

***EFFECT OF HYDROGEN INDUCTION ON COMBUSTION,
PERFORMANCE AND EMISSION BEHAVIOUR OF COMPRESSION
IGNITION ENGINE USING USED TRANSFORMER OIL AS A MAIN FUEL***

**A THESIS SUBMITTED IN THE PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF**

**Master of Technology
In
MECHANICAL ENGINEERING**

[Specialization: Thermal Engineering]

By

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Orissa-769008**

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Under the supervision of

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CERTIFICATE

This is to certify that the thesis entitled, "**EFFECT OF HYDROGEN INDUCTION ON COMBUSTION, PERFORMANCE AND EMISSION BEHAVIOUR OF COMPRESSION IGNITION ENGINE USING USED TRANSFORMER OIL AS A MAIN FUEL**" submitted by **Mr. ABHASH JAISWAL** in partial fulfilment of the requirements for the award of Master of Technology in Mechanical Engineering with "Thermal Engineering" Specialization during session 2010-2011 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

It is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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ABHASH JAISWAL

Abstract

Our present fuel resources are not going to be around forever and with the ever increasing consumption their extinction is nearly unavoidable. Also our fuel resources which are mostly made up of fossil fuels are not renewable in nature. In the present study hydrogen at a constant flow rate of 4lpm was inducted in the suction, at some distance away from the intake manifold, along with air. Two different fuels on volume basis were tested as main fuels in a single cylinder, 4-stroke, air cooled, direct injection diesel engine developing a power of 4.4 kW, at a rated speed of 1500 rpm. One fuel was the sole used transformer oil (UTO/UTO100) and the other one was the UTO at 40% blended with 60% diesel fuel (UTO40). The combustion, performance, and emission parameters of the engine were obtained in the investigation and compared with the baseline diesel fuel. The results indicated increase in brake thermal efficiency for both the main fuels when hydrogen is inducted and also high reduction in smoke levels.

Key words: Hydrogen, Used transformer oil, Performance, Emission, Combustion

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Nomenclature

Sl. no.	Short form	Full name
1.	TO	Transformer oil
2.	UTO/UTO100	Used transformer oil as a sole fuel
3.	UTO40	40% used transformer oil blended with 60% diesel fuel
4.	DF	Diesel fuel
5.	BP	Brake power
6.	BTE	Brake thermal efficiency
7.	BSEC	Brake specific energy consumption
8.	EGT	Exhaust gas temperature
9.	CO	Carbon monoxide
10.	HC	Hydrocarbon
11.	CO ₂	Carbon dioxide
12.	NO _x	Oxides of nitrogen
13.	NO	Nitric oxide
14.	TDC	Top dead centre
15.	Y	Total percentage uncertainty

CHAPTER 1

INTRODUCTION

CHAPTER -1

INTRODUCTION

1.1. General

The present energy situation has stimulated active research interest in non-petroleum, renewable and non polluting fuels. Much of the present world's energy demand may still be supplied by exhaustible fossil fuels (natural gas, oil and coal), which are also the material basis for the chemical industry. It is well known that combustion of fossil fuel causes air pollution in cities and acid rains that damages forests, and also leads to produce more carbon dioxide resulting environmental degradation. In recent year, the concern for cleaner air, due to strict air pollution regulation and the desire to reduce the dependency on fossil fuels. Many attempts are made to find various new and renewable energy sources to replace the existing petroleum fuels. Alternative fuels are available in the form of solid, liquid, and gas. Biomass, biodiesel from different vegetable oils and LPG are some of the examples for solid, liquid and gaseous alternative fuels respectively which are commonly used to run the internal combustion engines. Although these fuels are used, they generate considerable pollutants from the internal combustion engines. Hydrogen is found to be cleaner fuel among all other alternative fuels. Hydrogen is largely available and renewable in nature.

1.2. Alternative fuels

In view of the problem of fast dwindling reserves of irreplaceable petroleum fuels and the hazards of environmental pollution caused by their combustion, attempts must be made to develop the technology of alternate clean burning synthetic fuels. These fuels should be such that they have attributes of perennial renewal, they perform well in the engine, and their potential for environmental pollution should be quite low. Some alternative fuels in the form of solid, liquid and gaseous fuels have been studied.

1.2.1. Solid Fuels

The best example of solid alternative fuel is energy from biomass. Biomass in its traditional solid mass (wood and agriculture residue) and biomass in its non traditional form (converted into liquid fuel). The first category is to burn the biomass directly and get the energy. The second category, the biomass is converted into ethanol and methanol to be used

as liquid fuels in engines. The third category is to ferment the solid biomass anaerobically to obtain a gaseous fuel called bio gas. Three solid bio fuels- wood, straw and refuse are being burnt on an increasing scale in many countries to provide useful energy. Wood in the form of cut logs, chips, and saw dust is currently used as a solid bio fuels. Now a day's straw burning furnaces are common in many countries. Municipal refuse is far from an ideal fuel. It is messy to handle and has a low and variable energy content on average only about one third of that of coal.

1.2.2. Liquid fuels

Alcohols and derivatives of vegetable oils are the best examples of this category, replacing petrol and diesel as transport fuels in many countries and this process is likely to accelerate as oil prices rises.

Alcohols:

Alcohols are of two types, ethanol and methanol which can be produced from sugarcane waste, and many other agricultural products (renewable sources). Alcohol is derived not directly from sugarcane but molasses – sugarcane by- products. All starch rich plants like maize, tapioca, and potato can be used to produce alcohol as well as cellulosic waste materials can also be used [1]

The advantages of using alcohol fuel are that it produces less overall emissions compared to diesel and gasoline. Pure alcohol and their blending with various proportions with diesel are utilized on diesel engine by many researchers. Methanol by itself is not a good CI fuel because of its high octane number, but if small amount of diesel oil is used for ignition, it can be used with good results. Ethanol has been used as alternative fuel for many years in various countries. Brazil is probably the leading user. Minor engine modifications are necessary for blends containing more than about 20% alcohol, or for almost pure alcohol: these include on increased compression ratio, and altered timing etc. [2]

Vegetable oils:

Vegetable oils can also be used as a alternate liquid fuel for diesel engine. From crushed seeds and nuts (for example, sun flower and rape seed, peanuts, palm, soya, and corn) can be burnt in unmodified diesel engine. They can be blended with diesel fuel or used directly.

