.3.2.3 Volumetric Efficiency: The Figure 5.26 (c) indicates the variation of volumetric efficiency for hydrogen with different engine speeds at different spark timings for full load condition. As observed from the plot volumetric efficiency decreases for both the spark timings than static timing this is due to pumping losses and as less air is drawn into the cylinder due to low density of hydrogen which displaces more air (Alasfour 1998).

5.2.3.3 Emissions Characteristics: This section provides the emission results of experiments conducted with hydrogen and gasoline at full load condition for three spark timings. Detailed exhaust emission graphs are shown in Figure 5.27 which compares toxic emissions for neat hydrogen with gasoline fuel.

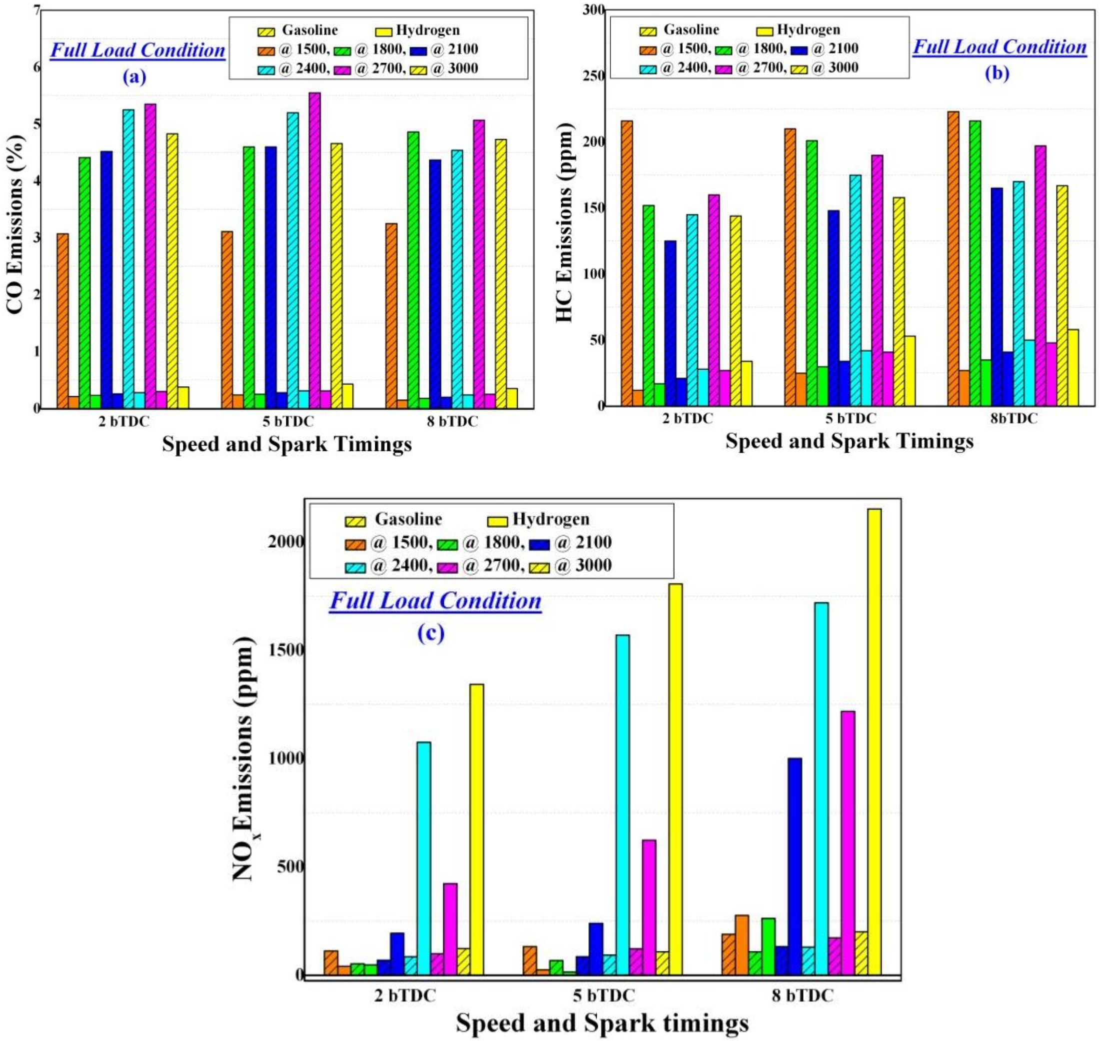


Fig.5.27 Emission Characteristics for Three Spark Timings

(a) CO Emissions (b) HC Emissions (c) NO_x Emission

5.2.3.3.1 Carbon Monoxide (CO)

Figure 5.27 (a) shows the carbon monoxide (CO) emissions. Neat hydrogen yielded very least amount of CO emission compared with gasoline. This is mainly because of wide flammable range and high flame speed of hydrogen which consumes adjacent air very quickly thus reducing post combustion period and CO oxidation time causing drop in CO emissions (Ji et al. 2012). From the figure it can be inferred that CO emission is decreased for hydrogen compared to gasoline but increases as the speed increases at all spark timings (Shivaprasad et al. 2016). However least emissions were observed for 8 bTDC condition in comparison with other spark conditions. There is a decrement of around 90-95% CO emission for all 2, 5 and 8 bTDC spark timing observed for neat hydrogen compared to gasoline operation at full load condition.

5.2.3.3.2 Hydrocarbon (HC)

Figure 5.27 (b) shows the hydrocarbon (HC) emissions. These are results of traces of oil present or trapping of unburned fuel air mixture within the cylinder. It was found that HC emissions are improved with neat hydrogen compared to gasoline fuel. Least values of HC emissions are observed for hydrogen operation, this was mainly because of presence of lubricating oil inside the combustion chamber. Shorter quenching distance, high flame speed and high diffusivity of hydrogen helps in reduction of HC emissions by increasing formation rate of OH radicals (Das 1991).

5.2.3.3.3 Oxides of Nitrogen (NO_x)

Figure 5.27 (c) shows the oxides of nitrogen (NO_x) which are prime emissions when hydrogen is used in IC engines. One of the most important engine variables that effect NO_x emission is the combustion temperature. Due to proper mixing of gaseous fuels with air causes an increase in the burning rate of the fuel and thus results in the complete combustion of the fuel. Hence the cylinder pressures and combustion temperatures will increase. This will lead in increment of NO_x emission. At Full load condition, NO_x emission is more for hydrogen compared to other throttle positions and gasoline. This is due to wide range of flammability of hydrogen and high combustion temperature attainment and in addition, there is an excess of oxygen that can combine with the nitrogen to form various oxides (Das 1991, Wang et al. 2014). NO_x emissions are lower for 8 bTDC condition compared with other spark timings.

5.2.3.4 Concluding Remarks on Comparison:

Thorough comparisons of the neat hydrogen operation with three spark timings with full load condition for the analysis of performance, combustion and emission led to the following remarks.

1. **Combustion Characteristics:** Higher cylinder pressure and net heat release rate is observed for 8 bTDC spark timing in comparison among three spark conditions. Maximum value of 46.51 bar cylinder pressure and 29.31 J/degree net heat release rate is observed at 8 bTDC spark timing.
2. **Performance Characteristics:** Compared among the three sparks condition for performance characteristics, brake power of neat hydrogen for 8 bTDC spark condition found to be improved compared with other two spark condition.
3. Brake thermal efficiency found to be lower for both the test ignition timings compared to static ignition timing. However brake thermal efficiency for 8 bTDC conditions found to be superior in comparison with 2 bTDC condition.
4. Volumetric efficiency found to be decreased for neat hydrogen operation compared with gasoline, and volumetric efficiency for both the test ignition timings (2 & 8 bTDC) is observed to be lower compared with static ignition timing of 5 bTDC.
5. **Emission Characteristics:** Carbon monoxide (CO) and Hydrocarbon (HC) emissions were found to be negligibly small for neat hydrogen operation in comparison with gasoline. CO emissions found to be least; HC emissions were moderately lower. Oxides of Nitrogen (NO_x) emissions were increased drastically with neat hydrogen for all three spark conditions compared with its counter fuel gasoline. However these emissions found to substantially lower for 8 bTDC condition compared with other 2 and 5 bTDC spark conditions.

