Chapter 1

INTRODUCTION

With the advent of enhancing environmental and fossil energy concerns, sustainability that can be done with the utilization of alternative energy sources is of major concern. The world of today is toiling hard to solve energy related problems, such as, energy supply security, emission control, economy and conservation of energy etc. A great potential lies in the hand of automotive engineers and scientists to fulfill inhabitants' insatiable energy need as well as caring for Mother Earth's atmosphere. Energy is most important entity for the economic development of any country in the world especially in large and developing country such as India where a high fraction of the world population is in need of satisfying their energy need. These large populations have increased the demand of energy rapidly in the recent years due to accelerated pace of industrial and economic growth. Considering the environmental protection and in the context of great uncertainty in future energy supplies, awareness is concentrated on the sustainable utilization of energy sources and the energy conservation methodologies. [1] [29]

Diesel engines are widely used for satisfying this energy demand of vehicles, power generation units in many industries, hospitals, CHP, residential sectors, commercial and institutional facilities. Main advantages of these are quick startups, have good part load efficiencies, and highly reliable. However, diesel is a non-renewable energy source and takes millions of years for its formation.Indiscriminate extraction of fossil fuels and lavish consumption of them have led to reduction in underground based resource and the world is confronted with the twin crisis of fossil fuel depletion and environmental degradation and the situation is expected to exfoliate more in the coming years. This led the researchers to search for some efficient substitutes, which promises harmonious correlation with sustainable development, management, efficiency, energy conservation, and environmental preservation. Hydrogen has the potential to provide a feasible solution to the crisis. [8][29][30]

1.1 Background

Diesel engines have been developed after some experimentation by Rudolf Diesel nas he patented in 1893, thenAkroyd Stuart builds his first working Diesel engine.In 1996. Opel Vectra marketed the first DI diesel engine with four valves per cylinder and has paced the acceptability of diesel and promoted its use among consumers. [2]World's energy consumption is growing rapidly in exponential way as shown in the figure below.

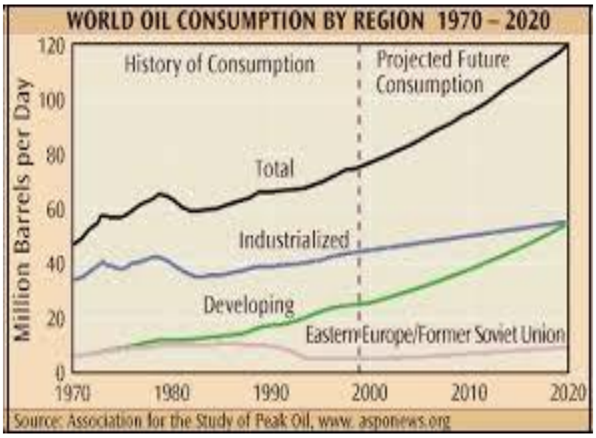


Figure 1.1: World's oil consumption [3]

Diesel fuels are highly consumed in agriculture sector, power sector and transportation sector (95% of transportation needs are met by fossil oil). It has been predicted that by the year 2016, average oil production will be highest in the world, and after that production will decline 2-3% each year and expected to wind up at a faster pace after 2050. [3]

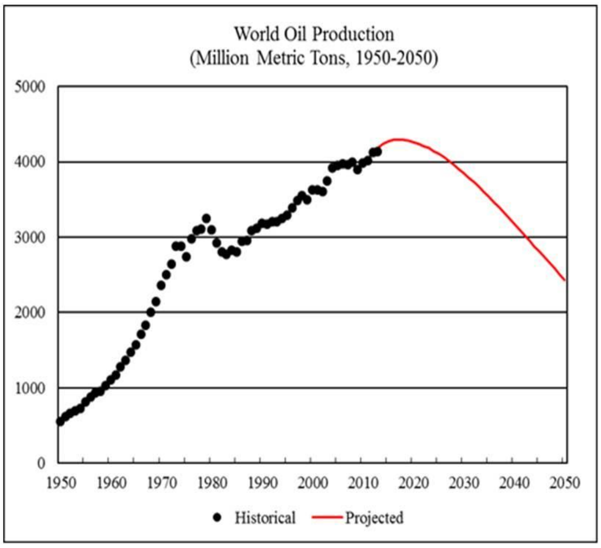


Figure 1.2: World's oil production [3]

This fossil fuels usage also causes global warming and local pollution hot spots and is further emancipating environmental and societal problems. Governments of various countries are getting concerned with their emission levels and the Kyoto protocol of

1997 that aims to reduce greenhouse gas emissions by 20% of that of 1990 levels by 2010 and has a long term goal of reducing emissions by 60% by the year 2050. This has led to the search of a cleaner alternative fuel. [4]Hydrogen may become an important energy carrier for sustained power consumption with reduced impact on the environment. It can be used in combustion devices or fuel cells without adding carbon into the atmosphere. [8]-[13],[24]-[30]

During recent years many efforts has been made by governments and diesel engine manufacturers to further improve diesel engine efficiency, reduce CO_2, and other particulate emissions, all this can be achieved by substitution of hydrogen partly. Researchers and scientists made many efforts in the past, but in most of the case investigation was not extended because at that time oil prices were low, oil availability was high and emission regulations were not so strict. But now diminishing petroleum supplies, increasing fuel cost and greenhouse effect have motivated to reduce carbon emissions and increase thermal efficiency. So scenario is altering and everybody is looking for alternative fuels. **[3]**

1.2 Alternative fuels

Alternative fuels are those fuels that are substantially non-petroleum and yield energy security and environmental benefits.

Alternative fuels that are used in engines for fueling are:

1.2.1. Alcohol (Ethanol and Methanol) is produced domestically from corn and other crops and produces less greenhouse gas emissions than conventional fuels.

1.2.2. Biodiesel is derived from vegetable oils and animal fats. It usually produces less air pollutants than petroleum-based diesel.

1.2.3. Natural gas Compressed or Liquefied (Methane)is a fossil fuel that generates less air pollutants and greenhouse gases.

1.2.4. Propane, also called liquefied petroleum gas (LPG), is a domestically abundant fossil fuel that generates less harmful air pollutants and greenhouse gases.

1.2.5. Hydrogen can be produced domestically from fossil fuels (such as coal), nuclear power, or renewable resources, such as hydropower. Fuel cell vehicles powered by pure hydrogen emit no harmful air pollutants.[6]

Fuel	Advantages	Problems
Alcohol	▪ Most of the engine related problems have been sorted out	▪ Technology of production needs further improvement ▪ Used for other purposes also
Hydrogen	▪ Clean burning ▪ Zero Carbon Pollution ▪ Lighter than air and low density makes it an inherently safe fuel	▪ Highly combustible ▪ Low energy content fuel ▪ Production, storage and handling is expensive, complex and still needs further development
LPG	▪ Reduced emissions, noise and lubricating oil deterioration ▪ Improved engine life	▪ Heavier then air, thus settles down when exposed, forming an explosive mixture ▪ Risky to handle
CNG	▪ Clean burning ▪ Improved combustion characteristics	▪ Costly operating systems involving high pressure storage (app. 200 bar) ▪ Being lighter can collect in overhead areas, creating an explosion hazard. ▪ Sudden releases due to collision damage or equipment failure can be dangerous
Producer gas	▪ Great potential in the agriculture sector	▪ Increased CO and smoke emissions.
Biogas	▪ Lean burn engine ▪ Reduced HC and CO emissions. ▪ Easy starting, reliable idling and stumble free acceleration.	▪ Storage problem ▪ Large size of plants ▪ Can be used for stationary engines
Biodiesel	▪ Domestically produced, safe and renewable fuel ▪ Reduced air pollutants such as particulates, CO, HC and air toxics. ▪ No engine modification required. ▪ Similarity in performance	▪ In some cases long term operational problems persist. ▪ Stability, solvency and material compatibility problems are there

Table 1.1*:* Alternative fuels, their advantages and problems

1.3 Energy Market Evolution

The market is evolution towards better product performance, decarbonisation and as well as satisfying customer needs. So this requirements is leading towards a greener future accomplished with alternative fuels.In this study, the potential of hydrogen in terms of its characteristics and economic and safety features are discussed and judged to know and suggest the barriers in its deployment.

3.1. Why Hydrogen is to be used?

Petroleum reserves are being depleted and prices are growing tremendously beyond our control. Bio fuels cannot meet the growing demand of fuels as like plants which provides bio-diesel requires a substantial amount of ground area, which is difficult for a country like India with so much of population. Plantation area may then scarce the residential space and vice versa.

3.2. Benefits of Hydrogen

3.2.1 Hydrogen is "the forever fuel", it won't be depleted and possess the ability to make society completely energy-independent.

3.2.2 Hydrogen can be mixed with other existing fuels and can be easily used in internal combustion engine with natural gas (commonly known as HANG), diesel, reformer gas, biomass, petroleum, etc.

3.2.3 No corrosion with conventional materials

3.2.4 It is easily available and inexpensive

3.2.5 Improve integrated engine efficiency as it is a clean burning fuel

3.2.6 Reduced energy consumption and save primary energy or fuel

3.3 Applications

Hydrogen has the capability to be used in various fields and their projected advantages are given below:

3.3.1 Transportation Sector

- Can be used in ICE (with modification, very low emissions); preferred for fuel cell (no emissions)
- Trains, automobiles, buses, and ships

3.3.2 Buildings Sector

- Combined heat, power, and fuel
- Reliable energy services for critical applications
- Grid independence

3.3.3. Industrial Sector

- Plays an important role as a chemical

- Opportunities for additional revenue streams

3.4 Physical Properties of Hydrogen

3.4.1 Element 1 on the Periodic Table (1 proton, 1 electron, no neutron)

3.4.2 Diatomic molecule (H_2) (2 protons, 2 electrons)

3.4.3 Highest energy content of common fuels on a weight basis

3.4.4 Lowest energy content of common fuels on a volume basis

3.4.5 Hydrogen is abundant on earth, but usually bound to carbon (CH_4) or oxygen (H_2O) or both (organic matter in form of carbohydrates : $C_6H_{12}O_6$)

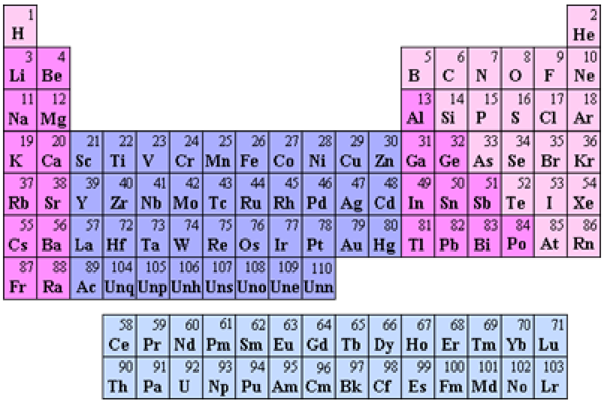


Figure 1.3: Periodic table (Source: immr.tu)

3.4.6H_2 is not found in abundance in pure state in nature although there are some underground gas deposits that have relatively high concentrations of H_2

3.4.7Most abundant element in the universe. Found in many forms on Earth

3.4.8A gas under standard conditions. Liquefies at -253 ^oC

3.4.9Odourless, Colourless, Non-toxic or non- carcinogenic

3.4.10 Highly flammable but has an invisible flame

3.4.11 No carbon in hydrogen fuel, so no production of CO,CO_2,PM emission. Any trace amount of these pollutants is due to burning of lubricating oil in combustion chamber

3.4.12 NO_x emissions are high and require specific strategies to control

3.4.13 It is more like an energy carrier rather than a fuel

3.4.14 Hydrogen is the perfect fuel to run fuel cells cause pure hydrogen reacts only with oxygen releasing water thus no emissions

3.4.15 Hydrogen burns more efficiently and creates energy more efficiently than gasoline

3.4.16 Environment friendly

3.4.17 Hydrogen, if not compressed, is available as gaseous fuel, which has many advantages like:homogeneous mixing with the air,Improved the flame propagation rates, reduces ignition lag, extends lean mixture operational limits.

3.4.18 Higher engine efficiency

3.5Fuelproperties:specific for engine application

3.5.1. Wide range of flammability

3.5.2. Low ignition energy

3.5.3. High auto ignition temperature

3.5.4. High flame speed at stoichiometric ratios

3.5.5. High diffusivity

3.5.6. Very low density

3.5.7. Energy content (9.5 kg of H_2 is equivalent to 25kg of petrol)

Fuel Type	EC per unit mass	EC per unit volume
Gasoline	1.0 (base value)	1.0 (base value)
Methanol	0.44	0.51
Ethanol	0.61	0.69
Methane	1.1	0.29
Hydrogen	2.6	0.2

Table 1.1 Comparison of fuel Energy content

Property	Hydrogen H_2	Methane CH_4	Methanol CH_3OH	Diesel	Gasoline
Boiling point (°C)	-253	-162	65	188-340	wide range
Physical state at 25°C	Gas	Gas	Liquid	Liquid	Liquid
Heating Value - weight basis					
LHV (MJ/kg)	120	48	20	42	42-44
HHV (MJ/kg)	142	53	23	44	44-46
Heating Value - volume basis					
LHV (MJ/Nm^3)	11	35	15,700	~33,000	~32,000
HHV (MJ/Nm^3)	13	39	18,100	~34,000	~33,000
Flammability limits (vol% in air)	4-75	5.3-15	6.3-65	1.4-7.6	1-8
Explosive limits (vol% in air)	18.2-58.9	5.7-14	6.7-36		1.4-3
Molecular diffusion coeff. (cm^2/sec) in air	0.61	0.16	0.13	0.01	0.05
Auto ignition temperature in air (°C)	571	632	470	220	400
Liquid density (g/liter)	77	425	792	825	720-780
Flame Speed (m/sec)	2.7	0.4	0.5	0.3	0.35

Table: 1.2 Combustible Fuel Properties (Source: Ph.D thesis,Vinod)

3.6 Ways of producing Hydrogen

Hydrogen can be obtained from many source, most common is the water splitting or electrolysis. Electrolysis requires electricity to split the water, electricity can be generated from fossil fuels, coal, natural gas, biomass, solar thermal techniques, exhaust gas of engine, nuclear fuels and other renewable energy techniques like Solar PV, hydro, wind energy. TrappingSunlight for generating electricity for electrolysis is gaining popularity. Insolation that hits earth in 1 hour is equivalent to planet's power for 1 year. Capturing solar energy is well suitable for countries like India. This also leads to a prominent green fuel then.

3.7 Barriers to use hydrogen as a mono fuel

3.7.1 When hydrogen is used as a single fuel without assistance of any other fuel, the energy efficiency of Hydrogen is comparatively lower.

3.7.2 Fuel cell costs, operational reliability and lifetimes are in quest.

3.7.3 Efficiency, safety and reliability of hydrogen storage media for mobile systems are still in developing stage.

3.7.4 Low fuel energy content per unit volume as compared to other fuels.

3.7.5 Requires high Storage Space (Liquid H_2). Storing of 9.5kg of H_2 requires 55kg tank while 25kg of petrol of 17kg tank (Energy content of 9.5kg of H_2 is equivalent to 25kg of petrol). Fuel typically takes 3 times more space than petrol for same energy content

3.7.6 Cheaper technique to produce hydrogen.

3.7.7 To develop safe, efficient and cost effective hydrogen storage media and systems.

3.7.8 It’s difficult to transport.

3.7.9 There is no infrastructure to support a Hydrogen transition.

3.7.10 It is odorless, and therefore an odorant must be added to enable detection.

3.7.11 It is invisible and thus harder to extinguish or to avoid. A flame colorant would make detection easier.

1.4 Objectives of study

In the present study of exploring opportunities for hydrogen energy sources for fueling Internal Combustion Engine, following are the main objectives:

(i) To carry out literature survey on the topic and find state of art in the field

(ii) To study existing energy sources, collect data, their advantages, and limitations.

(iii) To propose experimental investigation areas and find out the deficient areas where researches has not been conducted till date.

(iv) To design and optimize the shortcomings which deteriorate engine performance.

(v) To verify the techno-economic feasibility of deploying hydrogen assisted IC engines.

(vi) To estimate the environmental benefits due to proposed hybrid fuels

Chapter 2

LITERATURE REVIEW

Hydrogen production systems have been successfully operating in India and other countries for many decades and advancements in producing hydrogen economically has been made possible with the advent of ample researches carried out across the globe. Hydrogen can be utilized by both petrol and diesel based automobile engine systems. Hydrogen has proved its suitability and has moved from experimental stage to commercialization stage. A remarkable development has taken place in the field of utilization of hydrogen as energy source in SI engine fuel, but less experimental investigation has been done in CI engine fueled by hydrogen for which hydrogen assisted CI engine are still not in use.[10][23]

Keeping this in consideration, a detailed literature survey has been carried out on the topic and it is decided to check the feasibility of hydrogen in terms of engine performance, emission levelfor meeting the energy needs and environmental norms of consumers and Governments respectively.

Currently, many countries in the world have starting to investigate on it. Using hydrogen as an energy source has opened up a new direction for improving the efficiency of engine for its higher Calorific Value based on its mass basis. The aim is to investigate the practical possibilities of hydrogen in diesel engines, to determine the optimum conditions and the ways to mitigate the disadvantages of hydrogen in board. In the present chapter many types of experimental and numerical investigations are discussed along with coupling hydrogen system with biofuels. Effect of varying compression ratios in diesel engine fueled in dual fuel mode are studied and analyzed and correlation between VCR in hydrogen fueled CI engine is thrived. Also various updated costing and future of hydrogen is predicted assuming expected future cost of fossil fuels and Carbon taxation.

2.1 Literature on experimental works on hydrogen enriched CI engine

In these papers, the effect of hydrogen enrichment on diesel engines on the engine performance and emission characteristics is studied. Studies were conducted varying the percentage volume of hydrogen, at different engines at a particular Compression Ratio. Many research works are carried out on different engine running at different operating conditions optimizing the volume percentage of hydrogen to be used for substitution of diesel fuel, some of researches are discussed here.