1.2.3. Gaseous fuels

Alcohols, both ethanol and methanol, have been moderately successful as mixtures of alcohols and diesel fuel. But ethanol resource materials are inadequate to have an impact on the probable future requirements. Methanol, owing to its potential availability as a product of coal conversion, continues to commend considerable interest, but both alcohols release CO₂ gas on combustion, which tends to cause Green House Effect.

Gaseous fuels in comparison to the both solid and liquid alternate fuels have potential to solve both the problems of energy crisis and air pollution. Among all other gaseous fuels like Natural gas, LPG, CNG, Biogas, Fuel gas, hydrogen is best suited for compression ignition engines. Hydrogen is almost in exhaustible natural source present in water. Also hydrogen on combustion produces only water and NO_x whose toxic effects are very less compared to other fuels.

1.3. Hydrogen-Future fuel for IC engines

If we look at the past 2000 years history of fuels, usage has consistently moved in the direction of a cleaner fuel: wood → coal → petroleum → propane → methane. The fuel molecule has become smaller, leaner in carbon and richer in hydrogen. The last major move was methane, which is a much cleaner burn than gasoline and diesel. So it is expected, hydrogen to be a future fuel for the internal combustion engines [3]. Hydrogen has the potential to solve both the environmental hazard faced by humankind i.e. air pollution and global warming. Utilization of hydrogen for engine application is not a new concept. But previously, there was no other motive in the minds of the investigators as it appeared that petroleum, a perennial fuel source, would be available for all times to come. The problem of availability of petroleum products was first time realised just after the Second World War. So after that, hydrogen received special attention as an alternative engine fuel. A huge work is done since 1960 on hydrogen engines. There is no fuel other than hydrogen that could meet the twin challenges of the energy crisis and environmental pollution. Hydrogen is only one such fuel. It can be produced from the renewable energy sources and as far the effects of pollution is concerned, the common pollutants coming out of the exhaust of a gasoline or diesel operated engine fuel are practically absent. Hydrogen as an engine fuel is exceptionally clean burning. But use of hydrogen as an energy source in compression ignition engines involves four basic issues [2]:

1. Production
2. Storage and Transportation
3. Safety Aspects
4. Utilization

1.3.1. Hydrogen Production

The hydrogen molecule is the smallest and lightest of all the molecules with unique properties and uses. Hydrogen can be produced from water by using a variety of primary energy sources including hydrocarbons, coal, nuclear, wind, biomass, and solar. Since renewable energy sources (solar, wind, and /or biomass) are available in all parts of the world, all countries will have access to hydrogen fuel. Wind, solar, and nuclear electrolyses can produce pure hydrogen ready for use in fuel cells or in internal combustion engines. Also the use of solar, wind does not add to environmental pollution. However, hydrogen derived from the other energy sources will require separation and purification. Currently the dominant technology for direct production of hydrogen is steam reforming from hydrocarbons. Hydrogen is also produced as a by-product of some chemical processes.

The other methods are electrolysis and thermolysis. The discovery and development of less expensive methods of production of bulk hydrogen is relevant to the establishment of a hydrogen economy. Some common methods for the production of hydrogen are discussed in the following subsections:

1.3.1.1. Hydrogen Waste Stream

Hydrogen is used for the production of ammonia for fertilizer via the Haber process, converting heavy petroleum sources to lighter fractions via hydro cracking and petroleum fractions (dehydrocyclization and the aromatization process). It was common to vent the surplus of hydrogen, nowadays the plants are balanced with hydrogen pinch which creates the possibility of collecting the hydrogen for further use.

Hydrogen is also produced as a by-product of industrial chlorine production by electrolysis. It can be cooled, compressed and purified for use in other processes on site or sold to a customer via pipeline, cylinders or trucks.

1.3.1.2. From Hydrocarbon

a. Steam reforming

Fossil fuel currently is the main source of hydrogen production. Hydrogen can be generated from natural gas with approximately 80% efficiency or from other hydrocarbons to a varying degree of efficiency. Specifically, bulk hydrogen is usually produced by the steam reforming of methane or natural gas. At high temperatures between 700–1100 °C, steam (H₂O) reacts with methane (CH₄) to yield syngas. The reaction is given below:



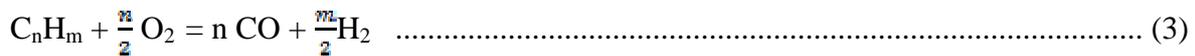
In a second stage, further hydrogen is generated through the lower-temperature water gas shift reaction, performed at about 130 °C.



Essentially, the oxygen (O) atom is stripped from the additional water (steam) to oxidize CO to CO₂. This oxidation also provides energy to maintain the reaction. Additional heat required to drive the process is generally supplied by burning some portion of the methane. Steam reforming generates carbon dioxide (CO₂). Since the production is concentrated in one facility, it is possible to separate the CO₂ and dispose of it properly, for example by injecting it in an oil or gas reservoir (see carbon capture), although this is not currently done in most cases.. However, even if the carbon dioxide is not sequestered, overall producing hydrogen from natural gas and using it for a hydrogen vehicle only emits half the carbon dioxide that a gasoline car would.

b. Partial oxidation

The partial oxidation reaction occurs when a substoichiometric fuel-air mixture is partially combusted in a reformer, creating a hydrogen-rich syngas. A distinction is made between thermal partial oxidation (TPOX) and catalytic partial oxidation (CPOX). The equations are as follows:



Possible reaction equation (heating oil):

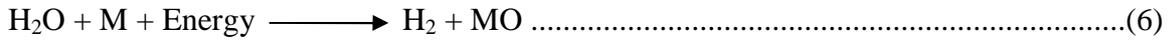


Possible reaction equation (coal):



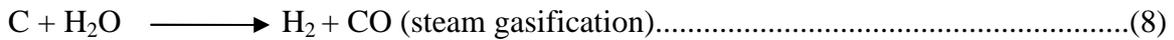
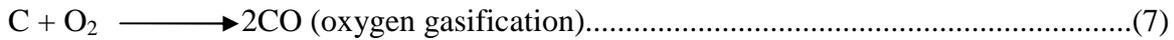
c. Coal

The method of producing hydrogen from water involves using a reductant M in an oxidation-reduction reaction.