These remarkable observations on comparison with spark timings for neat hydrogen have led us to select 8 bTDC conditions for further analysis with turbocharging to improve the brake thermal efficiency, volumetric efficiency and NO_x emissions.

5.3 ANALYSIS OF NEAT HYDROGEN WITH TURBOCHARGING FOR FULL LOAD AT 8 bTDC SPARK CONDITION

This section explores the experimental results of investigations on engine performance, combustion and emission characteristics for gasoline and neat hydrogen for turbocharging at 8 bTDC spark condition. A set of experiments has been carried out on the engine operating with full load condition for analysis.

5.3.1 Combustion Characteristics:

Combustion characteristics like pressure- crank angle, net heat release rate with full load and turbocharging condition at optimized 8 bTDC spark timing is discussed in this section.

5.3.1.1 P-θ Diagram:

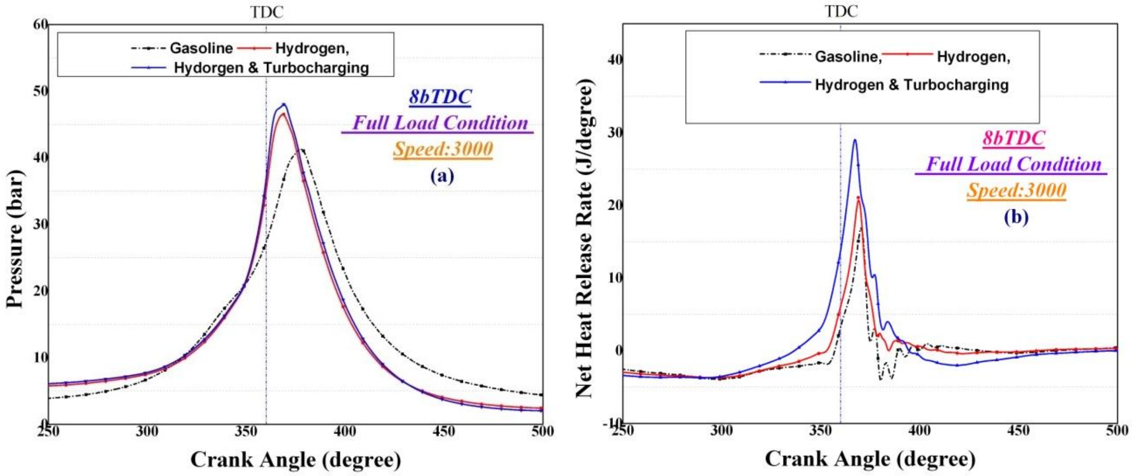


Fig.5.28 Combustion Characteristics for Turbocharging at 8 bTDC Condition

(a) Pressure - Crank angle (P-Theta) (b) Net Heat Release Rate

The pressure-crank angle diagram for gasoline, hydrogen and hydrogen with turbocharging at a speed of 3000 rpm for full load and at 8 bTDC condition is shown in Figure 5.28(a). As depicted in figure, the cylinder pressure is improved with neat hydrogen for turbocharging in comparison with gasoline. This is due to compatible property like high adiabatic temperature and high flame speed of hydrogen (Du et al. 2016) the combustion has improved and relatively raised pressure and temperature. Also peak pressure of hydrogen fuel was shifted towards the TDC position in comparison with its counter fuel (Ji et al. 2010a). The maximum value of 48.03 bars is observed for turbocharged hydrogen against 46.51 and 41.29 bar of hydrogen and gasoline operation respectively which is 12.64% and 3.26% higher.

5.3.1.2 Net Heat Release Rate:

The variation of the net heat release rate against the crank angle for gasoline, hydrogen and turbocharged hydrogen at 8 bTDC for full load condition and at 3000 rpm speed is shown in Figure 5.28 (b). Graph discloses that rate of heat release is improved with hydrogen and turbocharge hydrogen compared to gasoline. This is mainly because of boost pressure which increased the hydrogen’s fuel density and high rate of combustion within shorter period. This quality of hydrogen leads to reach higher value of net heat release rate nearer to TDC while reducing cyclic variations (Wang et al. 2012). The net heat release rate of 29.31 J/degree is observed for turbocharged hydrogen against 19.28 and 17.04 J/degree of hydrogen and gasoline respectively.

5.3.2 Performance Characteristics:

This section explores the engine performance results such as brake power, brake thermal efficiency and volumetric efficiency for gasoline, hydrogen and turbocharged hydrogen at 8 bTDC spark timing and full load condition.

5.3.2.1 Brake Power:

Figure 5.29 (a) demonstrations the plot of brake power with the engine speeds for gasoline, hydrogen and turbocharged hydrogen at 8 bTDC and for full load condition. The influx of fuel is more in full load condition, this result in the higher power generation in the larger throttle valve openings (Verhelst et al. 2009, Boretti 2011). From the graph it can be revealed that, brake power of hydrogen is increased further with turbocharging compared to hydrogen but not comparable with gasoline. This improvement is less in comparison with gasoline. Maximum value of 21.71 kW is observed for turbocharged hydrogen which is 2.84% higher in comparison with hydrogen.