Szwaja*et al* [2009] performed test on a two-cylinder in-line CI F2L511 Deutz manufacturer engine which was modified to work as a dual-fuel engine at a fixed compression ratio of 17:1. They investigated by a port fueled injection (PFI) system considering both pure hydrogen combustion under HCCI (homogeneous charge compression ignition) conditions and H_2/diesel co-combustion with various hydrogen doses in the range from 0% to 17% with respect to energypercentage in a compression ignition (CI) engine. 17% H_2 in the hydrogen–diesel–air mixture was stoichiometric and provided favorable conditions for generating combustion knock. With hydrogen of about 5% in a diesel engine shorten ignition lag and, thereby, decreases the rate of pressure rise which in long run increases engine durability. They observed that HCCI may lead to unstable engine as the fuel burns rapidly at its early stage and after their experimentation. They suggested that up to 15% H_2 substitution causes knocking free, smooth operation in hybrid diesel engine. [8]

Korakianitis*et al* [2010] experimentally investigated the effect of using hydrogen gas in CI engines via high-cetane pilot fuel ignition. In our previous studies, it was deduced that hydrogen dual-fuel operation with neat pilot fuels typically produce: high NO_x emissions; and high CC pressure rise rates, thereby, increasing knocking tendencies. In this work, he conducted his studies using two water-in-biodiesel emulsions as pilot fuels in hydrogen dual-fuel operation. Hydrogen dual-fuel operation only produces higher engine performance as compared to normal CI engine operation, while the emulsified biodiesel pilot fuels emancipates better thermal efficiencies and reduced NO_x emissions when compared with the neat biodiesel pilot fuel (without H_2) .The thermal efficiency increase is more prominent at higher engine speeds, whereas NO_x reduction is more intensified at lower engine speeds. The reduction of NO_x emission is due to the fact that emulsified pilot fuel lowers pressure rise rates compared with the neat pilot fuel, however efficiency increases due to more homogeneous charge resulting from the turbulent effect of micro-explosion of the emulsified pilot fuel. HCs, CO, $CO_2$and Smoke emissions remain comparable to neat pilot fuel tests. The general trends of reduced CO_2, reduced power output andincreased water vapour emission by hydrogen enriched diesel fuel are also maintained.[9]

Vinod*et al* [2012] conducted experiments on the dual fuel H_2 (constant flow rate of 40gm/hr) and Diesel along with EGR (of 0%,10% and 20%) as intake charge and operated a DI, single cylinder, four stroke, air-cooled, stationary diesel engine operating at CR of 16.5:1 coupled to an electric dynamometer and investigated the performance and emission characteristics of the dual fuel as compared to baseline diesel values. It has been observed from the experimentation that the dual fuel operation with hydrogen induction coupled with exhaust gas recirculation shows acceptable results. They have shown the trend of various performance parameters like BTE, BSFC, BSEC and emissions with respect to increasing load. BTE is highest for H_2+diesel operations and least for diesel +20% EGR, induction of H_2 with diesel and EGR is have a moderate acceptable BTE. Hydrogen enriched fuel shows higher BTE of 1.83% than neat diesel values. BSFC is highest for diesel+20% EGR and least for diesel+H_2. BSEC has been found highest for neat diesel with no EGR (i.e., 16426.66 kJ/kWh) and for diesel with H_2, it's been slightly higher (i.e., 17741.33 kJ/kWh). BSEC increases with increase in EGR % as then the intake air is replaced by some amount of EGR, this leads to improper combustion. Exhaust Gas Temperature is highest of 430^{O}C when H_2 is mixed as it has the property of enhanced combustion rates, for neat diesel its 415^{o}C at 80% rated load of the engine and EGT gets further reduced with induction of EGR and with increasing EGR percentage. Unburned HC, CO and CO_2 emission has been observed lower for diesel+H_2 with respect to neat diesel. Unburned HC, CO and CO_2 emission increases with % increase in EGR. NO_x emission of 470 ppm is higher in H_2 enriched diesel fuel than neat diesel case of 440 rpm at 80% load for its higher combustion temperature and it has been found that with NO_x percentage decreases with introducing EGR techniques and increasing EGR percentage. Oxygen percentage in hydrogen enriched is 15.2% by volume in Exhaust gas while that of neat diesel its 15.1% by volume. The percentage is slightly less as hydrogen does not contain carbon compounds, so less amount of carbon to react with oxygen and oxygen remains unreacted, whereas in EGR operations O_2 concentration reduces due to lower intake of fresh charge. [10]

Singh Yadav*et al* [2013] conducted an experiment in a single-cylinder, four-stroke, air-cooled, stationary DI diesel engine Kirloskar TAF1 (running at 1500 rpm, constant speed) and 4.4 kW capacity coupled to an electrical dynamometer with hydrogen-enriched air as intake charge and diesel as pilot fuel Injection timing and hydrogen flow rate were varied (80, 120, 150g/hr) to determine the optimum condition for hydrogen enrichment. The experiment results inferred that hydrogen enriched engine have maximum brake thermal efficiency and minimum brake specific energy consumption when flow rate is 120g/hr with 20° crank angle BTDC. BTE has been found to bemaximum with 16.4% hydrogen addition and at around 70% of full load but when operated with diesel BTE is maximum at around 80 %of full load and the values for baseline diesels are lower without hydrogen enrichment. Brake thermal efficiency increased by 11.6% with the supply of 120 gm/hr of hydrogen at optimum injection timing and at 70% of full load in comparison to neat diesel for the reason that hydrogen is a clean fuel. Then after finding the flow rate of 120g/hr as favourable and beneficial in terms of maximum BTE, studies have been conducted considering 120g/hr flow rate to find the other performance parameters like BSEC and other emission effects. A significant reduction in BSEC in case of hydrogen enrichment was observed i.e., 31.8 % less as compared to that of neat diesel operation at 70% full load operations due to higher calorific value of hydrogen at mass basis and 20^{o} CA BTDC has been found favourable. Neat diesel has favorable injection timing of 23^{O} CA BTDC. Experimental investigations are performed and compared between neat diesel at 23^{O} CA and hydrogen enriched fuel at 20^{o} CA BTDC. BSEC has been found to be19754.81kJ/kWh and 15797.18kJ/kWh for neat diesel and hydrogen respectively. Exhaust gas temperature has been found higher in case of hydrogen enriched charge due to enhanced combustion rate of hydrogen and higher EGT signifies higher NO_X production. [11]

Chiriac*et al* [2013] discussed the effects of blended biodiesel ((rapeseed methyl esters) up to 20% in diesel and also extended the study on B20 enriched with hydrogen by performing experimentation on a conventional tractor diesel engine running diesel at various speeds (2 speeds) and full load, at 60% load. . The main conclusions deduced are: It was found that compared with baseline diesel values, the engine fueled with B20 has significantly higher NO_x emissions at all speeds and lower smoke and CO emissions, while both fuels exhibits similar combustion characteristics. The addition of hydrogen to B20 by aspirating along with the intake air flow at 60% load led to an increase of NO_x emission and lowered smoke and CO emissions. The beneficial effect of reduced NO_x and CO emissions by hydrogen addition to petroleum diesel was more prominent at 2400rpm as compared to 1400rpm. FSN exhibits more reduced values for B20 enriched with hydrogen rather than hydrogen enriched in petroleum diesel only. It has been observed that when B20 $+H_2$ are mixed up to 4.366% and 2.6% for 1400 and 2400 rpm respectively, the NO_x emission is lower than other conditions considered. THCs are lower for almost at all speeds for emulsified fuel (B20+H_2+diesel). Thus all these observations proves that inclusion of B20 with a certain fraction of H2 enhances the emission characteristics of engine and the fraction highly depends on the engine operating speed. [12]

Christodoulou *et al* [2014], in this paper, the researchers discussed the utilization of exhaust gas by products (CO+H_2:60%) when hydrocarbons are oxidized during exhaust gas assisted fuel reforming (an attractive on-board hydrogen production method). While admission of reformed gas into the engine, it leads to an increase of intake air nitrogen to oxygen ratio. So, they have conducted experimental investigation on the performance and emissions of a Ford Puma diesel engine when a mixture of syngas and nitrogen are fueled in the inlet pipe of an HSDI engine along with diesel. They used a bottled gas mixture of H_2 and CO whose contents resembling those of typical diesel reformer product gas. And Nitrogen (drawn from a separate bottle) was simultaneously admitted at the same volumetric fraction to syngas. Exhaust analysis and performance calculation was carried out (at a CR 18.2:1, diesel injection pressure of 800bar) and compared to a neat diesel operation fueled on ULSD. It has been observed that NO_x and smoke emissions reduces at low speed operations but CO_2 and BTE have an adverse effect with introduction of syngas and N_2 gas as compared to baseline values. With increase in speed and BMEP, percentage volume of CO_2 increases and gets increased more with increasing H_2+CO+N_2 % i.e., from 4% to 12% (at 1:1 Ratio of H_2 and syngas). At 1500 rpm and 2.5 bar BMEP, CO_2 does not vary significantly but BTE is lower due to low BMEP. [13]

Christodoulou *et al* [2014] experimentally worked on a Ford Puma HSDI diesel engine (4 cylinders, 2L, 16 valves, water cooled, bore 86 mm, stroke 86 mm, compression ratio 18.2:1 and tried to devise techniques to reduce emissions, especially NO_x and Bosch Smoke Number (BSN) of automobile diesel engines. The authors, in their experiment, enriched the intake charge with H2 and N2 as gas mixture, extracted from diesel fuel reforming system, to verify if the technology can lead to low polluting diesel engines by checking the emission and combustion performance of the engine by admitting 2% H_2+ 2%N_2 up to 16%. The results obtained from the experiment have shown thatat 1500rpm,NO_x, BSN and CO emissions reduces when the H_2 and N_2 volumes are increased and they are lower as compared to baseline diesel emission level. When 12% H2+N2 is mixed in the intake charge, a 71.5% reduction in NO_xemissions has been observed as that of baseline diesel engine conditions. But it has been found that NO/NO_2 ratio gets increased when speed or load has been increased through a Schenk eddy current dynamometer connected to output shaft of the engine. At 2500 rpm, it has been observed that NO_x get increased when the percentage of H_2+N_2 is increased, but the NO_x production has been found almost equal for H_2+N_2 of 4%, 8% volume and that of NO_x in case of neat diesel. BTE reduces slightly with change in intake volume percentage of H_2 and N_2, however BTE is higher when the engine runs at 1500 rpm of about 29% to that of 24% at 2500 rpm. CO emission shows a unpredictable change with change in intake volume charges, rather it varies significantly with start of injection of change in crank angle degree. [14]

2.2. Literature on numerical analysis and simulated works on hydrogen enriched in CI engine

Numerical analysis of hydrogen enriched fuel also exhibits the same trend as shown by experimental works.

Lilik*et al* [2010] conducted experimental investigation on a DDC/VM Motori 2.5L, 4-cylinder,turbocharged, common rail, DI light-duty diesel engine fueling with hydrogen as a substitute for diesel on an energy basis of 0%, 2.5%, 5%, 7.5%, 10%

and 15% by aspirating hydrogen along with engine's intake air to find out the trend of exhaust emissions and studies were also conducted on four different speeds and load conditions (1800 rpm at 25% and 75% of maximum output and 3600 rpm at 25% and 75% of maximum output). It has been found that when increased aspiration of hydrogen takes place, injection timing retards significantly, which, thereby reduces NOX emission. Then, hydrogen assisted diesel combustion was examined, locking the injection timing of pilot and main fuel, to study the effects caused directly by hydrogen addition, it has been found that NO_X emissions increases and a shift in reduction of NO/NO_2 ratio as NO emissions decreases and NO_2 emissions increases, with NO_2 becoming the dominant NO_x component. He validated the experimental results with Computational fluid dynamics analysis (CFD) of the hydrogen assisted diesel combustion process and reproduced the experimentally observed trends for same operating conditions considering a model that explicitly accounts for turbulence chemistry interactions using a PDF method that was prominent to reproduce the experimental trends, if the results have been deduced from a model that ignores the effect of turbulent fluctuations on mean chemical production rates then the results would not have been so much favourable, although it has been reported in some other recent modeling studies the role of the fluctuations is very low. CFD results shows CO and CO_2 get predominantly decreased with the increase of hydrogen. But the detrimental effect is that fuel economy decreases due to reduced volumetric efficiency from the displacement of air in the cylinder by hydrogen. [15]

Ghazal *et al* [2013] conducted numerical analysis on the performance parameters and combustion characteristics on a simulated DI diesel engine. He investigated the results varying parameters like H_2+diesel blend ratio with H_2 in the range from 0.05% to 50% (by volume), engine speed varying from 1000-4000rpm, and A/F ratio from 10-80. The results deduced that applying hydrogen to diesel fuel in the (CI) engine leads to improved engine performance and reduce emissions with respect to neat diesel operation and it also shortens the diesel ignition lag, which thereby, decreases the rate of pressure rise which provides better engine operating conditions. Results for various H_2/diesel ratio, engine speeds and loads are compared for conventional Diesel and dual fuel operation, revealing the positive impact of inclusion of H_2 as dual fuel combustion on engine performance like BTE, IMEP, and exhaust emissions. Generally BTE increases with increase in hydrogen enrichment due to higher CV of

H_2 (mass basis), but the percentage intake of H_2 gets constrained due to knocking. Maximum values of BTE (without knocking at full load) is observed at A/F ratio range (15-20) and hydrogen concentration between(30%-40%). CO is also lowered for hydrogen enriched fuel than baseline diesel conditions; however, the reduction is more prominent when the A/F ratio is lower than 20. [16]

2.3 Literature on effect of VCR on diesel fueled with a fraction of substitutes

These studies show that varying compression ratio has a huge impact on the engine performance parameters. Some studies have been discussed here to analyse the variation when a part of diesel is substituted by alternative fuels, like biodiesels

Anand*et al*[2009]prepared a methyl ester from cotton seed oil and blended with diesel in ratios of 5%, 10%, 15% and 20%. They performed test in a single cylinder variable compression ratio diesel engine at a constant speed of 1500rpm and varied the compression ratio. At 5% biodiesel blend (with compression ratio of 15 and 17) and at 20% biodiesel blend (with compression ratio of 20) it has been found that the engine has highest brake thermal efficiency and lowest specific fuel consumption. At 20% biodiesel blend and compression ratio of 17, it has been observed that the production of nitric oxide is maximum, even higher than when the engine is run with only diesel fuel. It has been observed that brake thermal efficiency increases with increase in compression ratio and there is negligible difference between neat and biodiesel blends and B10 and B5 have almost equal efficiencies at full load conditions. Smoke opacity, HC and carbon monoxide production is lower in almost all blends but carbon dioxide emission increases in most of the blends. Biodiesel blends have more heat release capacity and higher peak pressure than neat diesel, highest peak pressure is shown in B20 and peak pressure decreases with reduction in biodiesel blend ratio. It has been analyzed that no engine modification is required for using biodiesel blend of cotton seed oil up to 20%. [17]

Mohite*et al* [2012]in this paper studied the effects of ethanol blends on the engine performance and emission characteristics and compared with those of pure form of fuels and they also analyzed the effect on compression ratios on the blends. The result observed that change in brake powerwith change in load is almost same for various blends and pure form. With increase in load and at compression ratio of 18, fuel flow increases, with maximum observed in pure diesel and least observed in E5. With increase in load, brake thermal efficiency increases with highest observed as 36.36% in E5 blend and lowest observed in neat diesel. But in other compression ratios the results drastically changes. In compression ratios of 15 and 16, E20 has been observed to provide better engine performance. Exhaust heat increases with decrease in compression ratio for pure fuel and all other ethanol blends. [18]

Mohan T Raj *et al* [2012] in this paper used tamanu oil as a biodiesel to investigate the scope of esterified tamanu oil blends as an alternative fuel by analyzing its performance and emission characteristics at various compression ratios. The results inferred from the experimental investigation are- brake thermal efficiency, volumetric efficiency, exhaust gas temperature of the VCR engine increases, whereas delay period reduces at higher loads. At higher compression ratios, NO_x and CO_2 production increases due to high peak temperature whereas CO and particulate matter reduces. When the results are compared with the standard values, then it is found that there is not much significant difference from the performance characteristics of tamanu oil which assents the fact that tamanu oil could be a promising alternative fuel. [19]

Chotai*et al*[2013], in this paper studied, presented and compared the effects of pure diesel, biodiesel blends(B20), neat biodiesel(B100) on brake thermal efficiency, BSFC, exhaust temperature, CO emissions, smoke opacity and also investigated the changes with variation in compression ratio and separate test condition for the above three cases with variation in injection pressure and injection timing. The test has been performed at 1500rpm on a methyl-ester of Thevetiaperuvenia seed oil varying the compression ratio from 15 to 19 and their effects have been studied on the engine performance parameters. It has been inferred that effect on BSFC is minimum at CR 17 for neat diesel reason behind lower values of BSFC at lower and higher CRs is incomplete combustion and charge dilution respectively, whereas for B20 it was higher than B0 but minimum observed at CR 20.6, the reason leading to higher BSFC than neat diesel is its low Calorific value. Lower the BSFC, higher the brake thermal efficiency, so the cases where minimum BSFC is observed even the brake thermal efficiency will be highest approximately at those conditions. At CR 17, smoke opacity and CO is least for diesel 100% as for lower CRs the air temperature is low & at higher CRs more fuel consumption, which results in both the cases incomplete combustion and thus, produces more smoke. Exhaust gas temperature is comparatively lower for B20 than that of diesel and B100 and increases for higher CRs. Effect of compression ratio is almost same for blend and neat cases. [20]

Nagaraja*et al*[2013]performed an experimental study in a single cylinder four stroke variablecompression ratio engine and analysed the impact of compression ratios on performance and combustion of a preheated palm oil–diesel blends of 5% to 20% with an increment of 5%, the results are also compared with those of petroleum based diesel fuel(PBDF). For proper blending palm oil with diesel, palm oil is preheated at 90^0C and then experiments are carried out and compared for different blends to determine the trend of brake thermal efficiency, sfc and production of unburned HCs, CO_2 and heat release rate. Brake thermal efficiency is higher for blended fuels as compared to PBDF at higher compression ratios and full load, especially for O5 & O20, but O20 exhibits the highest brake thermal efficiency. SFC for O20 is lower than PBDF and other tested blends at higher compression ratio at full load. At higher compression ratios and at full load, the unburned HCs noticeably reduce and CO_2 increases for all blends of palm heated oil as compared to that of PBDF. It has also been found that heat release rate decreases when the compression ratio is increased and for blends it is lower than PBDF. [21]

Raut *et al* [2014]in this paper studied the impact of blend, load, speed, injection timing, brake power etc on thermal performance and emission characteristics by performing the experiment on a four stroke variable compression ratio diesel engine using jatropha blends. This paper aims to optimise the engine exhaust emission based on compression ratio, load, and blend to find the optimum operating conditions. It has been found that with increasing compression ratio, the performance of jatropha oil blends is similar to that of diesel operated engine operating at full loads especially at compression ratios of 17 and 18. But at higher compression ratios, NO_x emission increases remarkably. He suggested to find the optimum blend using GA (Genetic Algorithm). [22]

2.4 Literature on effect of VCR on SI engine fueled

Aina et al in this paper illustrated the theoretical and experimental investigation of effects of compression ratio on various engine parameters like BMEP, Brake thermal efficiency, brake power and SFC on a Ricardo variable compression ratio spark ignition engine. Effect of increasing CR and various speed on the performance of engine is observed. With increase in CR, SFC decreases and brake thermal efficiency and brake power increases, parameters are optimum at a CR of 9, the CR gets constrained with knocking. The authors also checked the theoretical were close to experimental analysis on the engine performance. [23]

2.5 Literature on achieving VCR in engines

These papers deal with obtaining VCR and their related benefits in a car. Former studies on VCR have been made in VCR experimental set up. But in practical, the engine runs at a particular CR. This study discusses the attainment of VCR in a engine without VCR set up and the constrictions that are posing barrier. [24]

Gabor [2011]in his paper discussed the technological restrictions and implementation of VCR engines in commercial cars. He devised a design of a mass produced engine that satisfies all indispensable and desired features in terms of durability, reliability etc. VCR has the potential to emanate part throttle efficiency and reduce CO_2 emission. Constraints rendering difficulties for current production of VCR engines is the adoption of those engines in current system and incompatibility in coupling them with standard products available in market. It has also been observed that VCR engines have a higher efficiency at light loads without significant loss of full load performance.