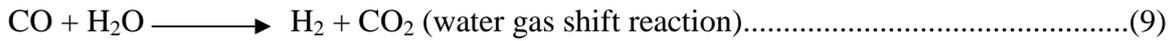


M may be a metal or carbon C. Fortunately, carbon is readily available from abundant materials such as coal (CH_mO_n). Production of hydrogen from coal is a well established technology, in which O_2 or steam is passed over coal to produce a mixture of H_2 , CO , and CO_2 from which hydrogen is separated.

In a gasifier, coal is converted to syngas by the following gasification reactions:



The gas-phase water – gas shift reaction is an important reaction that controls the equilibrium among CO , H_2 , CO_2 , and H_2O .



1.3.1.3. From water by electrolysis and thermal decomposition

In the electrolysis process, electrical energy is used to break the water into the hydrogen and oxygen. But this method has disadvantage as an energy conversion system because it requires high amount of electricity. Considerable research work is underway to develop a thermal cycle that would utilize heat to achieve the chemical splitting of water into hydrogen and oxygen. In electrolysis high electric voltage is required while in thermal decomposition high temperature (25000C) is required. Thermo chemical method is considered most promising. It depends on complex series of interactions between the primary energy, water and some specific chemicals to produce hydrogen at temperatures substantially lower than thermal decomposition [3]. The chemicals used are recyclable. A variety of compounds of iron, iodine, lithium, and cadmium are used for this purpose.

1.3.2. Source and Method of storage

Hydrogen storage is the key element in the utilization of hydrogen as a fuel. Hydrogen is by far the most plentiful element in the universe, making up 75% of the mass of it is visible matter in stars and galaxies. But as the boiling point is very low for hydrogen, it cannot be stored conveniently like diesel, characteristic common to methane, furthermore, as the critical

temperature is also very low, hydrogen cannot be liquefied easily like propane or butane. Very low temperature refrigeration is required to liquefy hydrogen and maintain it in the liquid phase. An alternative method of storage is in the gaseous phase in high pressure cylinders. The compression of the gas to such high pressure requires the expenditure of much expensive compression work and the provision of necessary infrastructure. Also, these hydrogen gas cylinders would add significantly to the total weight, cost and bulkiness of the fuel installation.

Hydrogen can also be stored in the form of various metal hydrides that would permit the controlled release of hydrogen through the supply of heat, often from the engine exhaust gas or its cooling water. These methods are of limited usefulness as they add much cost and weight while reducing the flexibility of the fuel system and contributing to an increase in undesirable emissions.

1.3.3. Safety aspects of hydrogen

The safety aspects of any fuel are closely related to the fuel application and the postulated accident criteria. Hydrogen fuel cannot be handled exactly in the same manner as the conventional petroleum based fuel, primarily because of the wide difference in combustion characteristics of both fuels. In the event of a fuel spill, a fire hazard can develop most rapidly with hydrogen. This is because hydrogen has higher diffusion velocity, high buoyant velocity, wider flammability limits and lower ignition energy. The first two factors determine the rate of mixing of fuel with air. The third factor determines the range of equivalence ratio over which a flame can be sustained. The fourth factor determines the ease with which a flammable mixture can be ignited

The wider flammable limits coupled with its higher burning velocity makes hydrogen to possess greater potential for explosion compared to diesel. As the quenching distance is inversely proportional to the laminar burning velocity, hydrogen air mixtures have lower quenching distance increases the tendency of flashback. Also a flammable mixture of higher burning velocity has a greater tendency to cause transition from flame to detonation during flashback in long pipes.

Hydrogen is soluble in many materials including low alloy steels and stainless steels. The solubility of hydrogen increases with temperature. However, even if the gas is at room temperature, hydrogen embrittlement can still occur since it depends on pressure. The selection of the chemical for hydrogen use is a very important safety consideration because

hydrogen reacts with a number of chemicals. For example, it explodes with chlorine in light. Flame arrester should be incorporated in hydrogen fuelled engine so as to avoid backfire.

Tendency for knocking and pre-ignition could exist in some operating conditions. But this is not a serious problem if severe effective operating controls can be exercised. Basically hydrogen – air mixtures have high anti-knock characteristics due to high flame propagation rates. High energy release rate increases thermal efficiency in I.C engines but could lead to very rapid pressure rise and intolerable engine roughness.

Some important measures must be taken to prevent explosion from hydrogen cylinders like installation of explosion-suppression systems, flame traps, flame suppressors, explosion relief devices and rapid closing devices [2]. There are no safety problems in the industrial and commercial applications of hydrogen as indicated by the past experience in industry and commerce. However there may be safety problem in transportation and domestic uses, which require careful study before replacing present fuels by hydrogen.

1.3.4. Utilization of hydrogen in compression ignition engines

As far as the utilization of hydrogen in compression ignition engine system is concerned, the techniques of hydrogen induction play a very important role [8]. There are basically five different techniques of hydrogen induction that were carried out in the last few decades by the researchers. They are

1. Carburetion technique
2. Continuous manifold injection (CMI)
3. Timed manifold injection (TMI)
4. Low pressure direct cylinder injection (LPDI)
5. High pressure direct cylinder injection (HPDI)

The above five points are the techniques to optimize the basic procedure of induction of hydrogen on diesel engines. In general, hydrogen can be used in diesel engines by two ways [4]:

1. By introducing hydrogen with air and using a spray of diesel oil to ignite the mixture that is by the dual fuel mode.
2. By introducing hydrogen directly into the cylinder at the end of compression. It is also possible to feed a very lean hydrogen air mixture during the intake into an engine and then inject the bulk of the hydrogen towards the end of the compression stroke.