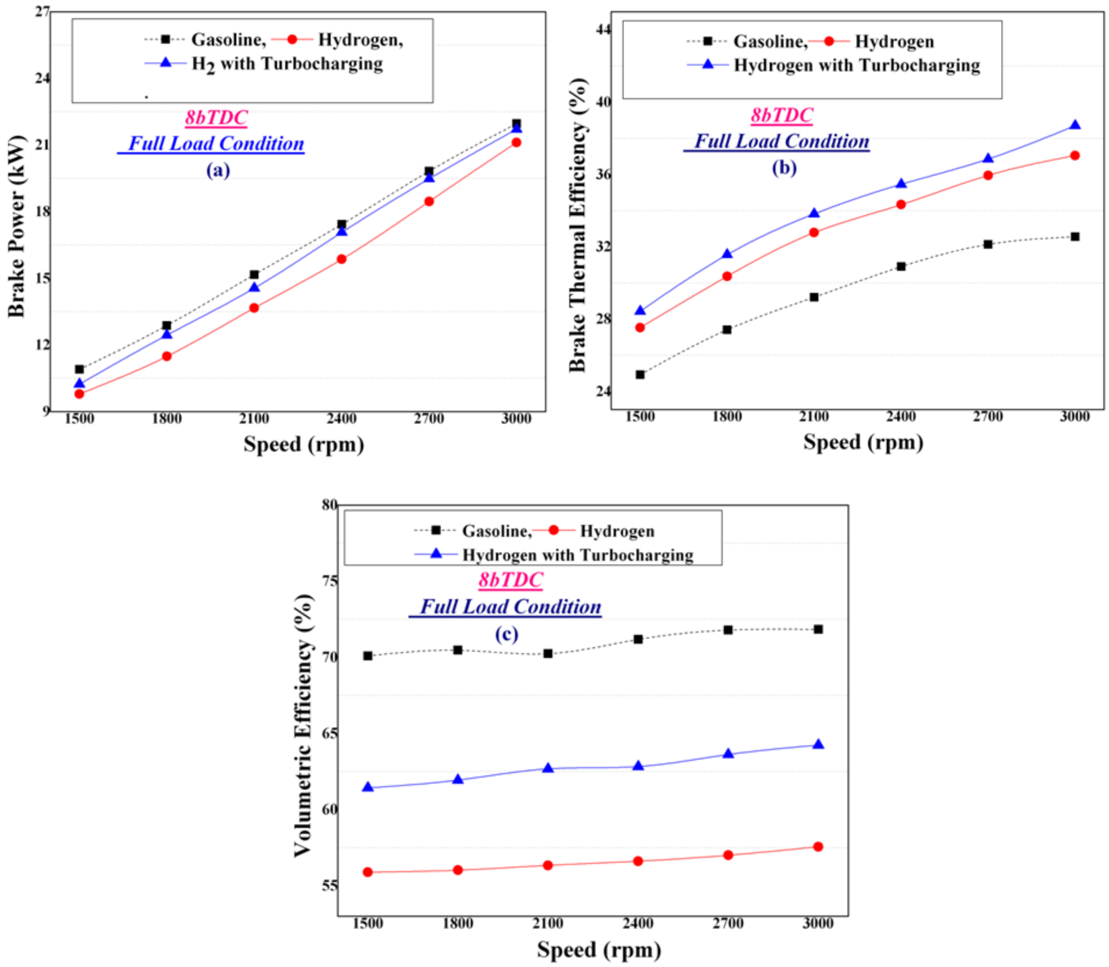


Fig.5.29 Performance Characteristics for Turbocharging at 8 bTDC Condition

(a) Brake Power (b) Brake Thermal Efficiency (c) Volumetric Efficiency

5.3.2.2 Brake Thermal Efficiency:

Figure 5.29 (b) shows the variations of brake thermal efficiency for gasoline, hydrogen and turbocharged hydrogen at 8 bTDC at different engine speeds and for full load condition. From the graph, it can be found that turbocharged hydrogen operation yielded higher efficiency than hydrogen and gasoline operation (Furuhama and Fukuma 1986, obermair et al. 2010). Maximum brake thermal efficiency of 38.7% is observed for turbocharged hydrogen operation counter to 37.04 and 32.55% of hydrogen and gasoline. Average of 3% and 14.6% improvement in efficiency found for turbocharged hydrogen compared to hydrogen and gasoline.

5.3.2.3 Volumetric Efficiency:

The Figure 5.29 (c) indicates the graph of volumetric efficiency for gasoline, hydrogen and turbocharged hydrogen at 8 bTDC for different engine speeds and at full load condition. From the plot it is revealed that volumetric efficiency increased for turbocharged hydrogen compared to hydrogen by 11.58%. Average of 2.8% increment was found for turbocharged hydrogen operation, this is due to boosting of air/fuel mixture density by turbocharging which improves the volumetric efficiency. However this improvement is lower in comparison to gasoline operation.

5.3.3 Emissions Characteristics:

Detailed exhaust emission graphs was shown in figure 5.30 which compares toxic emissions of CO, HC and NO_x for gasoline, hydrogen and turbocharged hydrogen at 8 bTDC for full load and all speed conditions.

5.3.3.1 CO Emissions

Figure5.30 (a) shows CO emissions, which are result of incomplete combustion of the fuel or because of presence of residual oil/gas fraction. CO emissions found to be slightly reduced with turbocharged hydrogen compared to hydrogen. This is mainly because of wide flammable range; high flame speed of hydrogen and turbocharging which boosts combustion by the addition of pressurized gas hence reduces post combustion period and CO oxidation time causing drop in CO emissions which is also confirmed from literatures (Ma et al. 2010, Ji et al. 2009b, 2012). From the figure 5.30 (a) it can be inferred that CO emission is decreased for turbocharged hydrogen operation compared to gasoline but increases marginally as the speed increases. Maximum value of 0.32% which is 8.57% lower in comparison with hydrogen is observed at 3000 rpm speed.

5.3.3.2 HC Emissions

Figure5.30 (b) shows the hydrocarbon (HC) emissions which are results of traces of oil present or trapping of unburned fuel air mixture within the cylinder. It was found that turbocharging condition compared non-turbocharged operation with hydrogen resulted in lower emissions. It was also observed that as the speed increases the HC emissions also increases for all cases of hydrogen operation.

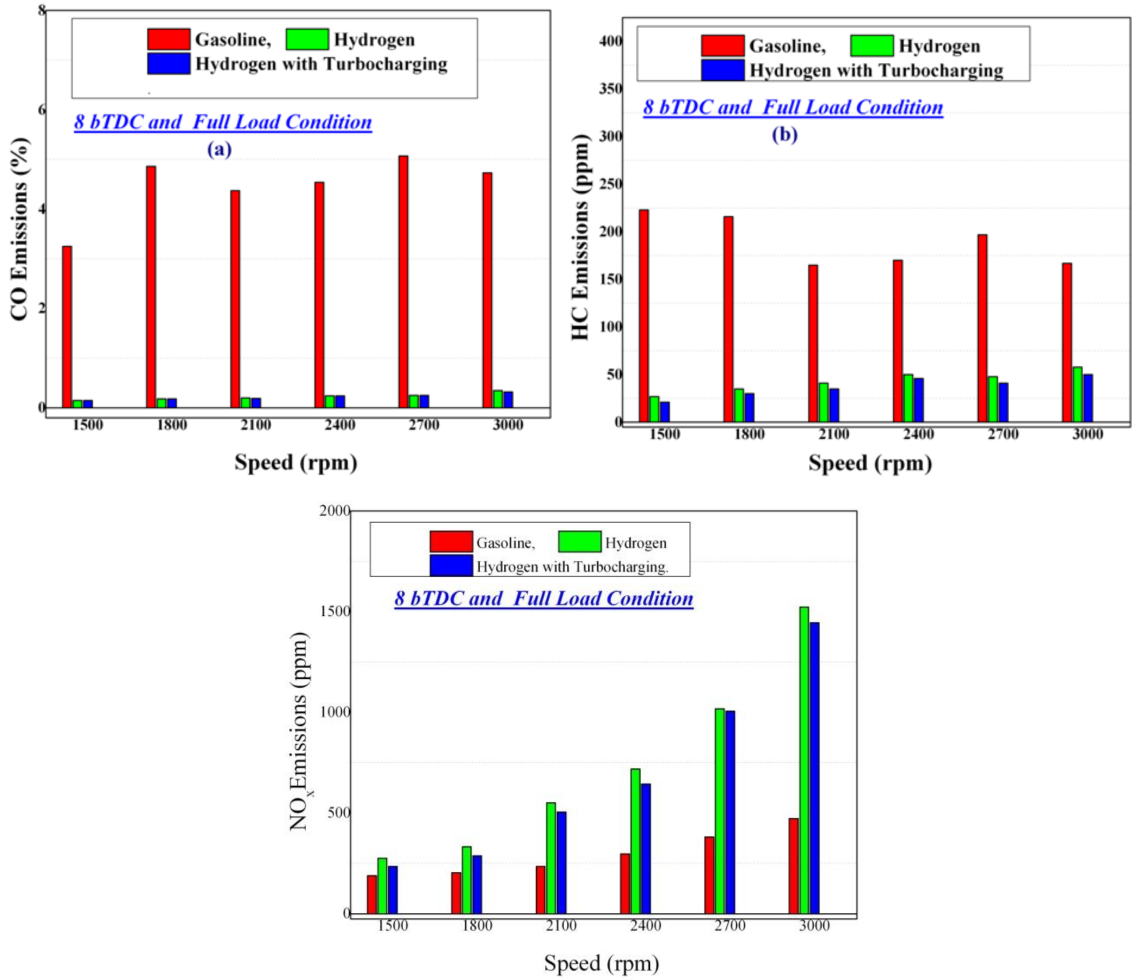


Fig.5.30 Emission Characteristics of Turbocharging at 8 bTDC Condition

(a) CO Emissions (b) HC Emissions (c) NO_x Emission

Hydrogen's high flame speed, high diffusivity along with turbocharging helps in reducing HC emissions by increasing formation rate of OH radicals (Ji and Wang 2009b). Maximum value of 50 ppm is found for 3000 rpm speed which is 13.79% lower compared to hydrogen and maximum decrease of 14.58% is observed at 2700 rpm speed against hydrogen by turbocharged operation.