Tomar *et al* [2013] in this paper has strived to improve the efficiency of SI engine and reducing pollution by optimizing the design of connecting rod. They suggested the most economical and simplest design by incorporating two stage VCR systems with modified design of connecting rod instead of continuous variable compression ratio system which will lead to reduction in fuel consumption. This VCR system has the ability to improve the part load efficiency of SI engine as the SI engine exhibits comparatively lower part load efficiency as compared to diesel engine. VCR helps in down-sizing the engine, alters emission characteristics and provides multi-fuel flexibility, controls the exhaust gas temperature. [25]

2.6 Literature on minimizing emission levels of diesel engines

In this study, researchers suggested different methods of minimizing engine emission levels. Few among them discussed about various technologies like SCR, diluents to make the hydrogen powered hybrid vehicle to fit in environmental standards by reducing the NO_x level.

Mathur*et al* [1992] discussed the way of mitigating the barrier that is paving the way of hydrogen, i.e., excessive production of NO_x. He performed experiments on a low horse-powered engine introducing various diluents in the intake charge like N_2, He and water in various proportions and observed the trends of smoke and NO_x. It has been observed from the experimental observations that N_2 is efficient enough to reduce smoke level, helium shows a positive impact on controlling these pollutants, however, water, when induced in small proportions of ppm, has shown the best results which allowed up to 66% full load energy substitution by H_2 without any knocking and reduces exhaust smoke density and NO_x emission level. [26]

Mathur*et al* [1992]performed experiment on a single cylinder, four stroke, water cooled DI diesel engine genset system of 4 kW and the system was run from the range of 0 to 60LPM in dual fuel mode. The increase BTE is highest for 20LPM without any knock. In other cases, it increases but the value is most fruitful at 20LPM. When the hydrogen flow rate increases above 30LPM, knocking is predominant with subsequent loss of power, BTE. Diluent does not take part in chemical reaction but reduces the temperature acting as a chemical sink. As up to 30 LPM, the engine fueled in dual mode runs in trouble free mode, so the testing of diluents are conducted at and above 40LPM hydrogen flow rate. Although 10% He diluted in Hydrogen is the suitable proportion to be used for charge dilution reduces knocking effect yet provides no improvement in engine performance. N_2 reduces knocking and allows more hydrogen substitution, gives best BTE when N_2 introduces is 30% of hydrogen volume. 2460 ppm of water allows knock free hydrogen substitution by 66% with a slight loss of engine power and efficiency. [27]

Cholakov[2001] in this paper discussed various ways to curb environmental pollution caused by IC engines (CI engine, SI engine, Jet engine). From vehicle exhaust primary pollutants and various toxic compounds are emitted. He also discussed the factors contributing pollution like emissions from cargo in normal transportation, vehicle production and maintenance etc. the author devices way to reduce pollution from engine exhaust by employing cleaner fuels, modifying engine design, post combustion control devices, vehicle design etc. the author also tries to estimate the pollutants produced by internal combustion engines. [28]

Saravanan *et al* [2009] experimentally investigated the performance on a water cooled, direct-injection fueled diesel engine designed to operate in dual fuel mode with timed port and manifold injection techniques. Results have been more favourable in timed port injection as the SEC and smoke level reduces by 15% and 18% respectively. Their analysis has shown very negligible variation in performance when the engine is run by both the injection techniques but significant positive impact on BTE and SEC has been observed as compared to neat diesel performances. It has been found the unburned hydrocarbons and CO is lesser in port injection while the oxides of nitrogen are higher when run in hydrogen than neat diesel. This paper also illustrated the conversion of setup from simple diesel engine into hydrogen operated dual fuel engine by incorporating with carburetor, timed port and manifold injection techniques and fabrication of SCR to reduce the amount of $NO_x$and it has been found that with this technique, NO_x reduces up to a maximum of 74% with slight deterioration in BTE values [29]

Zhang in this paper focused on the control of particulate matter emission in diesel engines. here analysis has been done by replacing the conventional standard diesel oxidation catalyst(DOC)+ DPF system commonly used with closely coupled DPFs(one assistant DPF and other main standard honeycomb DPF . This new after treatment is both economical and adheres to the emission control regulations. to investigate engine performance and emission, fuel injection parameters were also investigated. it has been found that NOx and smoke emissions were lowered by more than 80% when normal multiple injection is substituted by single injection PCCI combustion. effect of non-volatile particulate emissions were studied and effect of fuel quantity and injection timing were investigated. Impact of pilot injection along with main injection on the particulate emissions was illustrated. The author also examined the amount of particulate matter by taking some blends of alternative biofuel-diesel blends and it has been observed that there has been a significant reduction but however the number of nucleation mode particles might increase in few cases and especially during warming up. [30]

2.7 Literature on future of hydrogen, its usage and economics

In this study, hydrogen potential as future fuel is assessed and their potency as hybrid as well as FCV technologies are discussed. The authors tried to scale the cost of hydrogen in terms of increasing fossil fuels and discussed the cost expectations of hydrogen in future days for their diminishing and better production technology.

Gillingham [2007] discussed the hydrogen ICE technology, focusing on aspects such as power, fuel economy, tank size, and the state of the technology required to design or modify the vehicle accordingly and he also performed an economic analysisto examine the possibility of adoption of hydrogen ICE vehicles in US. He made a comparative analysis of vehicles incorporated with gasoline ICE, gasoline hybrids, hydrogen ICE, and hydrogen FCVs technologies. Recent technological and research developments largely control the cost of ICEs. He reviewed many studies and deduced that efficiencies and fuel economies are rather better for hydrogen fueled engines. Engine cost is lower for gasoline ICE and gasoline hybrid than H_2 fueled ICE, FCV. Gasoline fueled engine meets emission standards, hybrid shows lower pollutant emissions than gasoline, whereas mono H_2 fueled produces high NO_x but very less UHCs and FCVs does not fit into emission norms. State of art is developed for gasoline, for hybrid its developing, for H_2 it could be developed once the hybrid is getting developed and FCVs are in the infant stage of development. [31]

Moriarty *et al* [2010], in this paper, discussed the potentiality of hydrogen to be the future energy source. Energy accounting gets difficult when the input energy source are from multiple sources. Using intermittent sources like wind and solar are also getting popularized, which also pre-requisites the need of thermal energy storage systems for over time uses. They assumed four possibilities of energy production in future, and one among them is the direct production of hydrogen from nuclear reactors or from photolysis which he believes to account for most energy inputs.So, the authors demarcated clearly the needs of a new energy accounting framework, based on the energy content of hydrogen and energy production, demand and technical potential for renewable energy sources. [32]

Lemus *et al* [2010] in this paper discussed the literature review of economic analysis of producing hydrogen from conventional, nuclear and renewable sources during the last eight years. He also marginalized the costs in accord to a common year (2009) considering the yearly inflation rates. The study also takes into account whether the hydrogen has been produced in centralized or distributed facilities and most of the studies revealed that distributed facilities are costlier than the former. From his studies, the expected costs for conventional production of hydrogen are determined considering several scenarios on carbon emission taxations and varying fossil fuel prices. He briefly predicted the range of cost for various hydrogen production techniques like electrolysis, water splitting, steam methane reforming techniques (SMR), from nuclear energy, biomass and biofuels and some non-conventional techniques like, hydropower, wind, geothermal, tidal, photovoltaic, solar technologies. Based on these estimations, he estimated the predicted future costs (2019–2020 and 2030) for hydrogen from alternative sources and analyzed several hydrogen cost-parity for renewable and nuclear energies. It has been concluded that if carbon tax of 50 $ is added to coal gasification, then biomass hydrogen can favourably compete with coal hydrogen, and even nuclear hydrogen will be in the acceptable range at present. He predicted that in coming future, most renewable energies will achieve cost parities with coal hydrogen by 2030, or even a few years earlier if carbon taxation has high penalties. In distributed facilities, the present hydrogen production costs are high for all renewable energies than SMR hydrogen production costs. He compared and elaborated several hydrogen production technologies using the conventional (steam methane reforming and coal gasification) technologies, and alternative techniques known in the state of the art and ascertained several predictions on the time-periods to reach cost parities. It is foreseen to achieve cost parities first in distributed renewable energy; one of the major reasons is due to savings in hydrogen transport and liquefaction. Among the available alternative energies, biomass and biofuels are quite comparable to conventional and distributed systems in terms of cost parities. Wind has the potential to come in cost parity for hydrogen production in a period of about eight years even without carbon taxation. Factors like increased efforts in the development of advanced technologies to improve hydrogen production systems based on renewable energy, heavy carbon emission penalties, increased cost of fossil fuels, intensive investment growth in renewable energies, etc., could make cost parities to be reached earlier than that forecasted in this study, especially for biomass gasification. [33]

2.8 Summary of the review

As literature review pin-pointed the multiple advantages of hydrogen powered hybrid vehicle, so relevant technological growth can make it superior. [8]-[30] Generally, it has better engine performance and reduced emission level which leads to its growing popularity in the state of art. Variable Compression Ratio has a wide impact on engine performance and emission level. So, investigation incorporating VCR in a diesel engine has to be conducted. This investigation can be quickly assessed with coupling the engine with a VCR set up.

In summary measure finding from the review of the previously published literatures is observed that the study of hydrogen use in SI engine are widely available and it’s also commercialized. But incorporating hydrogen fuel in CI engine is still in its nurturing period and more attention on Hydrogen enriched diesel fuel has to be made. Besides, the previous studies were limited to consideration of either changing the H_2/diesel ratio or reducing NOx using some state of art technologies. All above literatures conclude various newer methods of green energy source using alternative fuels.

Chapter 3

Objectives and Scopes

3.1 OBJECTIVES OF THE PROJECT

To carry out the combustion and performance analysis of hydrogen fueled diesel engine at varying compression ratios and loads at a fixed injection timing and injection pressure and compare the effects with that of neat diesel.

3.2 SCOPES OF THE PROJECT

By conducting such analysis, we can know about the effects of hydrogen enriched diesel fuel on the combustion and performance analysis of diesel engine, and if the obtained results are satisfactory, then we can develop engines incorporating provisions for hydrogen in it and it can prove beneficial for the sustainable development of nations in terms of both economy and environmental constraints. An experimentation has been conducted to compare the effects of hydrogen enriched diesel fuel with that of neat diesel fuel for determining the variations and improvements in performance parameters at different compression ratios in Variable Compression Ratio Research Engine set up.

3.8 Methods to use H_2 in IC Engines

3.9.1. H_2 alone (In S.I. engine).

3.9.2. H_2 + Gasoline (In S.I. engine).

3.9.3. H_2 + Diesel (In C.I. engine).

3.9.4. H_2 + CNG (In C.I. engine).

3.9.5. Electric hybrid with H_2 ICE

3.9.6. H_2 fueled Fuel Cells

Chapter 4

METHODOLOGY

Thermo-couple k type

For experimental investigation of hydrogen operated diesel engine, we need to find out first what the characteristics are when the engine is run with diesel as fuel only (baseline diesel). The engine is run at different compression ratios to have a optimized value of compression ratio and then the observed parameters are checked with that of hydrogen enriched diesel fuel. Experimentation has been carried out on variable compression ratio C.I. Kirloskar single cylinder, four stroke, Multi-fuel, research engine at varied loads and compression ratios, and investigation finds out various engine parameters like brake power, indicated power, frictional power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, Mechanical efficiency, volumetric efficiency, specific fuel consumption, Air fuel (A/F) ratio, heat balance and combustion analysis. Research Engine set up 240 PE experimental setup consisted of a diesel engine coupled with eddy current type dynamometer for loading shown in figure 3.1. The compression ratio can be varied without stopping the engine and without altering the combustion chamber geometry by specially designed tilting cylinder block arrangement. Fuel supply system consists of a burette meter to measure the volumetric fuel consumption. Sensors were inbuilt at various sections of the engine to measure temperatures of air, cooling water, exhaust gases, maximum fuel pressure, combustion pressure, cylinder pressure, Diesel line pressure and crank-angle measurements etc. These signals are interfaced with computer for pressure crank-angle (P-θ) diagrams. Instruments are also provided to interface airflow, fuel flow, temperatures and load measurements. Rotameters are provided for calorimeter water flow and cooling water measurement.. Labview based Engine Performance Analysis software “Enginesoft” is provided for on line engine performance evaluation.

3.2. Assumptions considered during experimentation

1) Combustion Parameters are assumed to be constant, increase in the parameters with temperature has been neglected.

   Specific Gas Const: 1 kJ/kg K, Air Density: 1.17 kg/m^3, Adiabatic Index : 1.41, Polytropic Index : 1.28, Diesel Fuel Density: 830 kg/m^3, Calorific Value of diesel: 42000 kJ/kg

2) Performance Parameters used in the calculation are measured, geometrical variations are neglected.

   Orifice Diameter: 20 mm, Orifice Coeff. Of Discharge,C_d: 0.60, Dynamometer Arm Length: 185 mm, Fuel Pipe dia: 12.40 mm, Ambient Temp.: 27^0C, Pulses Per revolution: 360, Specific heats

3.3 Experimental set-up

The basic engine set up is modified with a provision for hydrogen enrichment with air using a mixer in the inlet manifold. Hydrogen was supplied with the air to the engine at a pressure 2.5 psi (0.2 bar) from a high pressure cylinder (150 bar) regulating with pressure regulator. Hydrogen Flow rate was 40gm/hr, measured by gravimetric method (measuring the weight of the cylinder). Then hydrogen was passed through an Non Return Valve, which prevents the reverse flow of hydrogen into the system. Such type of arrangement is indispensable as there is a possibility of reverse flow in a hydrogen injected engine, particularly in the later part of injection during carburation technique. Hydrogen was allowed to pass through the flame arrestor and flame trap for added safety purposes. They suppresses the flashback, if any, in the intake manifold. The flame trap was made of thick cast iron sleeves to suppress the flame and water to put off the flame and cool down the gas. The hydrogen from the flame trap was sent into the inlet manifold to mix it with the air in a chamber known as ‘mixer’. The process of mixing the inlet air and fuel is called as enrichment. The passage from hydrogen cylinder to mixing chamber of inlet manifold is done by copper pipe as copper does not react with hydrogen gas even at high temperature and pressure. Thus by keeping the flow of hydrogen as 40 gm/hr, engine performances has been evaluated.