Hydrogen, due to its wider ignition limits, the requirement of throttling is less compared to operation on diesel. This restricts the pumping loss and increases the thermal efficiency. The hydrogen can be used as a sole fuel in petrol engine but cannot be used directly in a diesel engine. The reason is due to high auto ignition temperature (858K) which cannot be achieved by compression alone. Therefore some other fuel of low self ignition energy (it may be diesel or other fuels) is required which acts as an ignition source for hydrogen. The combustion of the hydrogen occurs by only achieving its auto ignition temperature by flame initiation [27]. Therefore the hydrogen is always used in a dual fuel mode in compression ignition engine. Less cyclic variations are encountered with hydrogen than with other fuels. This lead to a reduction in emissions, improved efficiency, and quieter and smoother operation. Due to its high burning velocity, it can also be used to improve the combustion rate of fuels having slow burning characteristics [31]. Apart from the above five techniques, hydrogen can also be inducted continuously at a less flow rate, at some distance from the intake manifold.

1.3.5. Physical properties of hydrogen

Hydrogen shows the lowest boiling point and melting point next to helium. The boiling point of hydrogen is 20.27K while that of helium is 20K. Fuels that are gases at atmospheric conditions (such as hydrogen and natural gas) are less convenient as they must be stored as a pressurised gas or as a cryogenic liquid.

Pure hydrogen is odourless, colourless and tasteless. A stream of hydrogen from a leak is almost invisible in day light. Compounds such as mercaptans and thiophanes that are used to scent natural gas may not be added to hydrogen for fuel cell use as they contain sulphur that would poison the fuel cells.

Hydrogen is non-toxic but can act as a simple asphyxiant by displacing the oxygen in the air.

In an enclosed area, small leaks pose little danger of asphyxiant whereas large leaks can be serious problem since the hydrogen diffuses quickly to fill the volume. The potential for asphyxiant in unconfined areas is almost negligible due to the high buoyancy and diffusivity of hydrogen.

Hydrogen is detonable over a wide range of concentrations when confined. However, it is difficult to detonate if un confined, similar to other conventional fuels.

The hydrogen-air flame is hotter than methane air flame and cooler than gasoline at stoichiometric conditions (2207⁰C compared to 1917⁰C for methane and 2307⁰C for gasoline and that of diesel 2327⁰C).

The lower calorific value of hydrogen on mass basis is about 2.5 times that of most hydrocarbon fuels. Yet the flame temperature for hydrogen-air mixtures is not much higher than that for hydrocarbon fuels-air mixtures.

The property of wider flammability limits for hydrogen air mixtures are advantageous in diesel engines, to control the energy rates. The effects of hydrogen on flame stability are opposite to those of methane and diesel. While the tendency of flashback is more, the tendency for the blow off is less because of its high burning velocity and small penetration distance.

Hydrogen possess high rate of diffusion into air than diesel fuel. This promotes rapid mixing and enables to avoid premixing of fuel with air.

Hydrogen operated engines have tendency to knock. But this is not a serious problem if severe effective operating controls can be exercised. Various chemical properties of hydrogen and their comparison with diesel fuel are given in Table 1. While some combustion properties of hydrogen are given in Table 2.

Table 1. Some relevant properties of hydrogen

Property	Hydrogen	Diesel
Formula	H ₂	C ₈ -C ₂₀
Density at 1 atm and 300 K(kg/m ³)	0.082	833-881
Stoichiometric air fuel ratio (kg/kg)	34.3	14.5
Higher Heating Value (MJ/kg)	141.7	45.9
Lower Heating Value (MJ/kg)	119.7	43.0
Kinematic viscosity at 300 K(mm ² /s)	110	3.292
Thermal conductivity at 300 K (W/mK)	182.0	0.1768
Diffusion coefficient into air at NTP (cm ² /s)	0.61	-
Specific gravity	0.091	0.83
Boiling point(K)	20.27	436-672
Cetane number	-	40-55
Molecular weight(g/mole)	2.015	170

Table 2. Combustion properties of hydrogen and diesel fuel

Combustion energy per kg of stoich. mixture (MJ)	3.37	-
Flammability limits (% by volume)	4-75	0.7-5
Flammability limits (Equivalence ratio)	0.1-6.9	-
Laminar flame speed at NTP (m/s)	1.90	-
Max deflagration speed (m/sec)	3.5	0.3
Minimum ignition energy (mJ)	0.02	-
Adiabatic flame temperature (K)	2318	2200
Auto ignition temperature (K)	858	530

1.4. Non conventional fuels from waste substances

The polymer energy system is the innovative and appropriate method to get energy from waste substances like plastics, tyres, etc. Previous waste management method like land fill, incineration and recycling failed to provide opportunities for the complete reuse of waste substances. The polymer energy system suits the best way to extract energy from waste substances. It involves special techniques called pyrolysis.

1.4.1. Plastics

Waste plastics are one of the most promising resources for fuel production because of its high heat of combustion and higher availability in local areas. The advantageous property of plastics is that they do not absorb much moisture due to which its water content is very low compared to that of biomass. With the abundance of plastic that ends up in landfills and the ocean, though this could be a great new **alternative energy** source. After pyrolysis treatment, the waste plastic can be converted into liquid fuel.

Pyrolysis is a technique of thermal decomposition of the substances under an inert gas like nitrogen. The pyrolysis of plastics needs around 450 to 550° C temperature inside the reactor.

1.4.2. Tyres

Waste tyre is also another medium from which energy can be obtained. This also involves the technique of pyrolysis at a high temperature inside the reactor. The materials in a tire are heated and separated to be reused or disposed of. A tire has steel fibre in it which makes reuse difficult. But all the organic polymers and stuff give tires a good energy value and some of the organics can be heated and reused.

1.4.3. Waste/Used Transformer Oil

The oil that is used in the transformers for the cooling purpose is thrown out in the form of waste after use. The waste transformer oil possesses lots of dirt. After cleaning, it can also be used as a alternate fuel for the internal combustion engines. The advantage of this waste transformer oil is that it does not need the technique of pyrolysis.