5.3.3.3 NO_x Emissions

Figure 5.30 (c) shows the oxides of nitrogen (NO_x) emissions which are the prime emissions when hydrogen is used in IC engines. Hydrogen operation yielded high NO_x values compared to gasoline. One of the most important engine variables that effect NO_x emission is the combustion temperature. But due to turbocharging this combustion temperature is abated thus reducing NO_x emissions. Proper mixing of gaseous fuels with excess air produced by turbocharging caused decrease in NO_x emission (Kumar et al. 1985, Obermair et al. 2010, Zhen and Yang 2013). Highest value of 1445 ppm is observed for turbocharged hydrogen counter to 1523 ppm of hydrogen operation at 3000 rpm. This is 5.12% lower compared to earlier operation with hydrogen.

5.3.4 Concluding Remarks on Turbocharging:

Experiments with neat hydrogen operation at full load and at 8 bTDC spark timing for the analysis of performance, combustion and emission directed to the following remarks.

1. **Combustion Characteristics:** Higher cylinder pressure and net heat release rate is observed for 8 bTDC spark timing in comparison with gasoline and hydrogen operation.
2. **Performance Characteristics:** Brake power of turbocharged hydrogen for 8 bTDC spark condition found to be improved compared with hydrogen but slightly low compared to gasoline condition.
3. Brake thermal efficiency for turbocharging found to be improved compared with hydrogen and gasoline operation.
4. Volumetric efficiency, found to be increased for hydrogen with turbocharged operation compared with hydrogen, but in comparison with gasoline it is lower.
5. **Emission Characteristics:** There is not much significant reduction is observed for carbon monoxide (CO) emissions, but slight lower values of Hydrocarbon (HC) emissions were found with hydrogen and gasoline operation for turbocharged hydrogen fuel condition. Oxides of Nitrogen (NO_x) emissions were

decreased marginally with turbocharged hydrogen compared with earlier hydrogen version. However these emissions are high in respect of gasoline.

These notable observations on comparison with turbocharged hydrogen fuel have directed us to make use of water mixed with methanol to control the NO_x emissions further and to verify the performance and combustion parameters.

5.4 ANALYSIS OF NEAT HYDROGEN WITH TURBOCHARGING AND WATER-METHANOL INJECTION FOR 8 bTDC SPARK CONDITION:

This section explores the experimental results of investigations on engine performance, combustion and emission characteristics for hydrogen and gasoline with turbocharging and water-methanol injection at 8 bTDC spark condition. Set of experiments has been carried out on the engine operating at multi speed condition, full load and at 8 bTDC spark timing for analysis.

5.4.1 Combustion Characteristics:

Combustion characteristics like pressure- crank angle, net heat release rate for hydrogen and gasoline with full load and 3000 rpm speed condition at optimized 8 bTDC spark timing with turbocharging and water-methanol injection is discussed in this section. For convenience of comparison turbocharged hydrogen is named as **hydrogen-1** and turbocharged hydrogen with water-methanol is named as **hydrogen-2**.

5.4.1.1 P-θ Diagram: The pressure-crank angle diagram for gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC and for full load condition is shown in Figure 5.31(a).

As depicted in figure, the cylinder pressure is improved for hydrogen-2 compared with hydrogen and gasoline, however slightly decreased with hydrogen-1. This is due to the fact that water-methanol injection reduces the charge temperature through vaporization and likeliness of knock and backfiring (Boretti 2011). Whereas high adiabatic temperature and high flame speed of hydrogen improves the combustion and relatively raises pressure and temperature compared with hydrogen (Du et al. 2016). Also peak pressure of hydrogen fuel was shifted towards the TDC position in comparison with its counter fuel (Ji et al. 2010a). The maximum value of 48.03 bars is observed for hydrogen-2 operation which is 2.91, 3.27 and 16.32% higher compared with hydrogen-1, neat hydrogen and gasoline respectively.

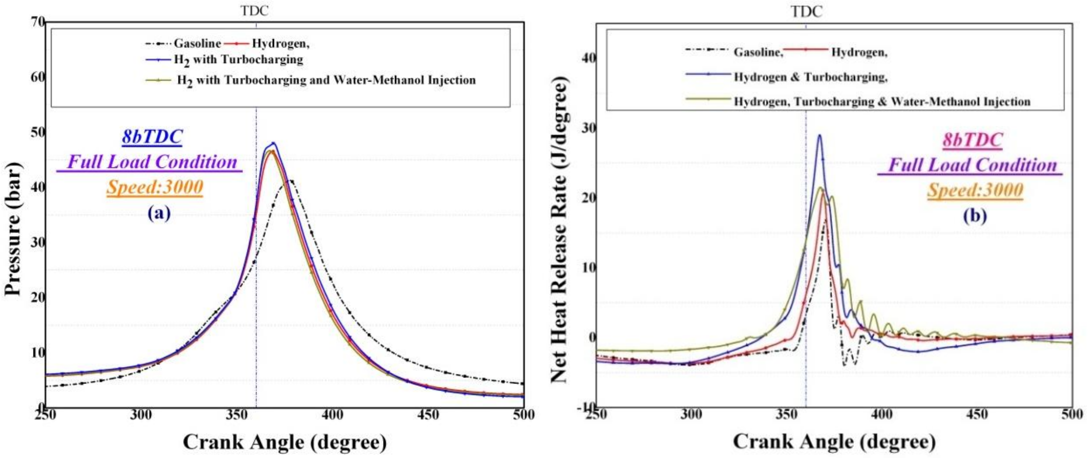


Fig.5.31 Combustion Characteristics for Turbocharging, Water-Methanol Injection

(a) Pressure - Crank angle (P-Theta) (b) Net Heat Release Rate

5.4.1.2 Net Heat Release Rate: The variation of the net heat release rate against the crank angle for gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC and for full load condition is shown in Figure 5.31(b).

From the graph it is revealed that rate of heat release is improved with neat hydrogen and its allies compared to gasoline. However heat release rate of hydrogen-2 is slightly lower compared to hydrogen-1 operation. This is mainly because of boost pressure which increased hydrogen’s fuel density and promoted high rate of combustion within shorter period. This property of hydrogen leads to reach higher value of net heat release rate nearer to TDC while reducing cyclic variations (Wang et al. 2012).The maximum value of 21.61, 29.31, 21.07 and 17.04 J/degree is observed for hydrogen-2, hydrogen-1, neat hydrogen and gasoline respectively. This rate is lower by 26.27% with hydrogen-1 option. The water and methanol combination plays a significant role in oxidizing and adding oxy-hydrogen molecules for improvement of the combustion process, and cooling down the temperature of burnt gases and cylinder thus improving NO_x emissions and further helps in preventing any abnormal anomalies if any.

5.4.2 Performance Characteristics:

This section includes the engine performance results such as brake power, brake thermal efficiency and volumetric efficiency for gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC spark timing and full load condition.

5.4.2.1 Brake Power: Figure 5.32 (a) shows the plot of brake power with the engine speeds for gasoline, hydrogen, hydrogen-1and hydrogen-2 at 8 bTDC and for full load condition.