Product	
Make	Apex innovations
Model	Research Engine test setup (240 PE), VCR (computerized)
Engine	
Make	Kirloskar Oil Engines
Model	TV1
No. of cylinder	1 (single)
Bore x Stroke	87.5 X 110 (mm)
Capacity	661 cc
Diesel mode (Rated Output)	3.5 kW
Compression Ratio range	12-22
Rated Speed (constant)	1500 rpm (varies from min 1200-max 2000rpm)
Injection Timing Variations	0^0-25^0 BTDC
Peak pressure	77.5 kg/cm^2
Direction of rotation	Clockwise (from flywheel end side)
Valve timing	IVO 4.5^0 BTDC IVC 35.5^0 ABDC EVO 35.5^0 BBDC EVC 4.5^0 ATDC
Lubrication system	Forced feed system
Lubrication oil pump	Gear type
Eddy curent Dynamometer	
Model	AG10
Make	Saj Test Plant Pvt. Ltd.
End flanges both side	Cardon shaft model 1260 type A
Connecting Rod length	234 mm
Water inlet	1.6 bar (Water cooling)
Minimum kPa	160 kPa
Continuous current	5 A
Load	3.5 kg (with loading unit)
Speed max.	10000 rpm
Range	Upto 400 kW

Propeller shaft	With universal joints
Fuel tank	Capacity 15 l, fuel metering pipe of glass
air box	M.S. fabricated with orifice and manometer
Calorimeter type	Pipe in pipe
ECU	PE3 Series ECU, Model PE3-8400P
Pump	Type monoblock
Rotameter	Engine cooling 40-400 LPH, Calorimeter cooling 25-250 LPH
Load sensor	Load cell, strain gauge type, range 0-50 kg
Fuel flow transmitter	DP transmitter, range 0-500 mmWC
Air flow transmitter	Pressure transmitter, Range (-) 250mm WC
Temperature transmitter	Type two wire
Piezo sensor	Combustion range 350 bar, diesel line range 350 bar
Crank angle sensor	Resolution 1^0, speed 5500 RPM with TDC pulse
Temperature sensor	Type RTD, PT100 and thermocouple K type
Data acquisition device	NI USB 6210, 16 bit
Software	”Enginesoft” Engine performance analysis software

Table 3.1 Specification of diesel engine and electric dynamometer

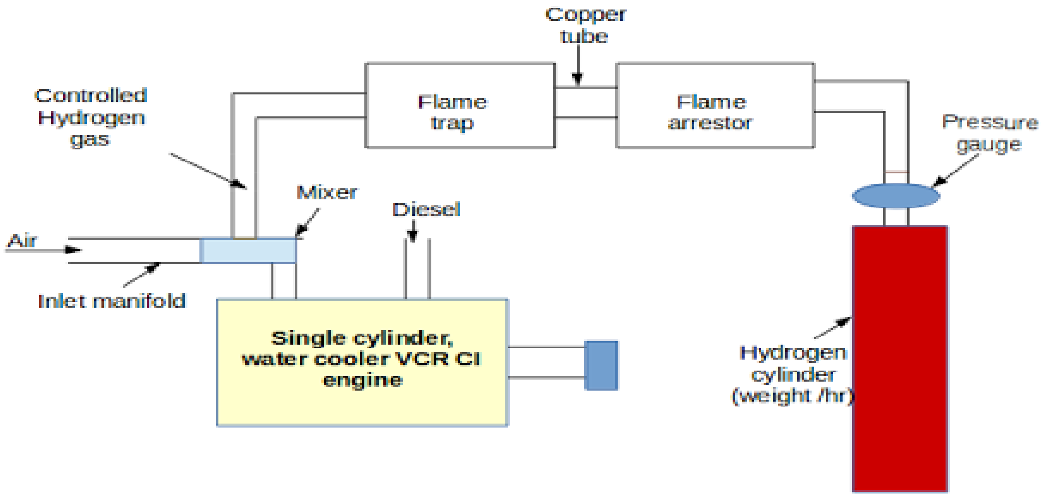


Fig.3.1 Schematic Experimental set up for hydrogen operated diesel engine

3.4. Auxiliary Equipments Required

Fig.3.2 Pictorial view of Pressure Gauge

Fig.3.2 Pictorial view of Mixer (air inlet and Cu pipe for hydrogen enrichement)

Fig.3.2 Pictorial view of Ferule for leakage free connection

Fig.3.2 Pictorial view of Copper Pipe bender to assemble the set up

Fig.3.2 Pictorial view of Pipe cutter

Fig.3.2 Pictorial view of modified Experimental set up

3.5. Performance parameters

Indicated thermal efficiency (η_{it}): Indicated thermal efficiency is the ratio of energy in indicated power to the fuel energy.

Brake thermal efficiency (η_{bth}): A measure of overall efficiency of the engine is given by the brake thermal efficiency. Brake thermal efficiency is the ratio of energy in the brake power to the fuel energy.

Mechanical efficiency (η_m): Mechanical efficiency is the ratio of brake horse power (delivered power) to the indicated horsepower (power provided to the piston).

Frictional power = Indicated power – Brake power

Volumetric efficiency (η_v): The engine output is limited by the maximum amount of air that can be taken in during the suction stroke, because only a certain amount of fuel can be burned effectively with a given quantity of air.

Volumetric efficiency is an indication of the 'breathing' ability of the engine and is defined as the ratio of the air actually induced at ambient conditions to the swept volume of the engine. In practice the engine does not induce a complete cylinder full of air on each stroke, and it is convenient to define

Brake specific fuel consumption and indicated specific fuel consumption, (BSFC and ISFC), are the fuel consumptions on the basis of Brake power and Indicated power respectively.

Fuel-air (F/A) or air-fuel (A/F) ratio: The relative proportions of the fuel and air in the engine are very important from standpoint of combustion and efficiency of the engine. This is expressed either as the ratio of the mass of the fuel to that of the air or vice versa.

Calorific value or Heating value or Heat of combustion: It is the energy released per unit quantity of the fuel, when the combustible is burned and the products of combustion are cooled back to the initial temperature of combustible mixture. The heating value so obtained is called the higher or gross calorific value of the fuel. The lower or net calorific value is the heat released when water in the products of combustion is not condensed and remains in the vapour form.

Power and Mechanical efficiency: Power is defined as rate of doing work and equal to the product of torque and angular velocity or the product of force and linear velocity. Thus, the measurement of power involves the measurement of force (or torque) as well as speed.

The power developed by an engine at the output shaft is called brake power and is given by Power = NT/60,000 in kW

where T= torque in Nm = WR

W = 9.81 X Net mass applied in kg.

R= Radius in m N is speed in RPM

Mean effective pressure and torque: Mean effective pressure is defined as a hypothetical pressure, which is thought to be acting on the piston throughout the power stroke.

Power in kW = (P_m LAN/n 100)/60

Where P_m = mean effective pressure (in bar)

L = length of the stroke (in m)

A = area of the piston (in m^2)

N = Rotational speed of engine (in RPM)

n= number of revolutions required to complete one engine cycle: n= 1 (for two stroke engine) and n= 2 (for four stroke engine).

If the mean effective pressure is based on brake power it is called brake mean effective pressure **(BMEP)** and if based on indicated power it is called indicated mean effective pressure **(IMEP)**.

Similarly, the **friction mean effective pressure** (FMEP) can be defined as FMEP= IMEP – BMEP

3.5.1 Basic measurements

The basic measurements, which usually should be undertaken to evaluate the performance of an engine on almost all tests, are the following:

Measurement of speed: Following different speed measuring devices are used for speed measurement.

1 Photoelectric/Inductive proximity pickup with speed indicator

2 Rotary encoder: A rotary encoder, also called shaft encoder, is an electro-mechanical device that converts the position or motion of a shaft or axle to an analog or digital code

Measurement of fuel consumption:

Volumetric method: The fuel consumed by an engine is measured by determining the volume flow of the fuel in a given time interval and multiplying it by the specific gravity of fuel. Generally a glass burette having graduations in ml is used for volume flow measurement. Time taken by the engine to consume this volume is measured by stopwatch. Burette method was used to measure the volumetric fuel flow rate. A glass burette having marks was connected to fuel tank and the engine.

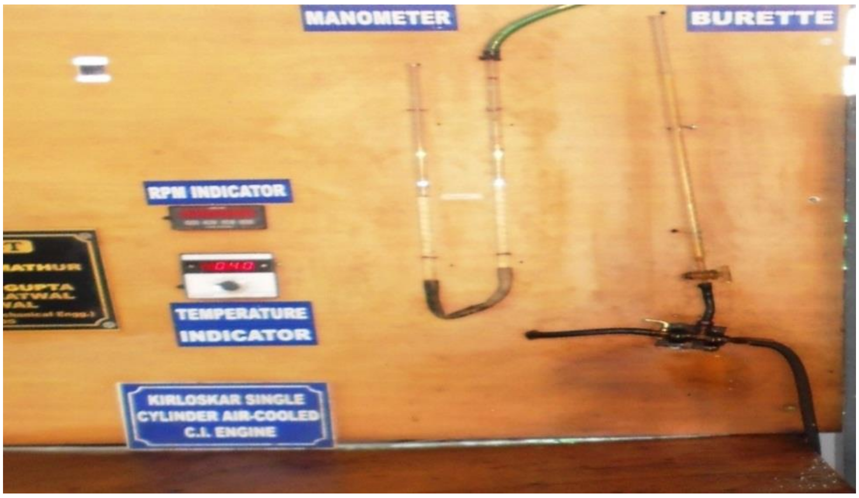


Fig 3.3 Fuel flow measurement system

The time taken by the engine to consume a fixed volume of fuel was measured with the help of stopwatch. This volume divided by the time gave the volumetric flow rate. For calculating the mass flow rate of fuel (m_f), volume flow rate of fuel was multiplied with density of the fuel. For example fuel consumption of 25ml taken 75 seconds at 3000 watt load. As we know that the 1ml is equal to 10^{-6} m^3 and fuel flow rate (in ml/s) X ρ (in kg/m^3).

So the fuel flow rate is: $(25/75)*10^{-6}*880 = 0.000293$ (kg/s)

At various load condition fuel flow rate is shown below figure. As we increase load fuel consumption also increase. Usually at 80% load, we get lower fuel consumption because engine always design for give maximum efficiency and fuel economic at 80% load. As observed in figure curve at 3.5 kW (80% load) load slightly turn down then increase. Hence after 80% load efficiency of engine decrease and fuel consumption increases.

Measurement of air consumption

Air box method: In IC engines, as the air flow is pulsating, 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. The differential pressure across the orifice is measured by manometer and differential pressure transmitter. Air flow to the engine was measured with the help of an air box. It was used to dampen out the pulsation of air. An orifice of diameter 20 mm having coefficient of discharge (C_d) is

0.6 was fitted at the entrance on one of the side walls. The outlet was at the bottom, through which it was connected to the air filter mounted on the engine. Pressure inside the air box remained less than atmospheric pressure during operation, which was provided for air suction from atmosphere due to favourable pressure gradient.

3.2 Photographic view to air box with filters

This engine works as constant rpm engine; hence it takes the constant air flow rate. The amount of air induced per second or volume flow rate of air (V_a) was obtained with the help of the following relation:

Where

C_d = discharge coefficient of orifice= 0.6

d_0 =Diameter of orifice = 25 mm,

$A_{orifice}$ = Area of orifice = $\pi d_0^2/4$ = 0.0004908 m^2

h_w = Manometric deflection = 0.016 m,

ρ_w = Density of water = 1000 kg/m^3,

ρ_a = Density of air = 1.2 kg/m^3

Mass flow rate of the air (m_a) can be calculated by following equation:

Mass flow rate of air (m_a) = (Volumetric flow rate) * (Density of Air)

$$m_a = 0.6*4098738521x10^{-4}*(2*9.81*.016*1000*1.2^{)1/2}=0.00572 \text{ kg/s}$$

Measurement of brake power

Measurement of BP involves determination of the torque and angular speed of the engine output shaft. This torque-measuring device is called a dynamometer.

Eddy current dynamometer is used for measuring the brake power. It consists of a stator on which a number of electromagnets are fitted and a rotor disc and coupled to the output shaft of the engine. When rotor rotates eddy currents are produced in the stator due to 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. A moment arm measures the torque. Regulating the current in electromagnets controls the load. While using with variable speed engines sometimes in certain speed zone the dynamometer operating line are nearly parallel with engine operating lines which result in poor stability, so the load measured by it fluctuates continuously.

Measurement of indicated power

There are two methods of finding the IHP of an engine. Morse test and indicator diagram. Morse test is applicable to multi-cylinder engines, here indicator diagram is used to measure the indicated power of the engine.

Indicator diagram: 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 simultaneously scanned by an engine indicator (electronic unit) and communicated to computer. The software in the computer draws pressure crank-angle and pressure volume plots and computes indicated power of the engine. Conversion of pressure crank-angle plot to pressure volume plot.

3.3 Temperature measurement

Make Radix Type K, Ungrounded, Sheath Dia.6mmX110mmL, SS316, Connection 1/4"BSP (M) adjustable compression fittingInput Thermocouple (type K), output 4-20mA, supply 24VDC, Calibration: 0-1200deg.C. K-type thermocouples are attached to a six-channel to meaure Calorimeter water inlet temperature (T_3 ^{0}K), Calorimeter water outlet temperature (T_4 ^{0}K), Exhaust gas to calorimeter inlet temp (T_5 ^{0}K), Exhaust gas from calorimeter outlet temp (T_6 ^{0}K), of the engine to measure temperature as shown in fig 3.3 and 3.1. These thermocouples can measure in the range of 0-1200 °C. Temperature at various load are shown in below figure. In the figure 3.5 shows that as increase load on engine exhaust gas temperature also increase. At full load get maximum temperature of exhaust gas and can say maximum engine exhaust heat.

3.4 Formulas for calculations

Various observations like fuel flow rate, air flow rate, various temperatures at engine exhaust, are taken as above discuss and this are shown in table 6.2. Calculation has been done using following formula. **:**

Mass flow rate of exhaust gas = $(m_a + m_f)$

Heat supplied by fuel (Q_f) = m_{fD} x C.V.$_{diesel}$ +m_{fH} x C.V.$_{hydrogen}$.

C.V. of diesel = 43,000 (kJ/kg) [34]

C.V. of hydrogen = 120,000 (kJ/kg) [35]

Heat carried by exhaust gas = $(m_a + m_f).Cp_{eg.}\Delta T$

Brake thermal efficiency (BTE) = (Brake power) / (heat supplied)

Brake specific energy consumption (BSEC) = (heat supplied) / (brake power**)**

Brake specific fuel consumption (BSFC) = (Fuel consumed in kg/hr) / (brake power in kW**)**

3.6 Geometrical parameters:

Engine Cylinder diameter (bore) (D): The nominal inner diameter of the working cylinder.

Piston area (A): The area of a circle of diameter equal to engine cylinder diameter (bore). $A = \pi \times 0.25 \times D^2$

Engine Stroke length (L): The nominal distance through which a working piston moves between two successive reversals of its direction of motion.

Dead center: The position of the working piston and the moving parts, which are mechanically connected to it at the moment when the direction of the piston motion is reversed (at either end point of the stroke).

Bottom dead center (BDC): Dead center when the piston is nearest to the crankshaft. Sometimes it is also called outer dead center (ODC).

Top dead center (TDC): Dead center when the position is farthest from the crankshaft. Sometimes it is also called inner dead center (IDC).

Swept volume (V_S): The nominal volume generated by the working piston when travelling from one dead center to next one, calculated as the product of piston area and stroke. The capacity described by engine manufacturers (in cc) is the swept volume of the engine.

$V_s = A \times L$

Clearance volume (V_C): The nominal volume of the space on the combustion side of the piston at top dead center.

Cylinder volume (V): The sum of swept volume and clearance volume.

$V = \mathbf{V_S} + \mathbf{V_C}$

Compression ratio (CR): The numerical value of the cylinder volume divided by the numerical value of clearance volume. $CR = V / \mathbf{V_C}$

The series of operation of an ideal four-stroke engine are as follows:

Suction or Induction stroke: The inlet valve is open, and the piston travels down the cylinder, drawing in a charge of air. In the case of a spark ignition engine the fuel is usually pre-mixed with the air.

Compression stroke: Both valves are closed, and the piston travels up the cylinder. As the piston approaches top dead centre (TDC), ignition occurs. In the case of compression ignition engines, the fuel is injected towards the end of compression stroke.

Expansion or Power or Working stroke: Combustion propagates throughout the charge, raising the pressure and temperature, and forcing the piston down. At the end of the power stroke the exhaust valve opens, and the irreversible expansion of the exhaust gases is termed ‘blow-down’.

Exhaust stroke: The exhaust valve remains open, and as the piston travels up the cylinder the remaining gases are expelled. At the end of the exhaust stroke,

3.7 VCR Experimental set up

As we have reviewed in papers [17]-[25], Compression Ratio has a major role in engine efficiency and emission level. This observation illustrates that before designing any engine, the engine must be tested at various CRs and the CR at which performance is optimum should be chosen to design the engine accordingly. In this experiment, hydrogen-diesel dual fuel has been analysed in VCR engine. The standard available engines (with fixed compression ratio) can be modified by providing additional variable combustion space. There are different arrangements by which this can be achieved. *Tilting cylinder block method* is one of the arrangements where the compression ratio can be changed without change is combustion geometry. With this method the compression ratio can be changed within designed range without stopping the engine.

Figure 4.6: VCR experimental set up (Source:edutekindia.com)

3.7.1. Setup Specifications

It consists of single cylinder, four stroke, VCR (Variable Compression Ratio) Diesel engine connected to eddy current type dynamometer for loading. The compression ratio can be changed without stopping the engine and without altering the combustion chamber geometry by tilting cylinder block arrangement.

Setup is provided with necessary instruments for combustion pressure and crank-angle measurements. These signals are interfaced to computer through engine indicator for diagrams. Provision is also made for interfacing airflow, fuel flow, temperatures and load measurement. The set up is consisting of air box, two fuel tanks for duel fuel test, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator and engine indicator. Rotameters are provided for cooling waterflow measurement. The setup enables to determine the performance for brake power, indicated power, frictional power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, Mechanical efficiency, volumetric efficiency, specific fuel consumption, A/F ratio and heat balance. Labview based Engine Performance Analysis software package "Enginesoft is provided for on line performance evaluation. A computerized Diesel injection pressure measurement is optionally provided**.**

Chapter 4

EXPERIMENT RESULTS AND DISCUSSION

Engine was operated at no load and various loads of 2.5 kg, 5 kg, 7.5 kg and 10 kg at each compression ratio from 16-22. When engine operates at different loads then the engine shows different values of the concerned parameters. The research shows that with increase in load, the speed of the engine reduces slightly even though the engine is constructed to run at constant speed RPM at every compression ratios.