1.5. Transformer oil

Transformer oils are an important class of insulating oils. It acts as heat transfer medium so that the operating temperature of a transformer does not exceed the specific acceptable limits. Transformer oils are produced from wax-free naphthenic oils. Although these types of crudes permit production of exceptionally low pour point insulating oils without the need for dew axing or special attention to the degree of fractionation or distillate cut width, they also contain high percentages of sulphur and nitrogen which must be removed in order to satisfy the stringent stability requirements of insulating oils [5]. It has been found that a highly aromatic, low paraffinic content naphthenic crude oil is a suitable raw material to prepare good transformer oil.

Mineral oil is the base material for transformer oil that is used as coolant in transformers in electrical substations and welding transformers. After prolonged use, the transformer oil becomes deteriorated and becomes waste. However, the waste or used transformer oil (UTO) posses a considerable heating value and some of the properties similar to that of diesel fuel [7]. Therefore, it can be used as an alternative fuel in compression ignition engines. But the use of UTO in compression ignition engine gives high vibration. Therefore attempts have been made to utilize the heating value of hydrogen to reduce the viscosity of UTO by inducting hydrogen into the suction.

1.5.1. Transformer oil identification [6]

Product Name:	Transformer Oil,
Chemical Name:	Severely Hydro treated Heavy Naphthenic Distillate
Chemical Family:	Petroleum Hydrocarbon Oil

1.5.2. Colour of Used Transformer oil

The used transformer oil appears to be dark brown in colour and the colour of sole used transformer oil is given in Fig 1.. The properties of UTO and UTO40 are given in Table 3.



Fig 1. Colour of used transformer oil

1.5.3. Use of Transformer oil in compression ignition engine

Transformer oil is used for cooling purpose and after its application it is thrown out in the form of waste. But, after testing the waste/used transformer oil, it has been seen that the property of used transformer oil are similar to that of diesel. So attempts have been made to substitute the diesel fuel with used transformer oil as an alternative fuel in the engine. . Recently, experiments have been carried out to utilize the used transformer oil as a non conventional in a single cylinder, four stroke, air cooled, direct injection diesel engine. Due to high viscosity of used transformer oil, it was blended with conventional diesel fuel and was tested in the engine. The used transformer oil of 10-60% was blended with diesel fuel at 90-40% respectively and neat used transformer oil i.e. UTO 100% was also used as alternative fuels [7]. Results indicated that the UTO40 was the most acceptable blend among all the tested used transformer oil based fuels. But while using the neat used transformer oil (UTO), the engine gave a lower performance and higher HC, CO and smoke. Therefore, it is necessary to explore more possible ways to improve the performance and reduce the emissions from a diesel engine fuelled with UTO. Inducting hydrogen is one such technique.

Table 3.Properties of UTO and UTO40

Property	UTO	UTO40
Sp.Gravity at, 27 °C	0.830	0.866
Kinematic Viscosity, cst at 27°C	13	7.3
Gross Calorific Value KJ/kg	39120	41928
Flash Point, °C	150	90
Fire Point, °C	172	102.4
Sulphur Content, %	0.020	0.035
Ash Content, %	NIL	.006
Carbon Residue, %	0.020	0.029

CHAPTER 2

LITERATURE SURVEY

CHAPTER 2

LITERATURE SURVEY

L.M.Das [8] studied that the mixture formation method plays a important role for the practical application of a hydrogen fuelled specific engine. The use of cryogenic hydrogen supplied from the liquid hydrogen tank, method of late fuel injection are studied and evaluated. It was suggested that the integrated fuel induction and storage method must be designed for an hydrogen specific engine

N.Saravanan et al. [9] did experiments on DI diesel engine supplemented with hydrogen fuel. Two techniques were adopted to inject hydrogen inside the engine cylinder ;(1) Carburetion technique and (2) TPI –Timed Manifold Injection technique and compared their performance, emission and combustion parameter with sole diesel by adopting both the techniques. It was concluded that TPI technique gives better performance compared to carburetion technique. The knock can occur at high flow rate of hydrogen. They concluded the optimum hydrogen enrichment with diesel was 30% by volume.

N. Saravanan et al. [10] inducted hydrogen in a DI diesel engine adopted EGR technique to reduce NO_x emission. The arrangement was provided in such a way that, some part of exhaust gases is sent back to the engine intake manifold. This arrangement is called as Exhaust Gas Recirculation (EGR). Minimum Concentration of NO_x is 464 ppm with 25 % EGR.

N.Saravanan and G. Nagarajan [11] conducted experiment were on a DI Diesel engine with hydrogen in the dual fuel mode The optimized injection timing was found to be 5CA before gas exchange top dead centre (BGTDC) with injection duration of 30 CA for hydrogen diesel dual fuel operation in hydrogen port injection. The optimum hydrogen flow rate is found to be 7.5 lpm based on the performance, combustion and emissions behaviour of the engine. The brake thermal efficiency for hydrogen diesel dual fuel operation increases by 17% compared to diesel at optimized timings. The NO_x emission is found to be similar at 75% load and full load for both hydrogen and diesel operation. However the concentration is lower at lower loads in hydrogen dual fuel operation due to lean mixture operation. The

smoke emission reduces by 44% in hydrogen diesel dual operation compared to diesel operation. The CO and HC for hydrogen operation at optimized conditions are same as that of diesel emissions. It was concluded that the engine operated smoothly with hydrogen except at full load that resulted in knocking especially at high hydrogen flow rates.

N. Saravanan et al. [12] investigated the combustion analysis on a direct injection DI diesel engine using hydrogen with diesel and hydrogen with diethyl ether as ignition source. Hydrogen was inducted through intake port and diethyl ether through intake manifold and diesel was injected directly inside the combustion chamber. The optimized timing for the injection of hydrogen was 5° CA before gas exchange top dead centre and 40° CA after gas exchange top dead centre for diethyl ether. They concluded that the hydrogen with diesel results in increased brake thermal efficiency by 20% and oxides of nitrogen showed an increase of 13% compared to diesel whereas hydrogen – diethyl ether showed a higher brake thermal efficiency of 30% with a significant reduction in oxides of nitrogen compared to diesel.