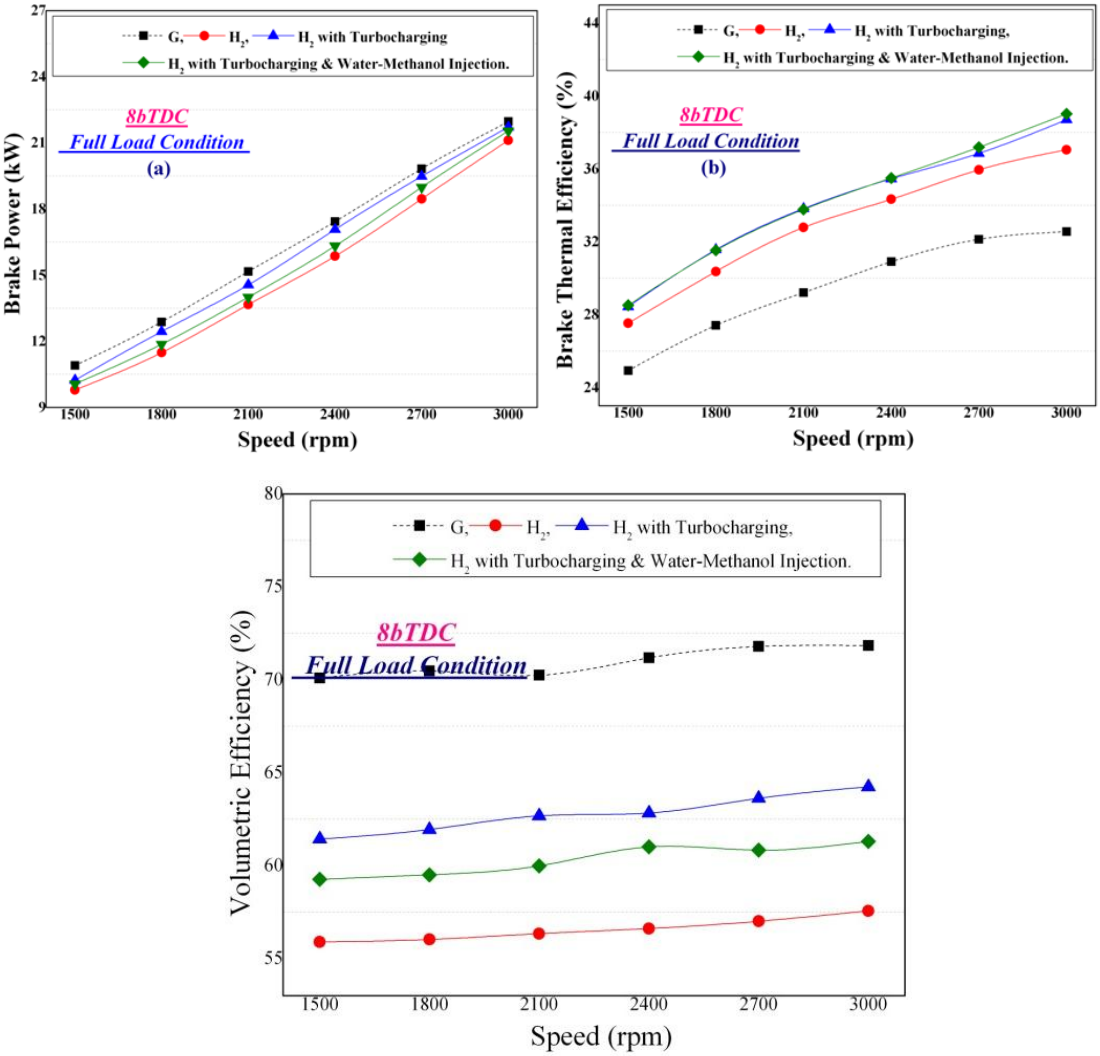


Fig.5.32 Performance Characteristics for Turbocharging, Water-Methanol Injection

(a) Brake Power (b) Brake Thermal Efficiency (c) Volumetric Efficiency

Turbocharging will lead to improve the power and water-methanol combination helps in cooling and accelerating the combustion process. This combination results in the higher power generation at full load condition (Verhelst et al. 2009, Boretti 2011). From the graph it can be revealed that, brake power of hydrogen increased with turbocharging but slightly decreased with turbocharging and water-methanol injection compared with hydrogen. However this brake power improvement is less in comparison with gasoline operation. A value of 21.54 kW is noted for hydrogen-2 compared with 21.71, 21.11 and 21.96 kW for hydrogen-1, hydrogen and gasoline operation.

5.4.2.2 Brake Thermal Efficiency: Figure 5.32 (b) displays the variations of brake thermal efficiency for gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC for different engine speeds and at full load condition. From the plot, it can be found that hydrogen-2 operation yielded higher efficiency than hydrogen and gasoline operation. However does not seem much difference against hydrogen-1 (Furuhama and Fukuma 1986, Obermair et al. 2010). Average of 3% improvement in efficiency was found for hydrogen-1/hydrogen-2 and non-turbocharged hydrogen comparison. A value of 39.02, 38.70, 37.04 and 32.55% was observed respectively for hydrogen-2, hydrogen-1, neat hydrogen and gasoline operation.

5.4.2.3 Volumetric Efficiency: The Figure5.32 (c) indicates the plot of volumetric efficiency for gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC for different engine speeds and at full load condition. From the plot it is revealed that volumetric efficiency increased for hydrogen-1 and hydrogen-2 compared to non-turbocharged hydrogen, however this value is lower compared to gasoline operation. This is due to boosting of air/fuel mixture density by turbocharging which improves the volumetric efficiency. Turbocharging (hydrogen-1) has improved the efficiency by 7% and (hydrogen-2) water injection increased 4% compared to non-turbocharged hydrogen operation. Maximum efficiency of 61.31% is reached by hydrogen-2 versus maximum efficiency of 64.24, 57.57 and 71.84% of turbocharged hydrogen, neat hydrogen and gasoline.

5.4.3 Emissions Characteristics: Detailed exhaust emission graphs is shown in figure 5.33 which compares toxic emissions of gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC for different engine speeds and at full load condition.

5.4.3.1 Carbon Monoxide (CO)

Figure 5.33 (a) compares CO emissions of gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC for different engine speeds and at full load condition.

CO emissions found to be slightly reduced with turbocharging and water injection condition compared to non-turbocharged operation. However these values are non-comparable or are too low compared to hydrogen operation. This is mainly because of wide flammability range and high flame speed of hydrogen which consumes adjacent air very quickly and oxygen from water-methanol thus reducing post combustion period and CO oxidation time causing drop in CO emissions which is also confirmed from literatures (Ma et al. 2010, Ji et al. 2009, 2012). From the Figure 5.35 (a), it can be inferred that CO emission decreases for all hydrogen and its allies operation compared to gasoline but increases marginally as the speed increases. Max value of 0.35% is observed for hydrogen with turbocharged & water-methanol injection operation (hydrogen-2).

5.4.3.2 Hydrocarbon (HC)

Figure 5.33 (b) compares HC emissions of gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC for different engine speeds and at full load condition. It was found that turbocharging and water-methanol injection condition compared to non-turbocharged operation resulted in lower emissions. However these emissions are significantly lower for hydrogen and its allies compared to gasoline fuel. It was also observed that as the speed increases the HC emissions also increases for all cases of hydrogen operation. Shorter quenching distance, high flame speed and high diffusivity of hydrogen helps in reduction of HC emissions by increasing formation rate of OH radicals (Ji and Wang 2009b) A max value of 50, 53, 58 and 167 ppm is observed for hydrogen-1, hydrogen-2, neat hydrogen and gasoline operation at 3000 rpm speed.