7.1 Test conditions:

Test conditions for the specified two fuels are as follows:

i) **100% diesel**
Injection pressure: 195 bar, injection 21^0 BTDC, speed constant 1500 rpm, Compression ratio varied from 16 to 22

ii) **Blend of diesel and hydrogen fuel**
Injection pressure: 195 bar, injection 21^0 BTDC, speed constant 1500 rpm, Compression ratio varied from 16 to 22

7.2 Effect on Brake Thermal Efficiency (BTE)

The result of effect on BTE for both the cases at compression ratio 16-22 is represented in the following graphs: For 100% diesel, BTE has been found maximum at CR 21. At higher values and lower values, BTE decreased, which implies BSFC increased as lower the BTE, higher the BSFC. The reason attributed is charge dilution at Compression ratio 22 and incomplete combustion at lower values. (Shown in Figure 7.1) For blend of diesel and hydrogen, increased BTE has been observed if we consider only heat generated by diesel fuel at all compression ratios due to high flame velocity of hydrogen leads to improved combustion because of enhanced combustion rate as compared to 100% diesel, but when we consider the heat produced by hydrogen fuel, BTE is lower as compared to BTE of that of diesel only due to high Calorific Value of Hydrogen. The maximum brake thermal efficiency of the engine with hydrogen enrichment is found to be 26% at 80% load and with CR 21, whereas with neat diesel alone was 28.84% at 80% load, with CR 21. It has also been observed in the experiment that as the hydrogen flow rate started increasing there was a decrease in the diesel flow rate, which indicates that hydrogen is taking part in the combustion and saving substantial amount of diesel fuel by producing the equivalent amount of power and speed with less diesel fuel consumption. BTE increases as load increases for all cases due to higher brake power attained, less losses and improved combustion.

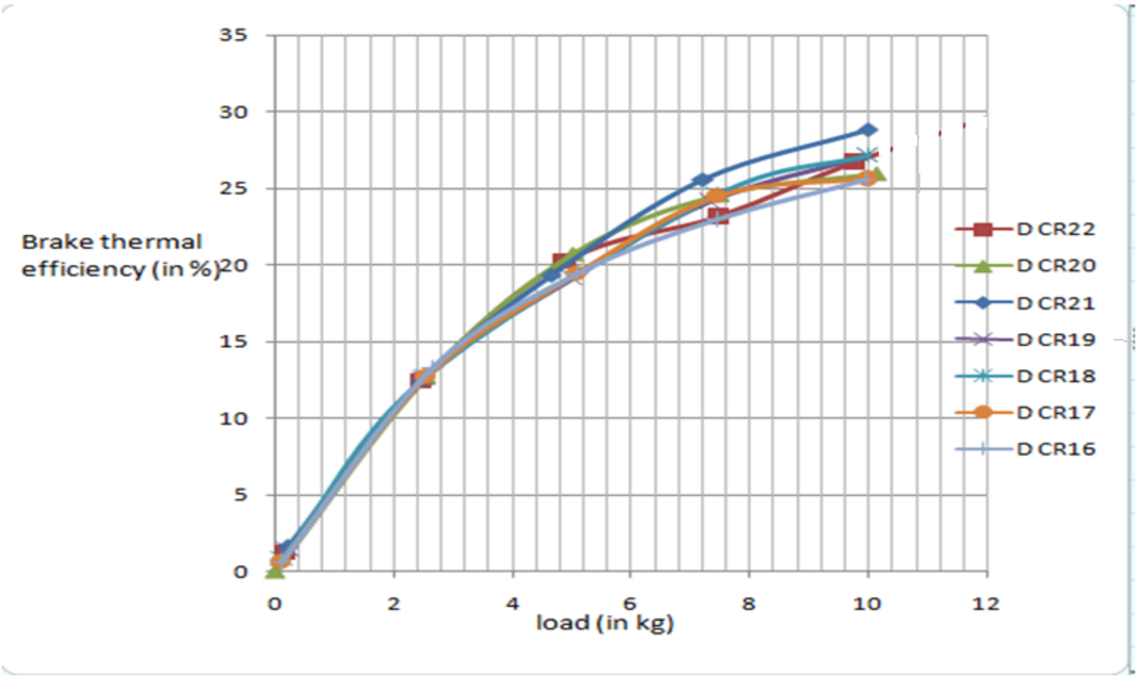


Fig 7.1 Variation of BTE with load when engine is run with 100% diesel at different Compression Ratios (16-22)

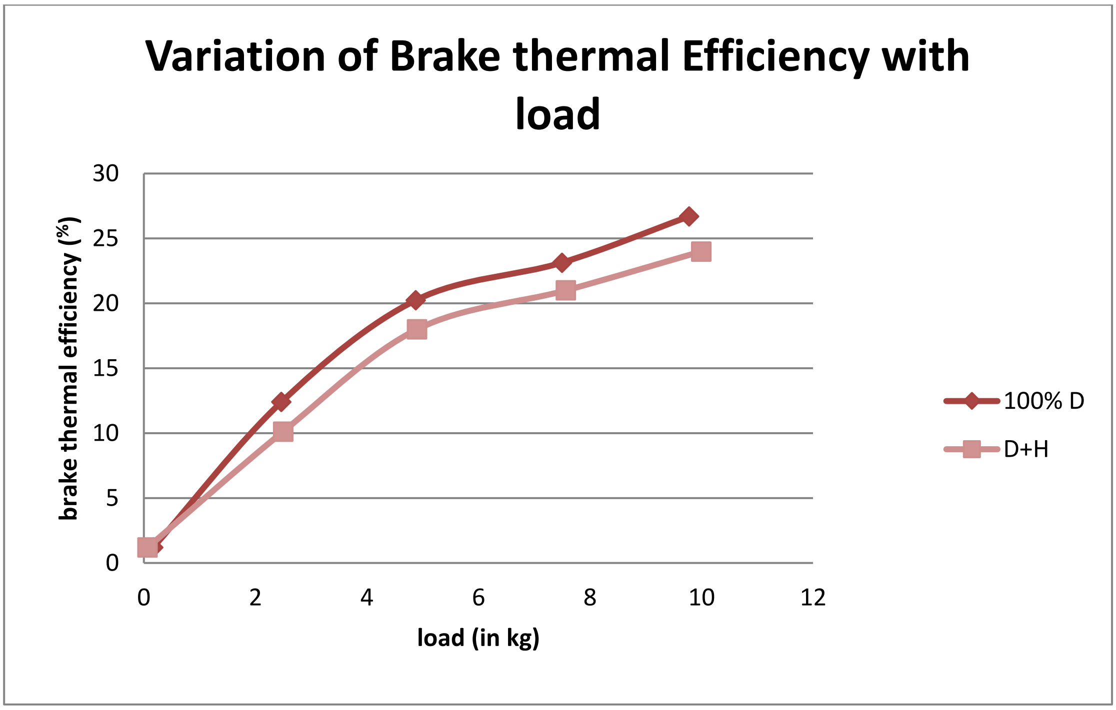


Fig 7.2 Comparison of 100% diesel and hydrogen-diesel blend in terms of BTE with load when engine is run at Compression Ratio 22

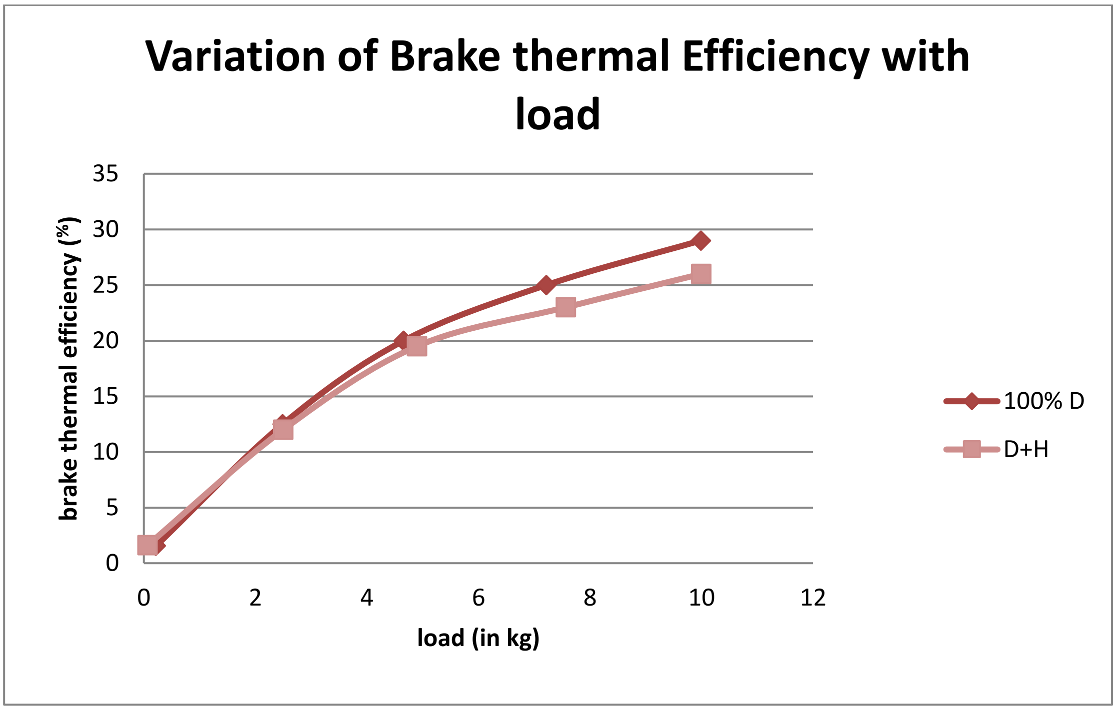


Fig 7.3 Comparison of 100% diesel and hydrogen-diesel blend in terms of BTE with load when engine is run at Compression Ratio 21

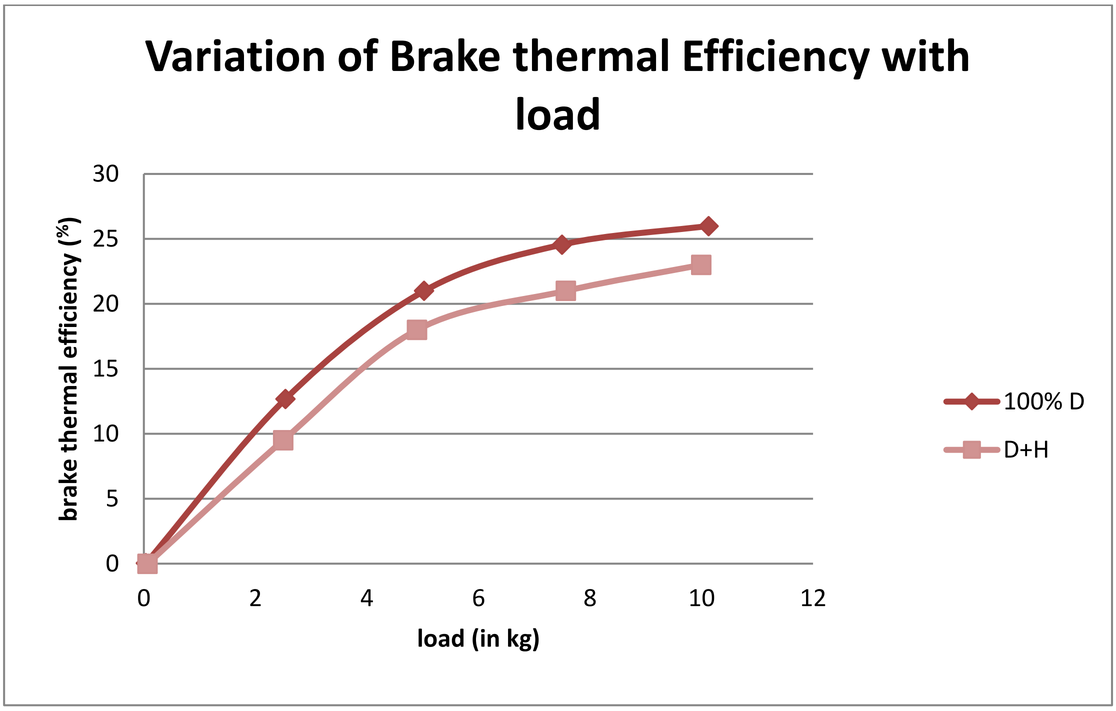


Fig 7.4 Comparison of 100% diesel and hydrogen-diesel blend in terms of BTE with load when engine is run at Compression Ratio 20

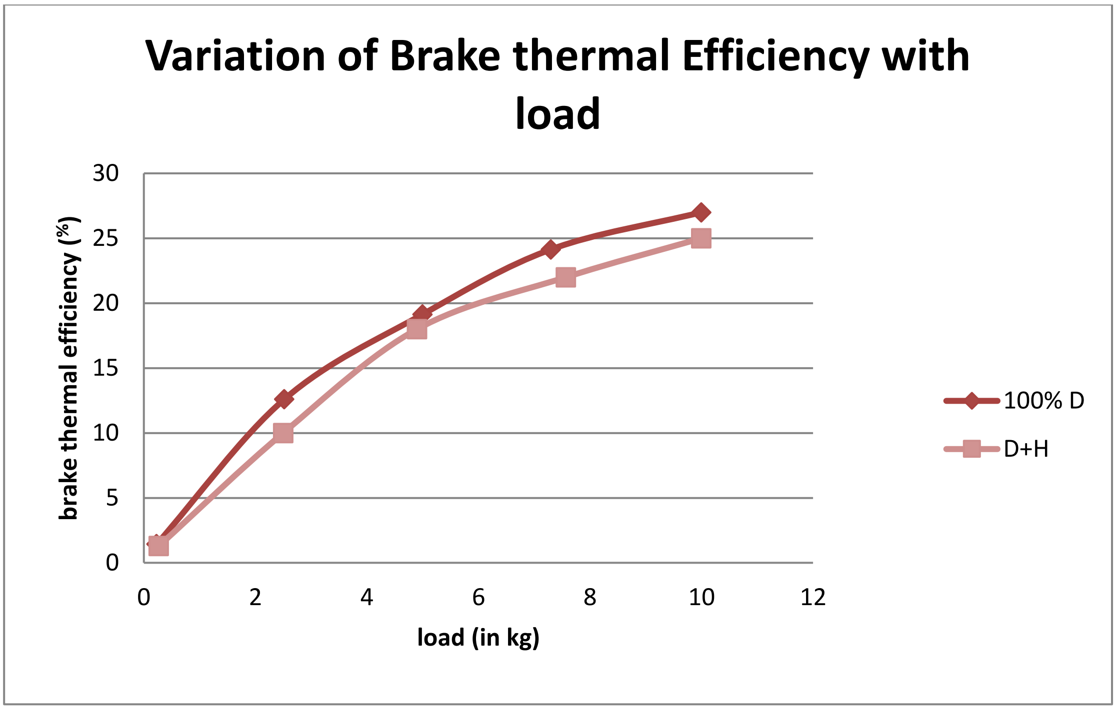


Fig 7.5 Comparison of 100% diesel and hydrogen-diesel blend in terms of BTE with load when engine is run at Compression Ratio 19

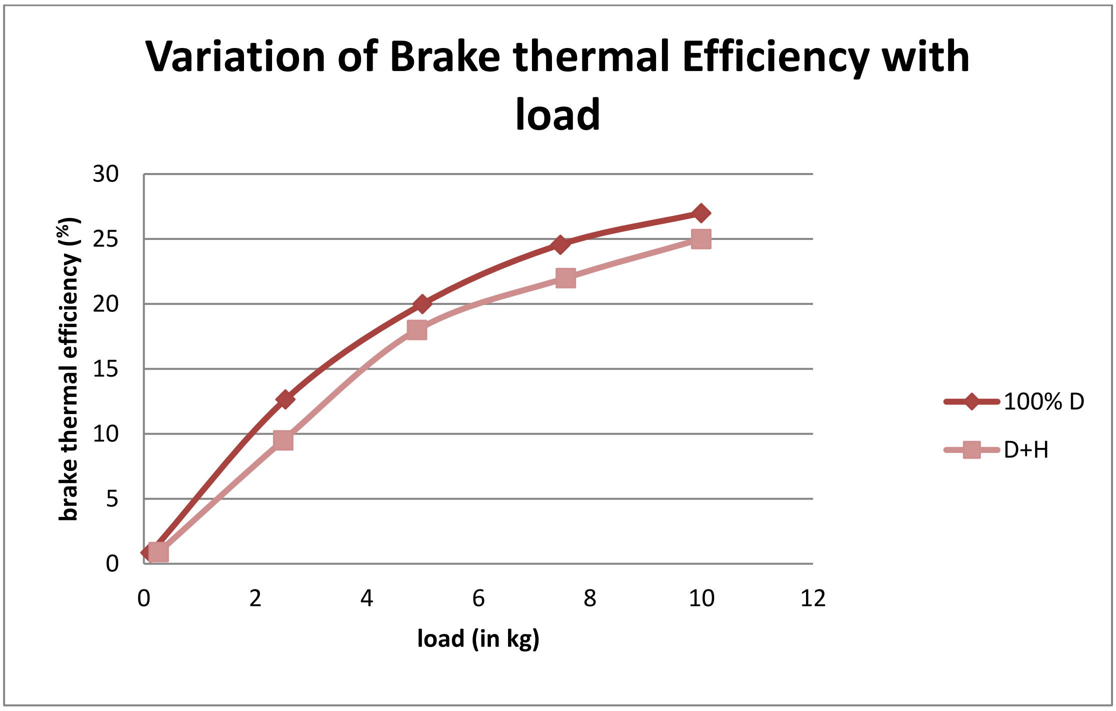


Fig 7.6 Comparison of 100% diesel and hydrogen-diesel blend in terms of BTE with load when engine is run at Compression Ratio 18