Li Jing Ding et al. [13] did experiment by using hydrogen as a sole fuel and then hydrogen mixed with petrol and hydrogen diesel oil mixed fuel. The main aim was to improve the combustion properties of hydrogen fuelled engine. It was concluded that increase in compression ratio is the best technique to make petrol engine or diesel engine free from back fire. An increase in compression ratio brings about a wider back fire free range of engine output and an increase in thermal efficiency and a reduction in exhaust gas temperature. Smoke can be reduced by using diesel oil – hydrogen mixed fuels (rather than oil alone). Under low speed and in high load conditions the result will be better.

J.M.Gomes Antunes et al. [14] described the development of an experimental set up for the testing of a diesel engine in the direct injection hydrogen fuelled mode. The use of hydrogen direct injection in a diesel engine gave a higher power output to weight ratio when compared to conventional diesel fuelled operation with approximate 14% high peak power. The direct injection of hydrogen allows much better control of engine operation compared to port injection in HCCI mode. Comparison of direct injection of hydrogen with HCCI mode of operation was done and concluded that the direct injection of hydrogen offers the possibility to control and limit excessive mechanical loads while this is virtually

uncontrolled in the HCCI mode of operation. They also observed the reduction of NO_x emission level.

L.M. Das [15] studied the phenomenon such as backfire, pre ignition, knocking and rapid rate of pressure rise and presented in his review paper on the development of hydrogen fuelled internal combustion engines. According to him, "Hydrogen is the only one such fuel which can meet the twin challenges of the energy crisis and the environmental pollution".

L.M. Das [16] suggested some safety measures to be adopted to avoid undesirable combustion phenomena. The use of special effective hydrogen sensors are advantageous to monitor this combustible gas in the hydrogen environment. The need for reliable ventilation of the hydrogen system surroundings is very important but in some operating condition it is not possible to permit sufficient ventilation to some test chambers. In such cases the potential hazards inside the chambers can be rendered non hazardous by building an atmosphere of inert gases. Nitrogen, Carbon dioxide etc can be used for this purpose. The flame arrester should be there so as to suppress the back fire. Flame trapper have been observed to work extremely satisfactorily in overcoming the undesirable combustion problems especially back fire. Installation of a non return valve in the fuel line is also very important which prevents a reverse flow to the system. The selection of the chemical for hydrogen is a very important safety consideration and to prevent hydrogen embrittlement because hydrogen reacts with a number of chemicals. For example, it explodes chlorine in light.

L.M. Das [17] studied the nature and formation mechanism of different types of pollutants emitted from a hydrogen operated diesel engine system. It was concluded that neat hydrogen operated engines produce close to zero ozone, particulates, sulphur dioxide, benzenes which are usually present in a conventional engines exhaust. It was also concluded that the equivalence ratio play a very important role for NO_x controlling parameter and the optimum should be 0.6. Hydrocarbons and carbon monoxide emissions which are extremely small could be eliminated by regular maintenance and inspection programmes and by excessive burning of oil.

H.B. Mathur et al. [18] did experimental investigation on a hydrogen fuelled diesel engine to measure the performance characteristics through charge diluents. The results shows

that the thermal efficiency of the engine of the hydrogen fuelled engine is better as compared to neat diesel at 10 LPM, 20LPM, 30 LPM of hydrogen flow rates. The thermal efficiency of engine at hydrogen flow rate of 20 LPM gives better thermal efficiency compared to 30 LPM of hydrogen flow rate. It is found that the engine started knocking when the hydrogen flow rate is exceeding after 40 LPM. After that helium, nitrogen and water was inducted as diluents respectively and checked the performance of engine. Nitrogen as diluents also helps control engine knocking and also improves the optimum full-load hydrogen energy substitution. In addition, it gives the best thermal efficiency and power output when its percentage is maintained at 30% by volume of hydrogen substituted. Among the various proportions of water which could be inducted for charge dilution, 2460 ppm water concentration has been found to be the optimum level which enables the highest full-load hydrogen energy substitution – around 66% without undue engine knock and with only a very nominal loss of engine power and efficiency.

H.B. Mathur et al. [19] reported the test results of the study relating to the effect of diluents like helium, nitrogen and water in various proportions on smoke and oxides of nitrogen emission on diesel engine. It was found that helium showed a positive effect on controlling these pollutants while nitrogen only reduced smoke emission levels. Water is considered as the best diluents because it has the best effect on the emission characteristics of the engine when compared with the other two diluents. The greater the amount of water induced, the better the control on the emission parameters. Smoke levels are almost negligible, while NO_x emission levels are reduced to baseline values. 10 % of helium by volume of hydrogen is considered the best proportion for helium and 10 % of nitrogen by volume of hydrogen is considered the best proportion for the nitrogen. Whereas the optimum level of water has been found to be 2460 ppm. Diluents with this optimum proportion gives better emission characteristics.

L.M. Das [20] studied the hydrogen combustion techniques in various thermal systems. He also studied the hydrogen – oxygen reaction mechanism. It has been observed that under ambient conditions of temperature, hydrogen and oxygen do not enter into any direct reaction between them in absence of catalyst. But if the mixture is exposed to light oxygen gets activated usually by dissociation. Also in the presence of sensitizers of Cl, N₂O and NH₃, a

set of secondary reactions takes place and form H atoms These H atoms enter into a reaction with the activated oxygen thus forming H₂O.

The burning of hydrogen gas was classified into two categories (1) Deflagration and (2) Detonation. The abnormal combustion in hydrogen engines are classified into three types:

1. Abnormally high pressure rise
2. Occurrence of pre ignition in combustion chamber and sequential advancement of pre ignition and backfire into intake manifold.
3. Occasional backfire in very lean hydrogen –air mixture or idling operation.

Varde and Varde [21] conducted work on hydrogen substitution on a diesel engine. Results shows the 50% reduction of smoke at part load when the hydrogen energy share was 15% of the total fuel. NO_x was seen to increase with hydrogen substitution at both part and full load.