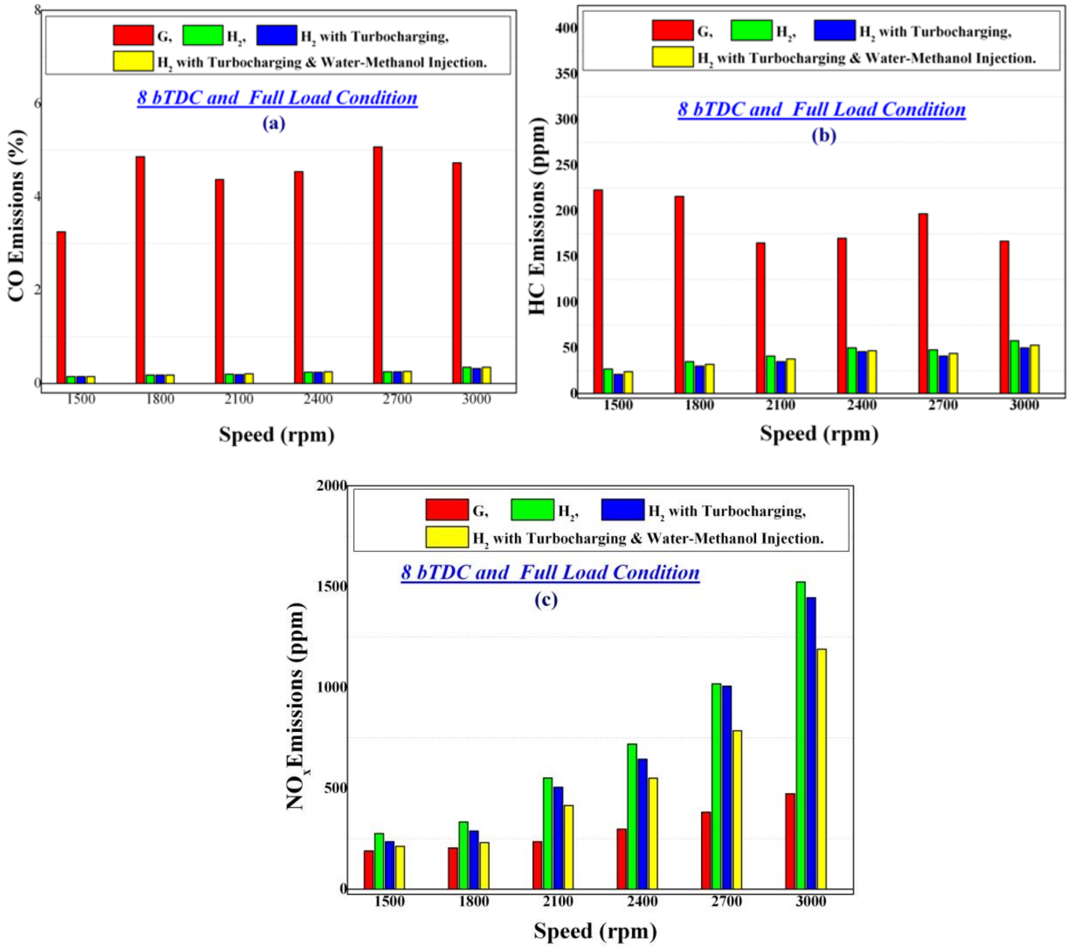


Fig.5.33 Emission Characteristics for Turbocharging, Water-Methanol Injection

(a) CO Emissions (b) HC Emissions (c) NO_x Emission

5.4.3.3 Oxide of Nitrogen (NO_x)

Figure5.33(c) shows the oxides of nitrogen (NO_x) emissions which are the prime emissions when hydrogen is used in IC engines. Figure 5.35 (c) compares toxic NO_x emissions of gasoline, hydrogen, hydrogen-1 and hydrogen-2 at 8 bTDC for different engine speeds and at full load condition.Hydrogen and its allies operation yielded high NO_x values compared to gasoline. One of the most important engine variables that effect NO_x emission is the combustion temperature. But due to turbocharging and water-methanol injection this combustion temperature is abated thus reducing NO_x emissions.

Proper mixing of gaseous fuels with excess air produced by turbocharging and temperature mitigation property of water-methanol injection caused decrease in NO_x emission (Kumar et al. 1985, Obermair et al. 2010, Zhen and Yang 2013). Maximum value of 1190 ppm NO_x emissions were observed for hydrogen-2 versus 1445, 1523 and 473 ppm for hydrogen-1, neat hydrogen and gasoline respectively.

5.4.4 Concluding Remark on Turbocharging with Water-Methanol Injection:

Experiments for neat hydrogen with turbocharging and water-methanol injection at full load at 8 bTDC spark timing for the analysis of performance, combustion and emission directed to the following remarks.

1. **Combustion Characteristics:** Cylinder pressure and net heat release rate is slightly increased compared to other operations with hydrogen.
2. **Performance Characteristics:** Brake power slightly reduced compared with hydrogen-1 but slightly higher compared to neat hydrogen operation.
3. No significant variation found for brake thermal efficiency compared with hydrogen with turbocharging (hydrogen-1) but elevated compared to neat hydrogen.
4. Volumetric efficiency, found to be increased compared with hydrogen but slightly reduced with turbocharged (hydrogen-1) operation, but in comparison with gasoline it is lower.
5. **Emission Characteristics:** There is no significant variation observed for Carbon monoxide (CO) emissions, but slight higher values of Hydrocarbon (HC) emissions were found. Oxides of nitrogen (NO_x) emissions were decreased with hydrogen with turbocharging (hydrogen-1) & water-methanol injection (hydrogen-2) compared with earlier hydrogen version. However these emissions are high in respect of gasoline.

5.5 INVESTIGATION OF NEAT HYDROGEN FUEL AT IDLE CONDITION

For an engine, idle condition plays an important role and its performance has a great influence on fuel economy, exhaust emissions and operational performance. This section provides the results of the experiments which have been conducted to investigate the effect of neat hydrogen fuel on combustion and emission characteristics for idle condition at 1500 rpm speed.

5.5.1 Combustion Characteristics:

Combustion characteristics like pressure- crank angle, net heat release rate at 1500 rpm speed and idle condition is discussed in this section.

5.5.1.1 P-θ Diagram:

The pressure-crank angle diagram for gasoline and neat hydrogen is shown in Figure 5.34 (a). As depicted in figure, the cylinder pressure is drastically elevated with neat hydrogen in comparison with gasoline. Owing to high adiabatic temperature and high flame speed of hydrogen the combustion has improved and relatively raised pressure and temperature which is also supported in (Han et al.1999). The peak pressure attained by the neat hydrogen fuel is 15.2 bars which is 14% higher than gasoline fuel (13.3 bars). Also peak pressure of hydrogen fuel was shifted towards the TDC position in comparison with its counter fuel.