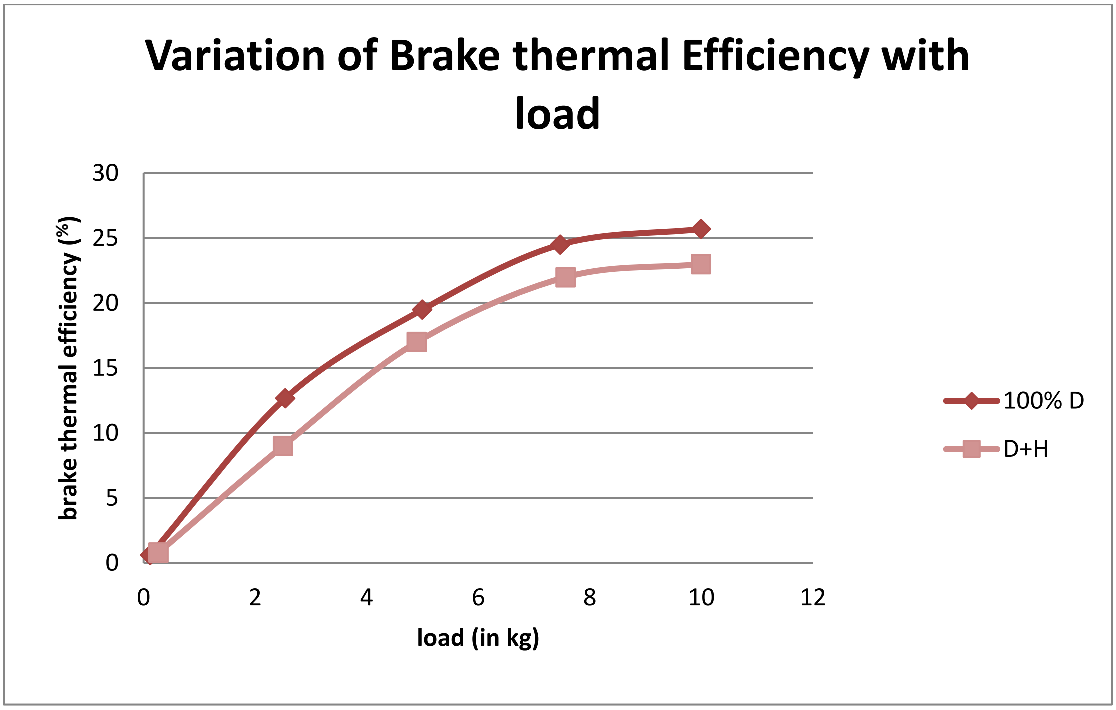


Fig 7.7 Comparison of 100% diesel and hydrogen-diesel blend in terms of BTE with load when engine is run at Compression Ratio 17

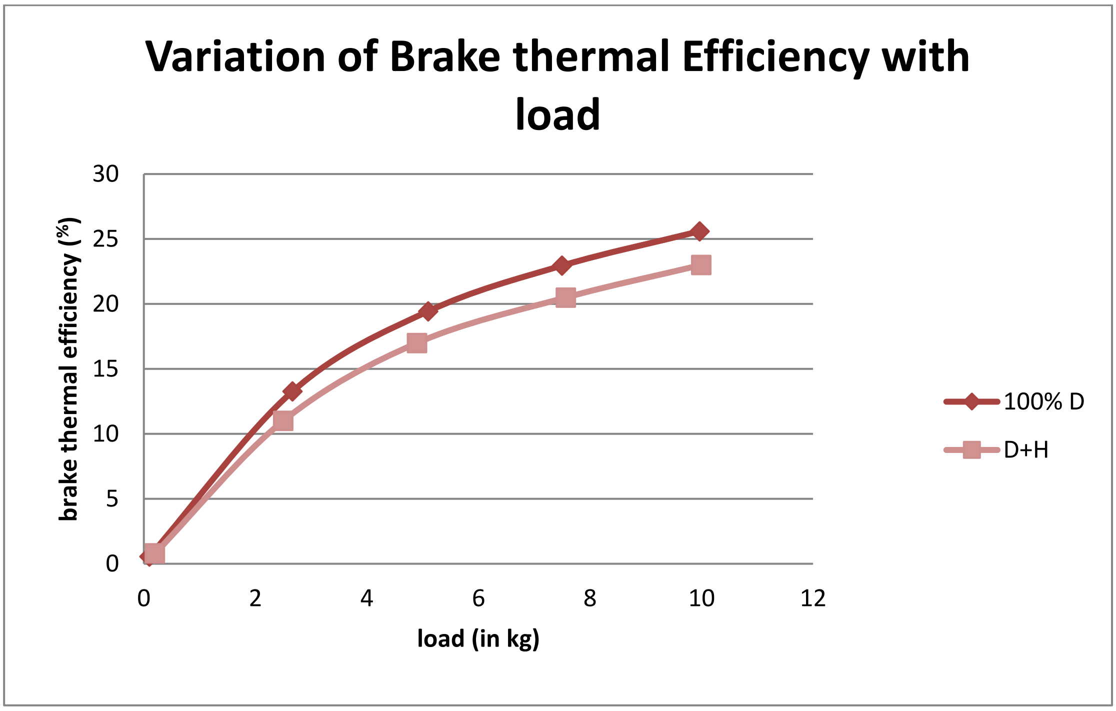


Fig 7.8 Comparison of 100% diesel and hydrogen-diesel blend in terms of BTE with load when engine is run at Compression Ratio 17

Figure 7.1 (b) shows the 80% energy is wasted in engine cooling at no load condition, as the load on engine increases, exhaust energy and useful energy (efficiency) also increase. For example at 3 kW load 55% of energy is wasted in engine cooling, radiation and friction, 23% energy convert into useful work and remaining 22% energy is carried away by the exhaust gases. There is no significant difference in engine efficiency if thermal energy storage system (pebble bed) is used. It is explained in the next section.

7.2 Effect on Brake Specific Energy Consumption (BSEC)

For 100 % diesel, fuel consumption is minimum at Compression Ratio 21. When the brake thermal efficiency will be high, brake specific energy consumption is low as BSEC is the reciprocal of BTE.

7.3 Effect on Exhaust Gas Temperature (EGT)

The variations of exhaust gas temperature with load for the above test conditions are shown in Fig. 8. Effectiveness of utilization of heat energy produced by combustion of fuel can be known with Exhaust Gas Temperature. However, with increase in load, exhaust gas temperature was observed to increase for diesel (Figure) and blend of hydrogen and diesel (Figure). The temperature has been found higher for hydrogen enriched diesel fuel. At lower compression ratio, the Exhaust Gas temperature is observed to be moderately high. The reason for this may be that with increase in compression ratio, combustion process shifts towards earlier stroke of cycle and hence more effective utilization of heat is obtained, lowering the waste heat from the engine and with higher loads, more power is produced and hence, exhaust gas temperature increases. As the VCR 240PE engine is water cooled, the temperature obtained after calorimeter outlet is moderately low to have any environmental implications. The maximum exhaust gas temperature for hydrogen enriched fuel after water cooling the exhaust gas was 264^0C at 80% load and CR 17 whereas that for diesel was 236^0C at 80% load and CR 20. This increase in exhaust gas temperature in hydrogen to that of neat diesel was due to better mixing of hydrogen with air as both hydrogen and air are in gaseous state resulting in complete combustion of fuel.

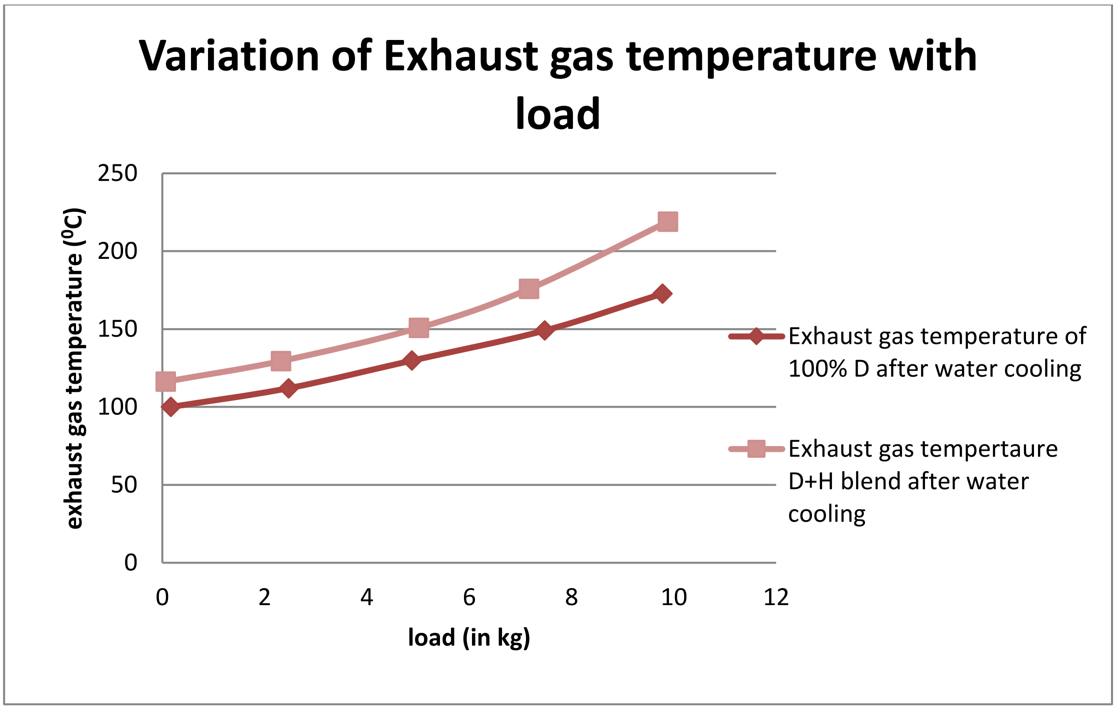


Fig 7.1 Comparison of 100% diesel and hydrogen-diesel blend in terms of EGT with load when engine is run with at Compression Ratio 22

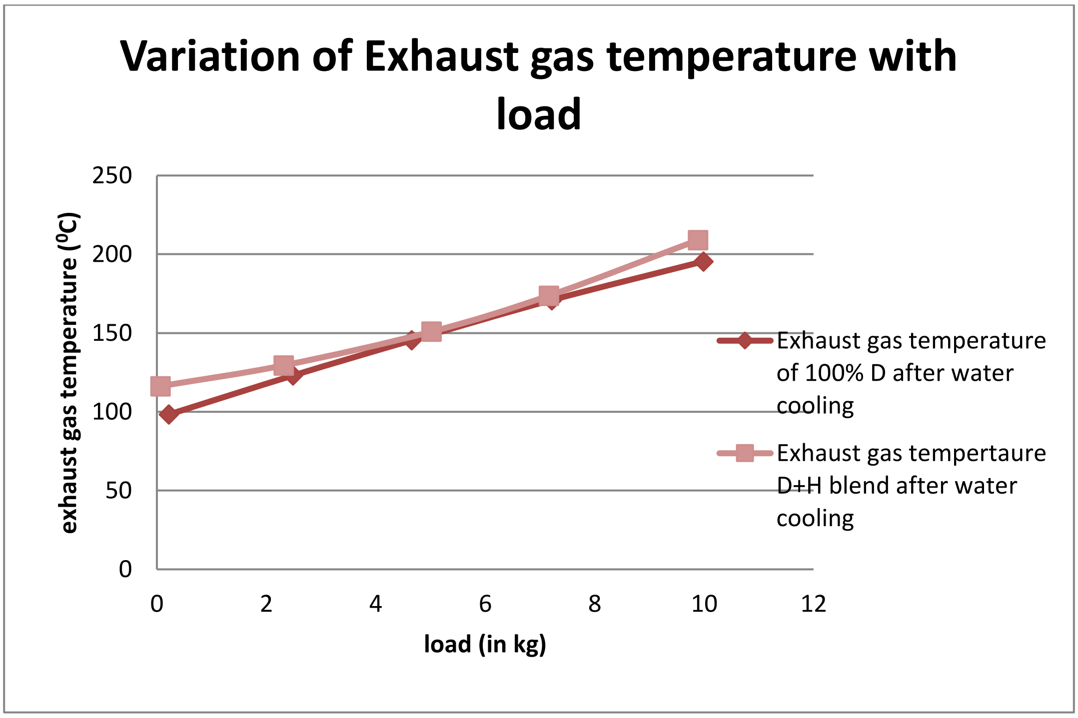


Fig 7.1 Comparison of 100% diesel and hydrogen-diesel blend in terms of EGT with load when engine is run with at Compression Ratio 21

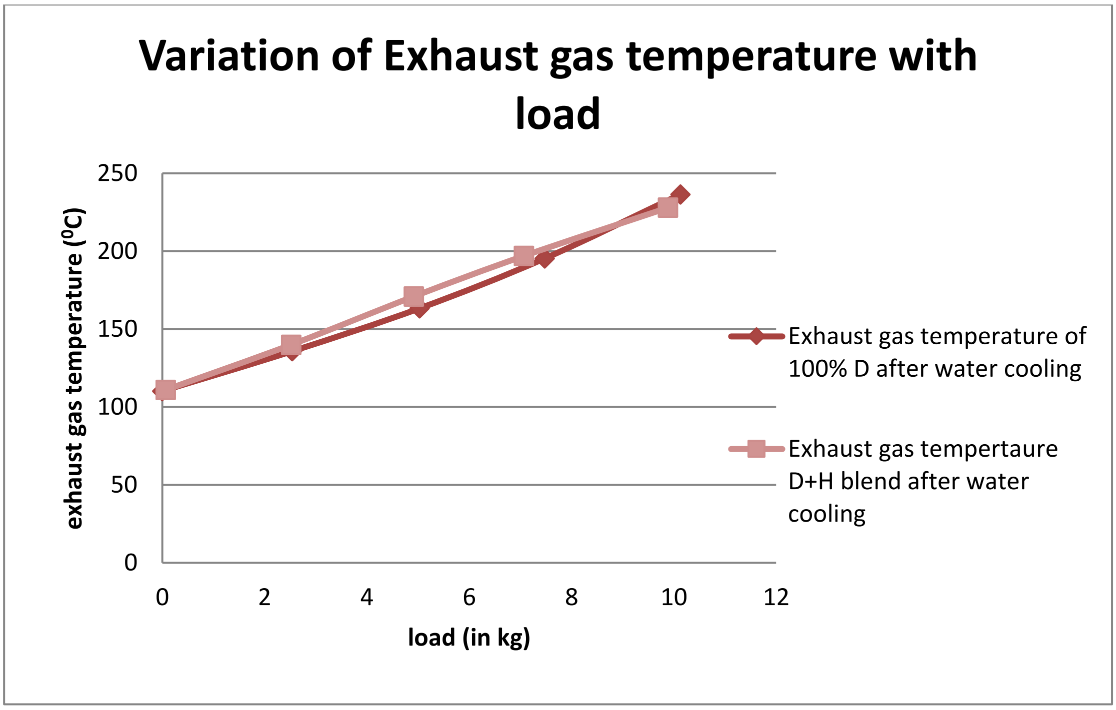


Fig 7.1 Comparison of 100% diesel and hydrogen-diesel blend in terms of EGT with load when engine is run with at Compression Ratio 20

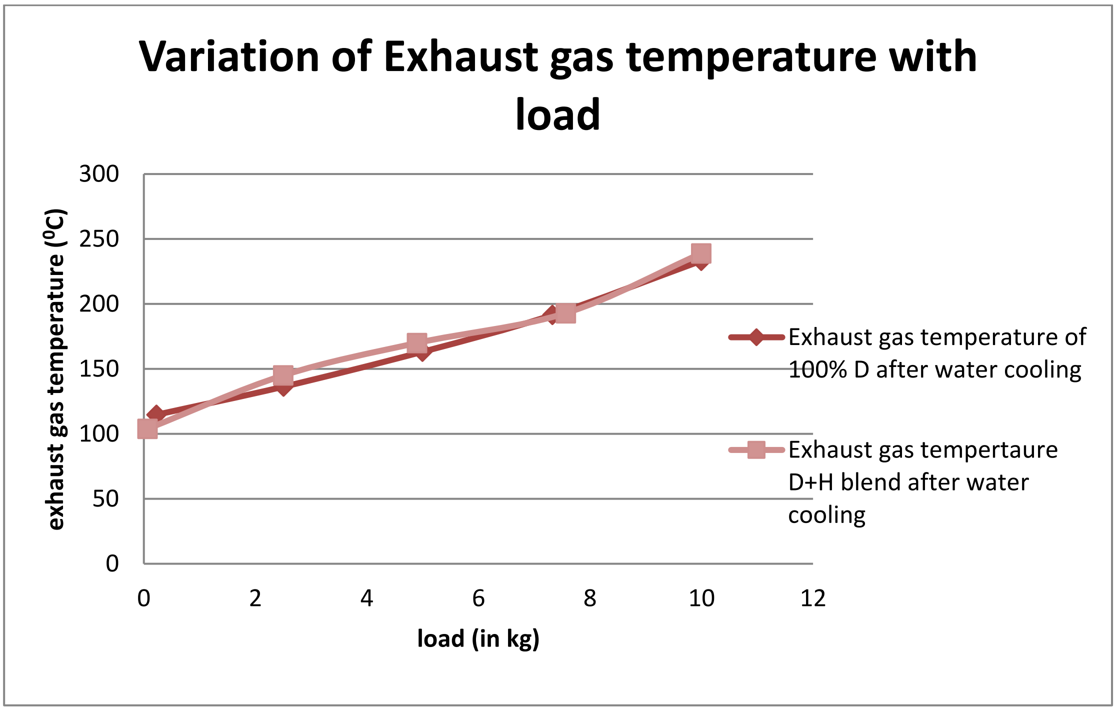


Fig 7.1 Comparison of 100% diesel and hydrogen-diesel blend in terms of EGT with load when engine is run with at Compression Ratio 19