T. Lakshmanan and G.Nagarajan [22] did experiment on a single cylinder, air cooled DI diesel engine by inducting acetylene gas at different flow rates in dual fuel mode. The diesel acts as a ignition source. It was found that the brake thermal efficiency was lower compared to baseline diesel operation but there is a reduction in HC, CO, CO₂ and smoke emission. However, a significant increase in NO_x emission was observed.

M.Senthil Kumar et al. [23] conducted research on dual fuel mode by inducting hydrogen on a compression ignition engine. Neat jatropha oil was taken as a main fuel and hydrogen was inducted for the dual fuel operation. Results were compared with diesel when used as main fuel, in addition with hydrogen. Results indicated increase in brake thermal efficiency and lower smoke levels, when hydrogen is inducted but NO emission was found to be high. The injection timing was optimized as 29° CA before TDC for jatropha-hydrogen operation.

J. Nazar et al. [24] did experiment on stationary agricultural type diesel engine in a dual fuel mode. For dual fuel mode, karanja oil and hydrogen gas was taken. It was seen that by operating the engine with neat karanja oil , there was slight reduction in thermal efficiency as well as emissions were also found to be high. But on operating the engine with dual fuel mode by taking karanja oil and hydrogen gas, the thermal efficiency increased from 30% to

32% at full load with 15% of hydrogen energy share out of total energy share of fuel. Also reduction in emissions was observed, except NO emission at full load.

G.Sankaranarayanan et al. [25] did experiment on madhuca indica oil enriched with hydrogen air mixture. The brake thermal efficiency was increased of about 24% with 40% hydrogen enrichment than of raw madhuca indica oil. At lean mixture of hydrogen NO concentration was found to be low. The maximum NO emission was found to be 402 ppm at full load when hydrogen energy share is 40%.

G.Nagarajan et al. [26] did experiment by taking ethanol as an fuel for conventional diesel engines. Since the cetane number of ethanol is very low, it cannot be used as a sole fuel in diesel engine. It was found that the temperature achieved after compression stroke was not sufficient to ignite the ethanol. Therefore a di ethyl ether (DEE) was used just before the port in the form of droplets that is drawn into the engine cylinder along with the intake of air. The DEE has low self ignition energy and gets ignited which in turn ignites the ethanol. Thus engine was modified to operate on dual fuel type. It was found that the brake thermal efficiency of the engine was higher than diesel at about 36% at 75% load for ethanol-DEE, while that of diesel was 30%. HC emission was found to be higher in ethanol –DEE than diesel at about 434 ppm due to the increased amount of HCs present in the quench and crevics zones. Soot formation and smoke was also low with ethanol-DEE combination.

T.Lakshmanan and G.Nagarajan [27] studied the possibility of utilizing the acetylene gas fuel in a dual fuel mode. Diesel acted as a ignition source. Acetylene was inducted at varied flow rates of 110 g/s, 180 g/s, and 240 g/s. Acetylene was introduced by timed manifold injection technique. For that ECU –Electronic Control Unit was mounted. The optimum condition in manifold injection was found to be 10⁰ ATDC with injection duration of 90⁰ crank angles. Reduction in all type of emission was noticed except smoke. There was slightly increase in smoke emission.

R.G.Papagiannakis et al. [28] did experiment on duel fuel mode on a single cylinder, air cooled direct injection diesel engine having bowl in piston type combustion chamber. Attempts have been made to utilize natural gas as a alternative fuel in diesel engine. The NO and soot formation was found to be very low with natural gas supplement liquid diesel fuel

operation on diesel engine. But the brake thermal efficiency was evaluated to be lower compared to neat diesel fuel.

Seung Hyun Yoon and Chang Sik Lee [29] carried out an experimental investigation to study the influence of dual fuel combustion characteristics on the exhaust emissions and combustion performance in a diesel engine fuelled with biogas- biodiesel dual fuel. The engine used for this study was based on four cylinder, turbo charged, pre-chamber, compression ignition engine with a single overhead cam. It was concluded that at 60% engine load, on dual fuel mode showed slightly higher peak combustion pressure and indicated mean effective pressure compared to ultra low sulphur diesel fuel, whereas the ignition delay gets shortened. The exhaust gas temperature was found to low in case of dual fuel mode. At low loads the total brake specific fuel consumptions for dual fuel combustion for both fuels were considerably higher than for single fuel combustion.

M.Senthil Kumar et al. [30] carried out experiment on dual fuel mode. Engine was modified to run using vegetable oils as primary and pilot fuels. Results indicated that the orange oil can be used as inducted fuel for reducing smoke and NO emissions with improved brake thermal efficiency in a diesel engine fuelled with vegetable oils and its esters for a dual fuel mode of operation.

G.A. Rao et al. [31] modified the engine to operate on dual fuel mode to reduce the usage of diesel and also to reduce pollution. The gaseous fuel LPG was used as a inducted fuel and diesel was used as a main fuel. The results indicated increase in brake thermal efficiency and lower smoke level.

From the above available literatures, it is understood that using used transformer oil as a main fuel and inducting hydrogen at a small and constant flow rate of 4 lpm is a new one and nobody has done research on these field (i.e. utilizing hydrogen and used transformer oil together in compression ignition engine).

CHAPTER 3

EXPERIMENTAL INVESTIGATION

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1. EXPERIMENTAL PROCEDURE

The engine used for the present investigation is a single cylinder four stroke air cooled diesel engine. Initially the engine was operated with neat diesel and the performance, emission and combustion parameters were evaluated. Then the engine was allowed to run with UTO40 and UTO100/UTO respectively without hydrogen. Again the performance, emission and combustion parameters were evaluated. Now for the third test, hydrogen gas is introduced by considering first UTO40 as a main fuel and then UTO100 as a main fuel respectively.