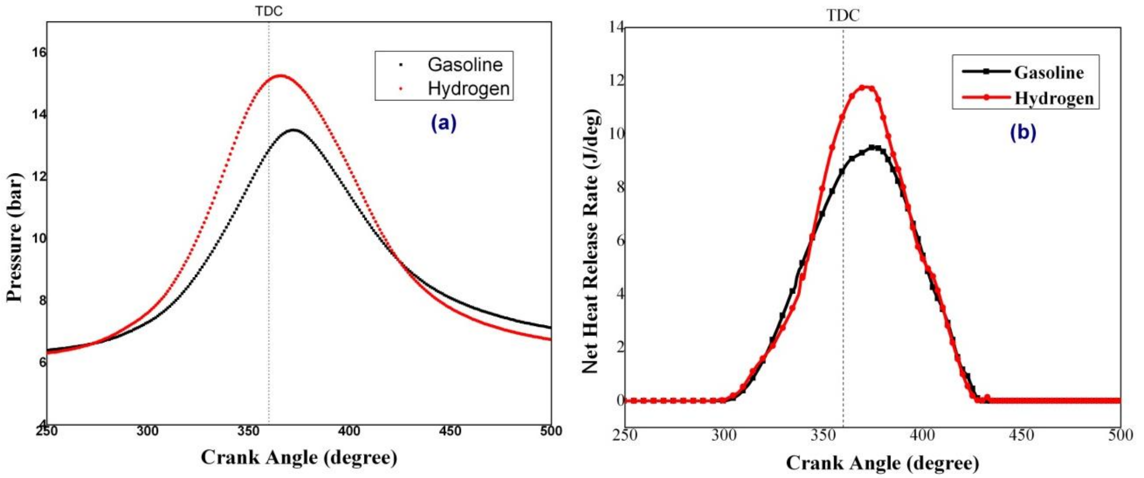


Fig. 5.34 Combustion Characteristics of Hydrogen & Gasoline at Idle Condition

(a) Pressure - Crank angle (P-Theta) (b) Net Heat Release Rate

5.5.1.2 Net Heat Release Rate: The variation of the net heat release rate against the crank angle for both the fuels at idle condition is shown in Figure 5.34 (b). From the graph it can be revealed that rate of heat release is improved with neat hydrogen compared to gasoline. This is mainly because of hydrogen's faster flame front propagation and high rate of combustion within shorter period. This quality of hydrogen leads to reach higher value of net heat release rate nearer to TDC while reducing cyclic variations. It is also supported by (Ji and Wang 2009a). The peak value of net heat release of about 11.8 J/degree is observed for neat hydrogen.

5.5.2 Emissions Characteristics:

At idle operating conditions SI engines suffers poor combustion and expel considerable amount of toxic emissions namely carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x) than at normal operating conditions. But hydrogen has better combustion qualities compared to gasoline, therefore the engine emissions seems to be better with it and supposed to yield only NO_x emissions as it is non-carbon content fuel (Verhelst 2014). Detailed exhaust emission plot was made in Figure 5.35 which compares toxic emissions of neat hydrogen with gasoline fuel at idle condition.

5.5.2.1 Carbon Monoxide (CO) Emissions:

Carbon monoxide (CO) emissions are result of incomplete combustion of the fuel. Because of presence of residual gas fraction, it was expected some minimum amount of CO emissions but surprisingly neat hydrogen yielded almost zero amount of CO emission compared with 0.4 ppm of gasoline. This is mainly due to improved combustion, caused by hydrogen because of its wide flammability range and high flame speed which consumes adjacent air very quickly thus reducing post combustion period and CO oxidation time causing drop in CO emissions (Ji et al. 2012). Therefore essential time for CO oxidation reaction decreases causing reduction in CO emission.

5.5.2.2 Hydro Carbon (HC) Emissions:

Hydrocarbon (HC) emissions are results of traces of oil present or trapping of unburned fuel air mixture within the cylinder. We found that neat hydrogen has yielded very less amount (11.5 ppm) of HC emissions compared to gasoline fuel (66.5ppm). This was mainly because of presence of lubricating oil inside the combustion chamber. Shorter quenching distance, high flame speed and high diffusivity of hydrogen helps in reduction of HC emissions by improved chain reaction and increasing formation rate of OH radicals (Ji and Wang 2009a).

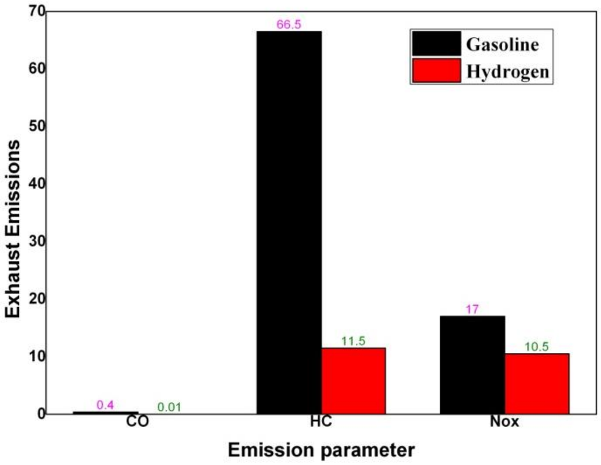


Fig.5.35 Exhaust Emissions for Hydrogen & Gasoline at Idle Condition

5.5.2.3 Oxides of Nitrogen (NO_x) Emissions

Oxides of Nitrogen (NO_x) are the prime emissions when hydrogen is used in IC engines. But from the following plot it was found that NO_x emissions were also found lower for neat hydrogen operation than gasoline fuel at specified condition. This was mainly because of non-availability of air to form oxides of nitrogen though temperature was high (Kahraman et al. 2007). Neat hydrogen has produced only 10.5 ppm of NO_x against 17 ppm of gasoline fuel.

5.5.3 Concluding Remarks on Idling:

On the basis of experimental results obtained from the investigation on use of neat hydrogen in SI engine, the following conclusions are highlighted.

1. Cylinder pressure was raised drastically with neat hydrogen than gasoline fuel. There was an increment of 1.9 bar pressure was observed with neat hydrogen. It was also observed that peak pressure moved towards the TDC position.
2. Net heat release rate has improved by neat hydrogen than that of gasoline fuel.
3. There was reduction in toxic emissions such as CO, HC and NO_x for neat hydrogen operation than that of gasoline fuel. It was observed that CO, HC and NO_x emissions were 0.01, 11.5 and 10.5ppm for neat hydrogen against of 0.4, 66.5 and 17 ppm of gasoline fuel respectively.

CHAPTER 6

CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 CONCLUSIONS

The present investigation is to study the performance, combustion and emission features of neat hydrogen fuel on a four cylinder 4-stroke MPFI SI engine. After exhaustive experimental analysis, the following conclusions are drawn.

- ✓ Cylinder pressure is drastically raised with neat hydrogen and was shifted towards the TDC in comparison with gasoline. Maximum raise in pressure of 30.27, 44.76 and 46.51 bar for 2, 5 and 8 bTDC respectively observed for neat hydrogen compared against 29.69, 33.3 and 41.29 bars at respective spark timings to gasoline operation.
- ✓ Cylinder pressure is also found improved with turbocharging and water-methanol injection on hydrogen fuel. The maximum value of 48.03 bars is observed for turbocharging with water-methanol operation which is 2.91, 3.27 and 16.32% higher compared with hydrogen with turbocharging, hydrogen and gasoline respectively.
- ✓ Net heat release rate is improved with neat hydrogen and its allies compared to gasoline. The maximum net heat release rate of 23.64, 15.62 and 29.31 J/degree is observed for 2, 5 and 8 bTDC respectively for neat hydrogen compared against 20.73, 13.27 and 21.61 J/degree at respective spark timings to gasoline operation.
- ✓ The maximum value of 21.61, 29.31, 21.07 and 17.04 J/degree is observed for hydrogen with turbocharging & water-methanol injection (hydrogen-2), hydrogen with turbocharging (hydrogen-1), hydrogen and gasoline respectively.
- ✓ Brake power of hydrogen operation increased almost linearly but not in appreciable amount. Maximum of 5.08, 8.12, 12.16 and 17.13 kW is observed for neat hydrogen at 3000 rpm which in average 19-20% lower compared to gasoline for all spark conditions.