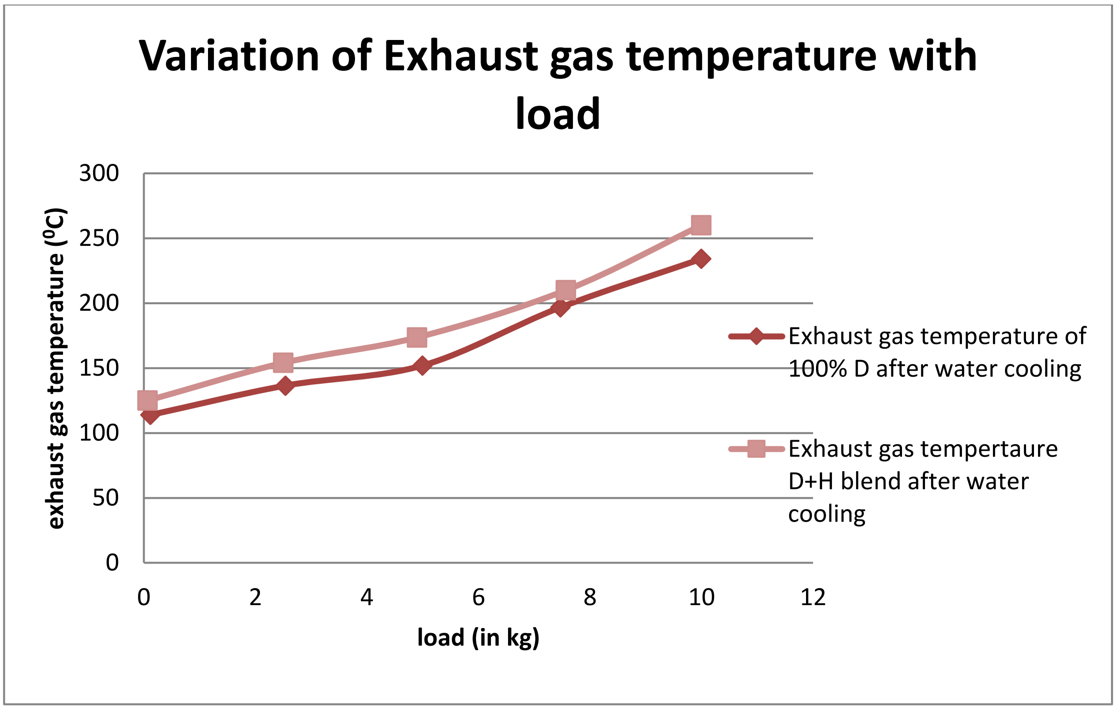


Fig 7.1 Comparison of 100% diesel and hydrogen-diesel blend in terms of EGT with load when engine is run with at Compression Ratio 18

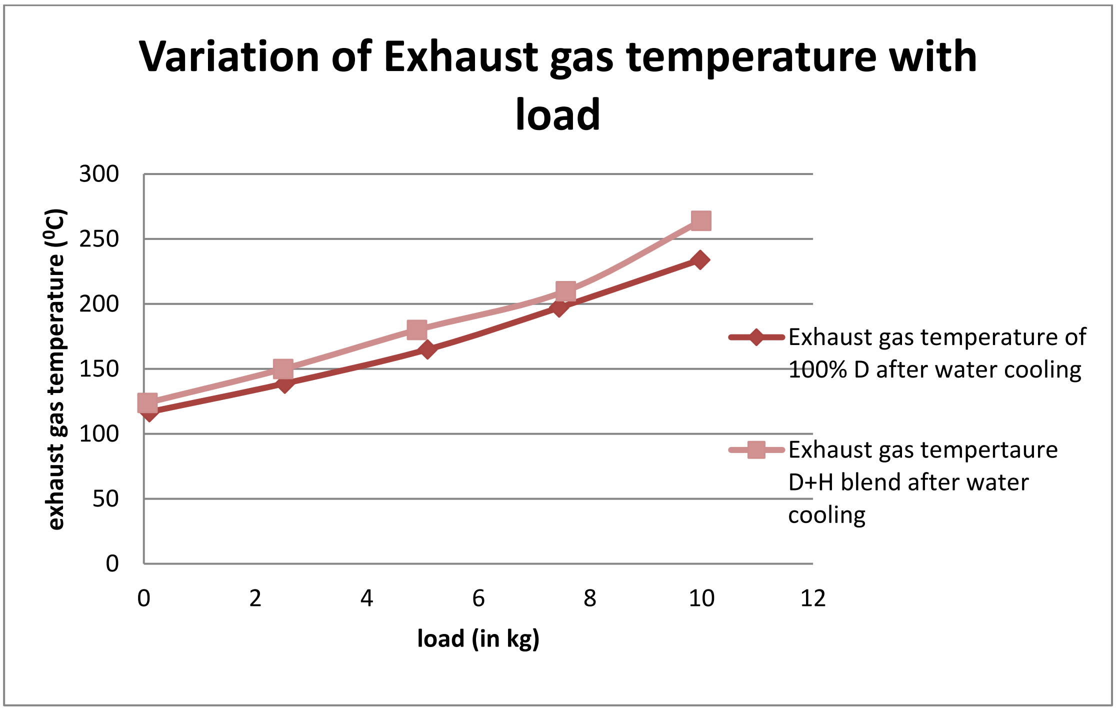


Fig 7.1 Comparison of 100% diesel and hydrogen-diesel blend in terms of EGT with load when engine is run with at Compression Ratio 17

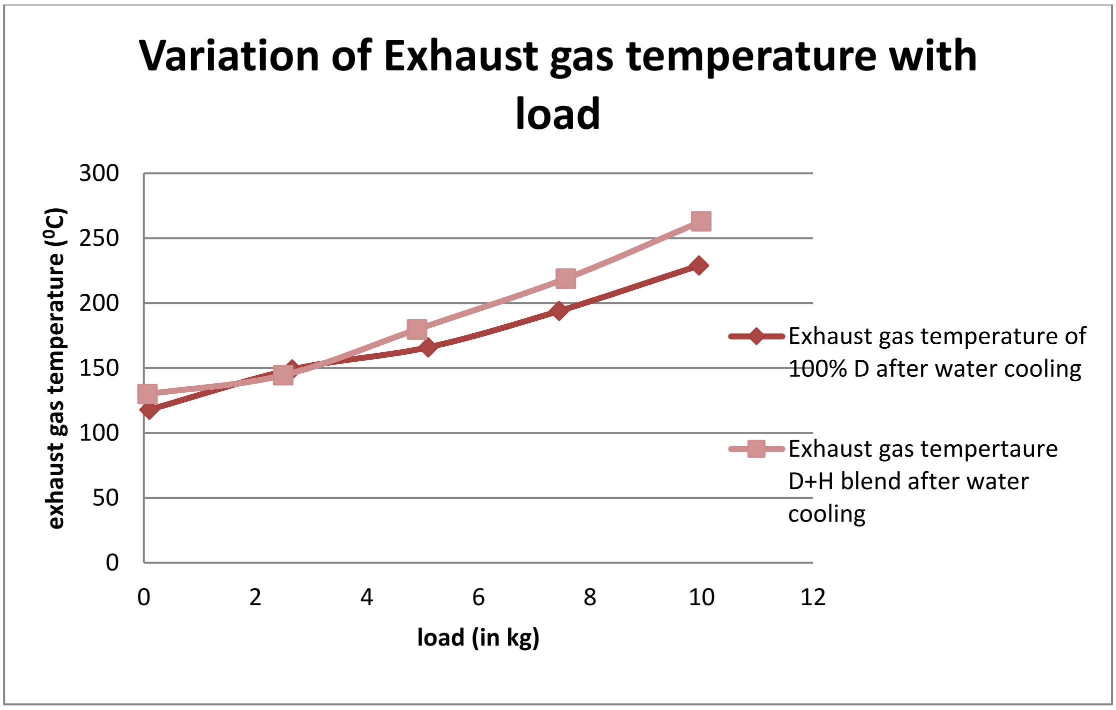
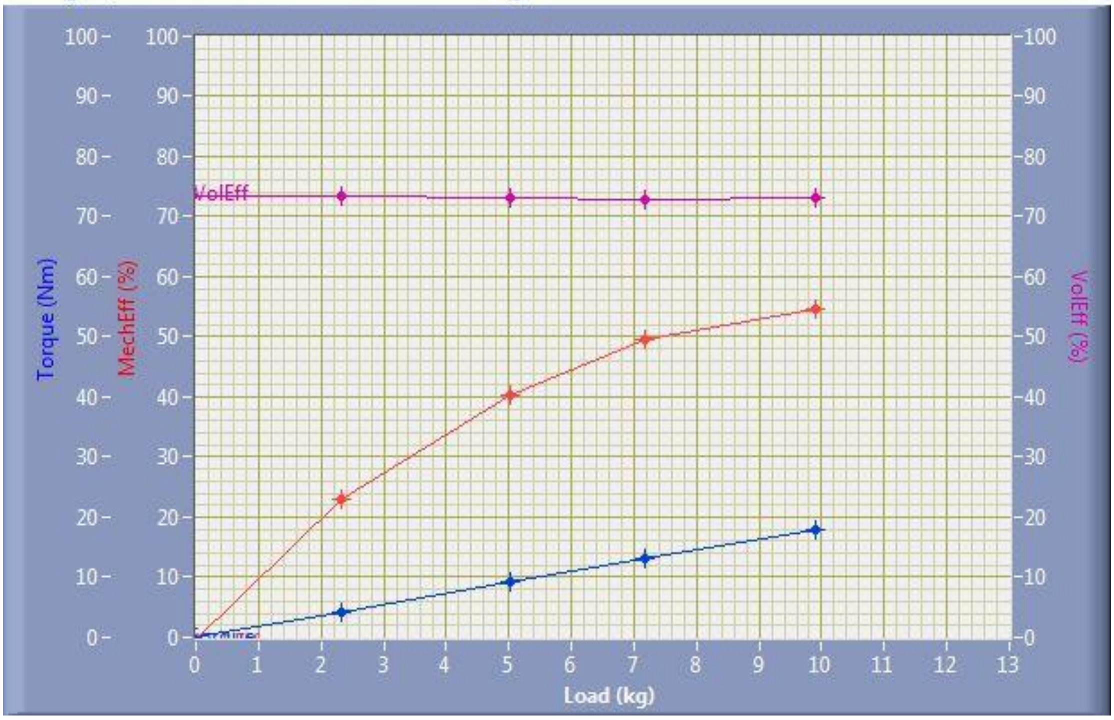


Fig 7.1 Comparison of 100% diesel and hydrogen-diesel blend in terms of EGT with load when engine is run with at Compression Ratio 16

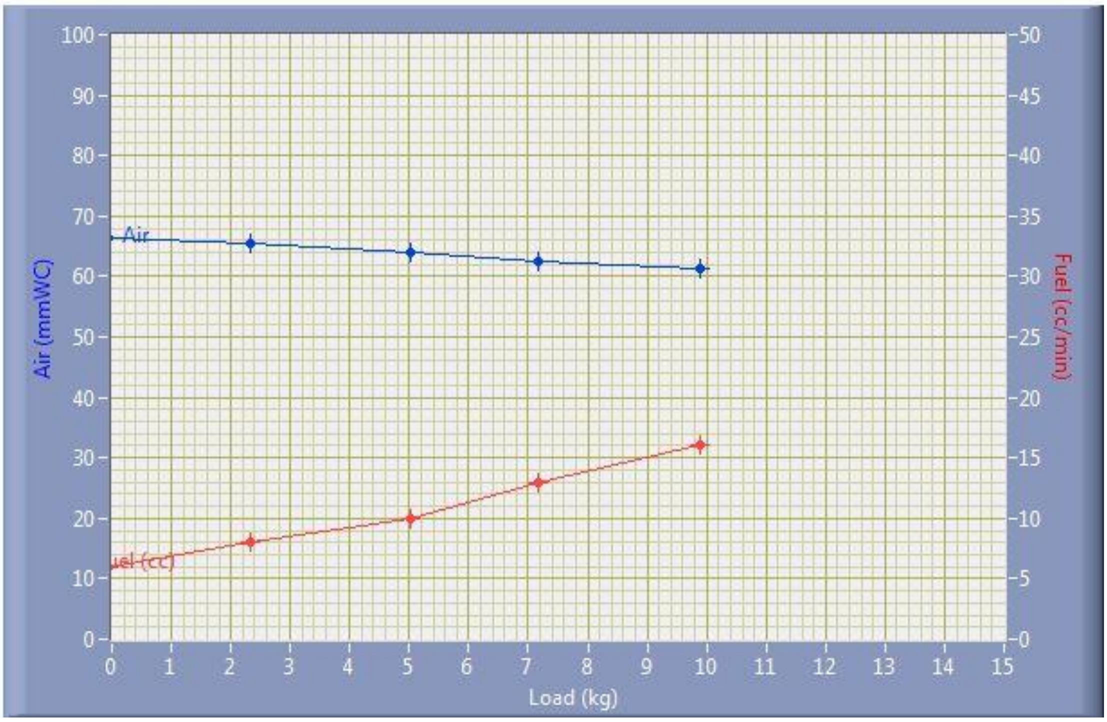
7.3 Effect on combustion parameters

As the maximum Brake thermal efficiency and Lowest BSEC observed at CR 21, comparison of Combustion characteristics when engine is run with H+D and 100 % D at CR 21 has been observed in the following figures.

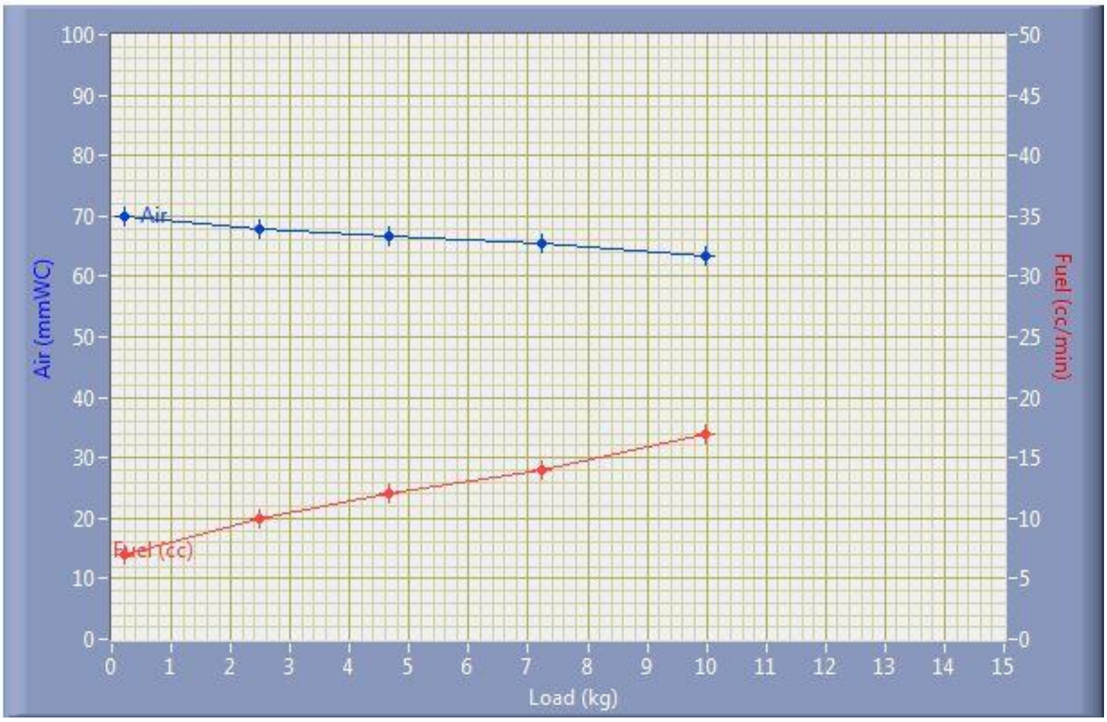
TORQUE, Mechanical & Volmetric Efficiency



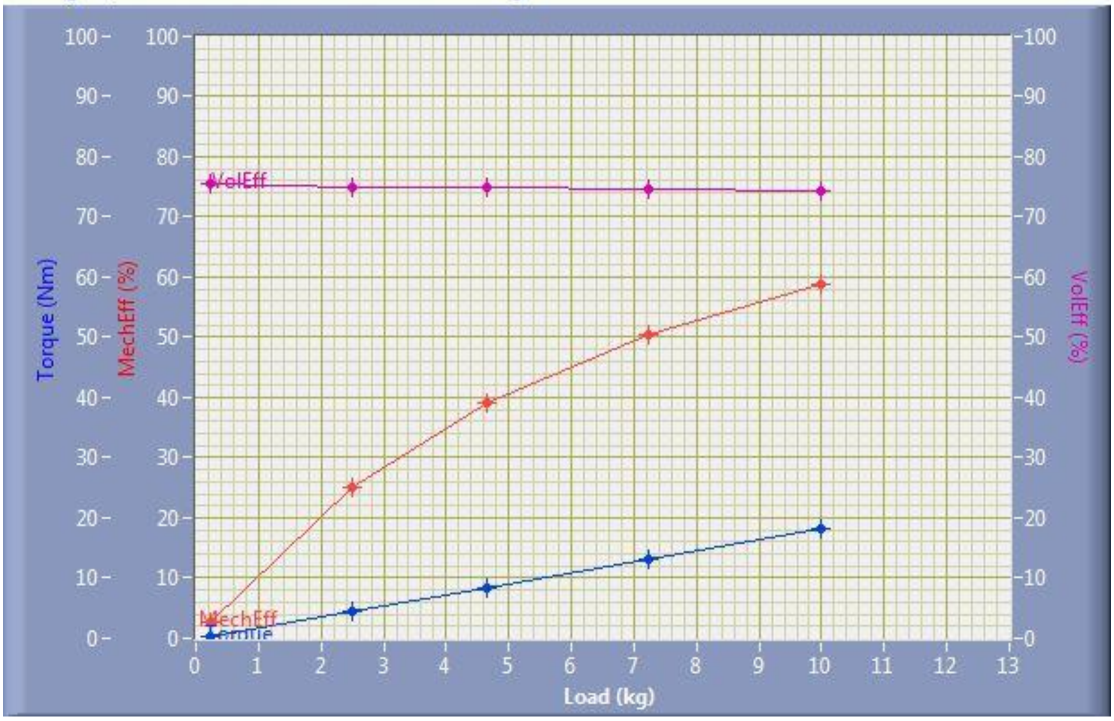
Air & Fuel Flow



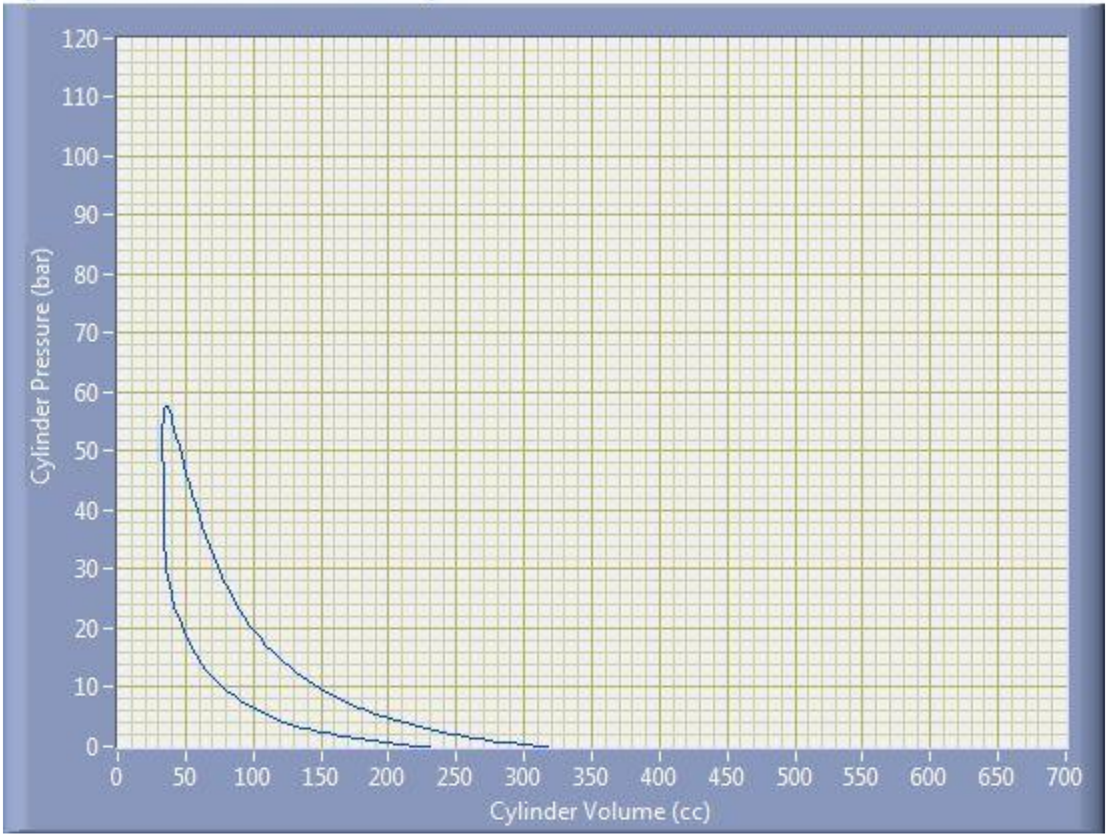
Air & Fuel Flow



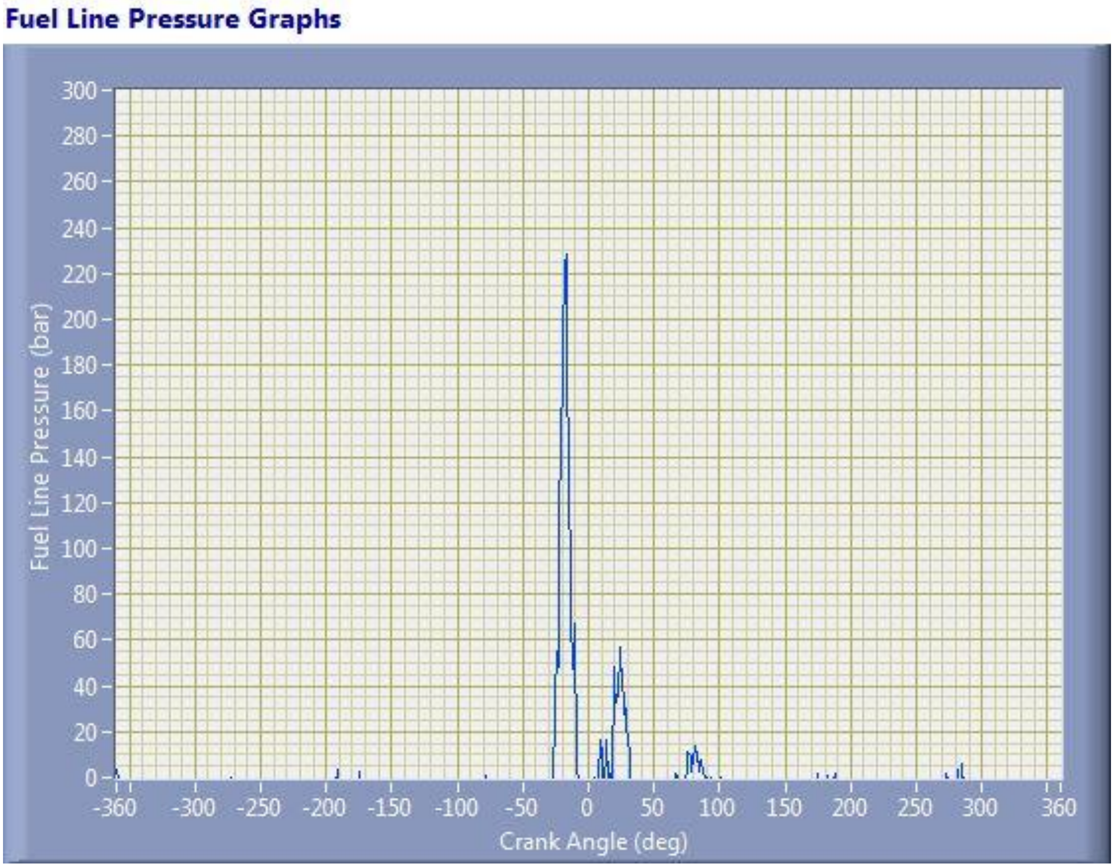
TORQUE, Mechanical & Volmetric Efficiency

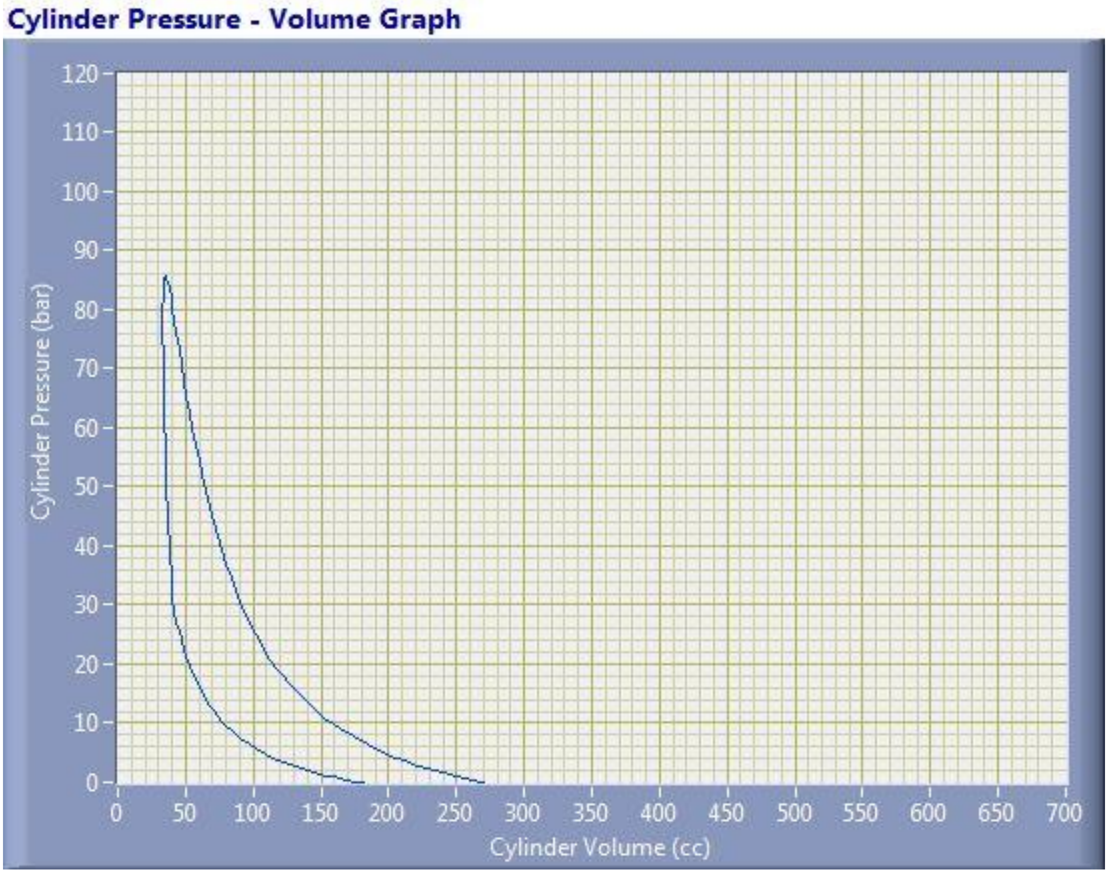


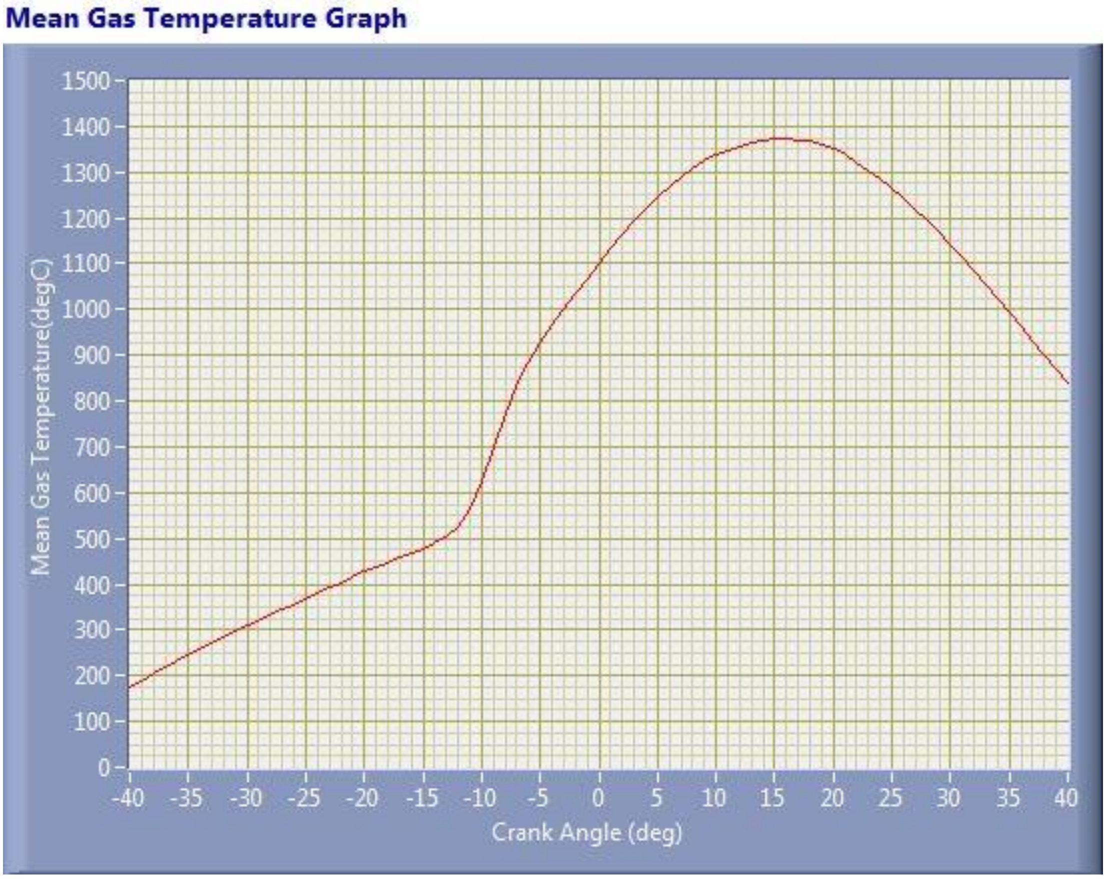
Cylinder Pressure - Volume Graph

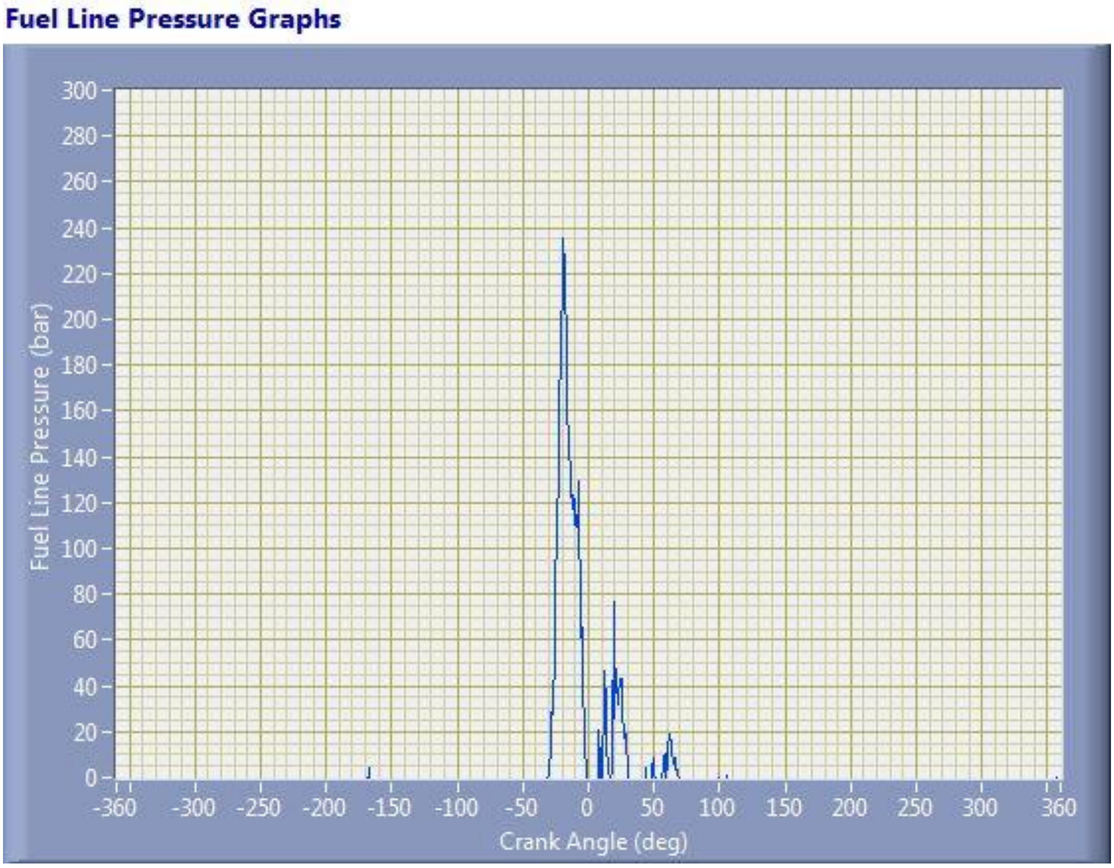


Mean Gas Temperature Graph


Fuel Line Pressure Graphs
Fuel Line Pressure (bar)
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
-360
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
300
360
Crank Angle (deg)


Cylinder Pressure - Volume Graph
Cylinder Pressure (bar)
120
110
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Cylinder Volume (cc)


Mean Gas Temperature Graph
Mean Gas Temperature(degC)
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
Crank Angle (deg)


Fuel Line Pressure Graphs
Fuel Line Pressure (bar)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
Crank Angle (deg)
-360
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
300
360

Chapter 5

CLOSURE

5.1 Conclusion of the study

The aim of study to know the present scenario of hydrogen production, its use as hybrid fuels, its advantages, limitations, safety issues, effect of introducing diluents and other techniques on SI and CI engine is achieved. It has been found that most of the researches done deal with liquid fuels such as Biodiesels and Alcohols, etc, and are already been accepted on commercial scale. Gaseous fuels such as LPG, CNG and Biogas have also been accepted widely because of several advantages over liquid fuels. Research using Hydrogen as a fuel is mostly being done on the stationary SI engines. Most of the studies using hydrogen in CI engines have been conducted mainly on water cooled single/multi cylinder engines using different injection techniques. However, meager work has been done on stationary air cooled, single cylinder engines of 5-8 HP (these engines are frequently used for agriculture, power generation, etc). Almost no work has been done varying CR of hydrogen fueled engine. Finding the performance at variable CR, will lead us to determine the optimum CR for a engine that is to be run with hydrogen substitution and during designing the engine that optimum CR can be deployed.

5.2 Research gap (Scope)

5.2.1 Study & evaluate the feasibility of production of hydrogen by various processes/technologies, especially based on renewable energy methods.

5.2.2 Development of materials/processes/sub-systems/systems for storage of hydrogen

5.2.3 Development of hydrogen for power generation and transport sector.

5.2.4 Hydrogen and Liquid Fuels from Biomass Gasification

5.2.5 Varying CR of hydrogen fueled engine, the optimum CR can be judged for a particular engine using VCR experimental set up.

5.2.6 Efforts must be done to abate NO_x emission without sacrificing BTE of engine.

5.2.7 The practicality of vehicles utilizing hydrogen substitution is limited by the equipment cost, so development of materials, components that cater the needs of hydrogen is to be searched.

5.2.8 Economic analysis for India can be carried and the financial feasibility is to be ascertained.

Thus, in order to fill this gap, to enhance maximum hydrogen energy share without knocking and to develop a simplified technique for hydrogen fuelling in CI engine operated end-utility systems for rural/remote applications, we researchers must come forward and fill the deficient of the present Hydrogen state of art. National Hydrogen Energy Board set up by **MNES,** and **MNRE** also supports the researchers and they make effort to abreast coordination amongst various stakeholders working in this area in India and integrate all efforts towards a common goal.

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APPENDIX

Safety features of Hydrogen

- Hydrogen being the smallest and lightest element in nature, it diffuses rapidly to the surroundings to non-combustible proportions.
- Low molecular weight of hydrogen results in high molecular diffusivity such that hydrogen diffuses 3-8 times faster than air.
- Excessive hydrogen leakage into open atmosphere has not resulted in any explosion-but disperses without any harm.
- Hydrogen fires burn very rapidly and radiate very little heat, and thus are relatively short lived.
- Hydrides are safer than gasoline tanks. Unless a continuous supply of heat is available to desorb the hydrogen, a leak from a hydride tank will be self-limiting.
- Hydrogen fires burn very rapidly and radiate very little heat, and thus are relatively short lived. A person can be closer to a H_2 fire than a gasoline fire without being burned.