- ✓ Brake power of hydrogen increased with turbocharging but slightly decreased with water injection compared to hydrogen with non-turbocharging. However this improvement is less in comparison with gasoline. A value of 21.54 kW is noted for hydrogen with turbocharging & water-methanol injection (hydrogen-2) compared with 21.71, 21.11 and 21.96 kW for hydrogen with turbocharging (hydrogen-1), hydrogen and gasoline operation.
- ✓ Brake thermal efficiency has improved for spark advancement whereas decreased for retard condition from static value. Brake thermal efficiency for hydrogen at 8 bTDC conditions is average 4.1% higher than static ignition operation, and for 2 bTDC condition it is lower by average 0.6%. Maximum brake thermal efficiency of 29,78%, 31.98%, 42.14% and 39.99% at 25, 50, 75% and full load conditions which is 21.25%, 14.5%, 14.95% and 14.91% higher than gasoline operation is revealed.
- ✓ Brake thermal efficiency for turbocharged and water injected hydrogen operation yielded higher efficiency than hydrogen and gasoline operation. However does not seem much difference among hydrogen-1 and hydrogen-2. Average of 14.6% and 3% improvement in efficiency found for turbocharged/water injected hydrogen and non-turbocharged hydrogen compared to gasoline. A value of 39.02, 38.70, 37.04 and 32.55% was observed respectively for hydrogen with turbocharged & water-methanol injected (hydrogen-2), turbocharged hydrogen (hydrogen-1), simple hydrogen and gasoline operation.
- ✓ Volumetric efficiency decreased for all the spark timings with neat hydrogen. Maximum of 26.26%, 36.55%, 40.39% and 47.07% for 25, 50, 75% and full load conditions at 3000 rpm which is 33.08%, 42.71%, 48.56% and 49.07% lower is observed for neat hydrogen.
- ✓ Volumetric efficiency increased for turbocharged/water injected hydrogen compared to non-turbocharged hydrogen, however this value is lower compared to gasoline operation. Turbocharging has improved the efficiency by 7% and water injection increased 4% compared to non-turbocharged hydrogen operation.

Maximum efficiency of 61.31% is reached by hydrogen with turbocharged & water-methanol (hydrogen-2) versus maximum efficiency of 64.24, 57.57 and 71.84% of turbocharged hydrogen (hydrogen-1), simple hydrogen and gasoline.

- ✓ CO emission is decreased for hydrogen compared to gasoline at all spark timings. Least emissions were observed for 8 bTDC condition in comparison with other spark conditions. There is a decrement of around 90-95% CO emission for all spark timing observed for neat hydrogen.
- ✓ CO emissions found to be slightly reduced with turbocharging and water injection (hydrogen-2) compared to non-turbocharged operation. However these values are too low compared to gasoline operation. Max value of 0.35% is observed for hydrogen with turbocharged & water-methanol injection (hydrogen-2) operation.
- ✓ Neat hydrogen has yielded very less amount of HC emissions compared to gasoline fuel. Also HC for turbocharging and water-methanol injection compared to non-turbocharged operation resulted in lower emissions. A max value of 50, 53, 58 and 167 ppm is observed for hydrogen with turbocharger (hydrogen-1), hydrogen with turbocharged & water-methanol injected (hydrogen-2), neat hydrogen and gasoline operation at 3000 rpm speed.
- ✓ NO_x emissions are higher by 100-225% for hydrogen than gasoline. NO_x emissions are lower for 8 bTDC condition compared with other spark timings. For turbocharging and water injection these emissions found to be lower. Maximum value of 1190 ppm NO_x emissions were observed for hydrogen with turbocharger & water-methanol operation (hydrogen-2) versus 1445, 1523 and 473 ppm for hydrogen with turbocharging (hydrogen-1), neat hydrogen and gasoline respectively.

6.2 SCOPE FOR FUTURE WORK

There is a potential scope for carrying out of the experiments on the engine for performance, combustion and emission analysis by following ways:

- Extensive study of the engine performance can be made by adopting direct injection of gaseous hydrogen.
- Study of Engine performance, combustion and emissions characteristics can be made by using liquid hydrogen.
- Extensive studies with NO_x reduction techniques can be carried out.
- Extensive engine performance tests can be made for verifying various parameters such as equivalence ratio, ignition timings, and pulse width time.
- Study for investigation on the cyclic variations in the combustion can be undertaken.

APPENDIXES

Appendix-I

Specifications of the Gasoline Engine and other Instrumentation

Engine	Make: Maruti, Model: Zen MPFI, Type: 4 Cylinder, 4Stroke, Petrol (MPFI), water cooled, Power: 44.5kW @ 6000 rpm, Torque: 78.5Nm @ 4500rpm, Stroke: 61mm, Bore: 72mm, Capacity: 993 cc, Compression Ratio: 9.4:1
Dynamometer	Make: SAJ, Model: AG80, Type: Eddy current, Water cooled.
Dynamometer Loading unit	Make: Cuadra, Model AX-153, Type: Variable speed, Supply 230V AC.
Propeller Shaft	Make: Hindustan Hardy Spicer, Model: 1260, Type: A, with universal joints
Air Box	M S fabricated with orifice meter and manometer
Fuel tank	Capacity 15 lit with glass fuel metering column
Manometer	Make: Apex, Model: MX-104, Range 100-0-100 mm, Type U tube
Piezo sensor	Make: PCB Piezotronics, Model: HSM111A22, Range:5000 psi, Diaphragm stainless steel type and hermetic sealed
Calorimeter	Type: Pipe in pipe
Crank angle sensor	Make Kubler-Germany, Model- 8.3700.1321.0360 , Diameter: 37mm, Shaft Size: 6mm x Length 12.5mm, Supply Voltage 5-30V DC
Engine indicator	Make-Cuadra, Model AX-104, Type Duel channel
Engine interface	Make-Cuadra, Model AX-408, No of channels 8.
Temperature sensor	Type: RTD, PT100 and Thermocouple, Type K

Load sensor	Make: Sensotronics Sanmar Ltd., Model: 60001, Type: S beam, Universal, Capacity 0-50 kg, Load cell type: Strain gauge
Fuel flow transmitter	Make: Yokogawa, Model: EJA110-EMS-5A-92NN, Calibration range 0-500 mm H_2O, Output linear DP transmitter
Rotameter	Make: Eureka, Engine cooling 100-1000 lph; Calorimeter 25-250 lph
Pump	Type: Mono block
Software	IC Engine Soft - Engine performance and Combustion analysis software
Overall dimensions	W 2000 x D 2750 x H 1750 mm

Appendix –II

Details of the Engine

Item	Value
Engine Make	Maruti Suzuki India Ltd.
Engine Type /Fuel	Zen (MPFI), Petrol
No. of Cylinder	4
No. of Stroke	4
Compression ratio	9.4:1
Power	44.5kW @ 6000 rpm,
Torque	78.5Nm @ 4500 rpm
Stroke length	61 mm
Bore dia	72 mm
Capacity	993 cc
Engine Cooling	Water cooled

Appendix-III

Specifications of the gas ECU

Model: Sequential gas injection controller of IV generation OSCAR-N OBD CAN of Europe Gas

Sr. No	Parameters	Specifications
1	Processor	16bit / 50MHz
2	Voltage Supply	12 volt DC
3	Input Signals	Gas Temperature
		Gas pressure
		Petrol Injection Time
		O_2 - sensor
4	Output Signals	Gas injectors

Appendix-IV

Specifications of the five gas exhaust analyzer

Make: AVL

Measured values	Measurement range	Resolution
CO	0 ... 10 % Vol.	0.01 % Vol.
HC	0 ... 20,000 ppm	10 ppm
CO_2	0 ... 20 % Vol.	0.1 % Vol.
O_2	0 ... 22 % Vol.	0.01 % Vol.
NO	0 ... 5,000 ppm	1 ppm
Lambda	0 ... 9.999 calculated	0.001

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