Hydrogen fuel from a high pressure cylinder was inducted through an intake pipe. A double stage diffusion pressure regulator was employed over the high pressure cylinder. The regulator is used to control the outlet pressure. Hydrogen fuel, at a pressure of 2 bars and a constant flow rate of 4 lpm is then supplied to the flame arrester and flame trap and finally to the intake pipe (a distance of 40 cms away from the intake manifold) where it mixes with air and finally, this hydrogen- air mixture get inducted into the engine cylinder. Used transformer oil of 40% blended with 60% diesel fuel (UTO40) on volume basis is introduced from the fuel tank into the engine cylinder by direct injection. Then engine is allowed to run for different loads. The same procedure is adopted by considering sole used transformer oil (UTO/UTO100) as a main fuel with hydrogen flow rate of 4 lpm. The performance and combustion parameter is obtained by computer provided into data acquisition system. AVL exhaust gas analyser is used to calculate the emission parameter whereas smoke meter is used to get smoke values. Combustion diagnosis was carried out by means of a Kistler make quartz piezoelectric pressure transducer (Model Type 5395A) mounted on the cylinder head in the standard position. The air flow rate is calculated according to the difference in the level of water in the U- tube manometer mounted into the air suction line. The engine specification is given in the Table 4. The test is also carried out by considering diesel as a main fuel without using hydrogen. All the test results of engine using UTO40 and UTO as a main fuel with hydrogen induction were compared with neat diesel fuel and other two main fuels without hydrogen.

Table 4. Test engine specification

Make	Kirloskar
Type of Engines	4-stroke cycle, single cylinder, compression ignition engine
Speed, rpm	1500 rpm
Bore, mm	87.5
Stroke, mm	110
Compression ratio	17.5
Method of cooling	Air cooled with radial fan
Injection timing, ° CA	23° before TDC
Nozzle opening pressure, bar	200 kg /cm ²

3.2. ENGINE MODIFICATION FOR HYDROGEN OPERATION

3.2.1. Hydrogen admission

The engine was modified to operate on hydrogen. A valve was provided at a distance of 40 cm from the intake manifold. Hydrogen was allowed to pass through this valve. A high pressure hydrogen cylinder is used having inlet pressure of 0-280 kg/cm² approximately 280 bars. The hydrogen gas purity is 99.999%.

3.2.2 Hydrogen Supply

The hydrogen gas is allowed to pass through the intake pipe at an outlet pressure of 2 bar pressure and a flow rate of 4 lpm. The pressure is regulated by a double stage diffusion pressure regulator mounted on to the hydrogen cylinder. The specification of pressure regulator is given below:

Inlet Pressure Max 0-280 kg/cm²

Outlet pressure Max 0-07 kg/cm²

Inlet Connection: 5/8" BSP (M) LH

Outlet Connection: ¼ inches OD Tube

Gas Service: Hydrogen

3.2.3. Flash back arrester

A flash back arrester is a safety device that shuts off gas flow in event of flash back. Flashback is the combustion of a flame mixture that can occur within your gas management system. This can travel back through the line of the gas management system to the gas

source if flash back arrestor is not in line. A flash back arrestor shuts off gas flow and extinguishes the flame before it can reach your gas source. Several factors can cause flash back, including failing to purge line properly, using improper pressure, leaks in your gas management system and improper system operation.

3.2.4. Flame trap fabrication

Water filled flame trap was utilized to suppress any flash back from the intake manifold. The flame trap is essentially a metal container with water and fitted with a diaphragm on the wall. In the event of any severe flash back, the diaphragm would burst and prevent any pressure built up leading to an explosion. The specification of flame trapper is given below:

Tank Size= 300 mm × 300 mm

Thickness = 2 mm

Flange diameter= 1 inches

Inlet and Outlet pipe diameter= ½ inches

Level of water = 150 mm from the bottom

The pictorial representation of the experimental set up is shown in the Fig 2. and the pictorial schematic representation of the set up is shown in Fig 3. respectively.

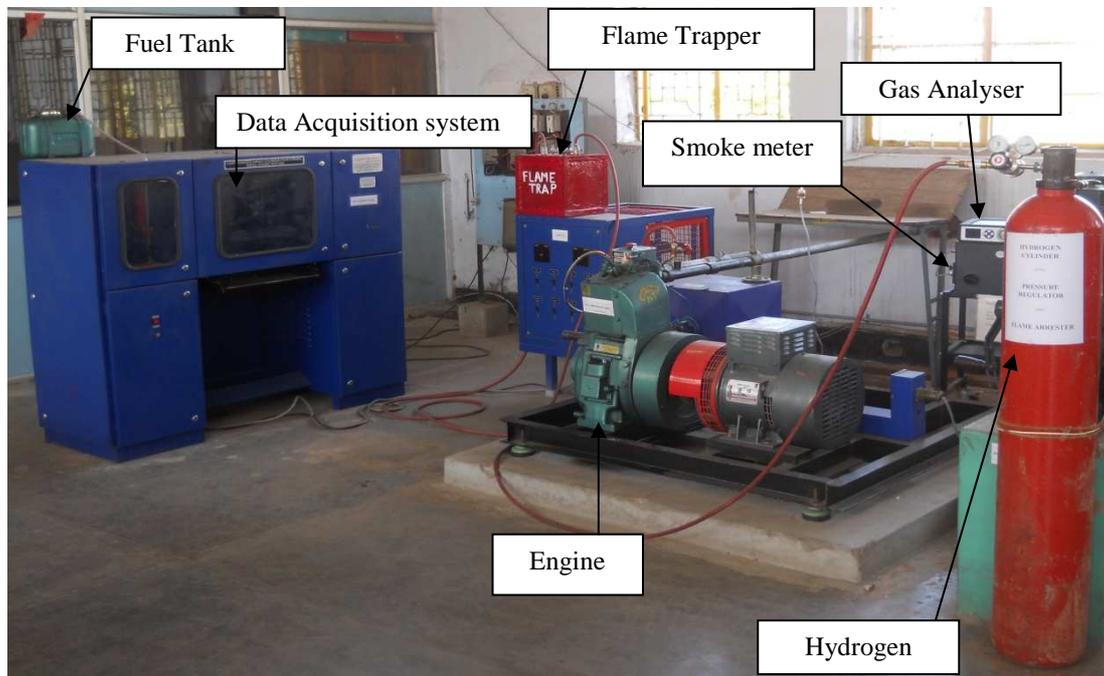
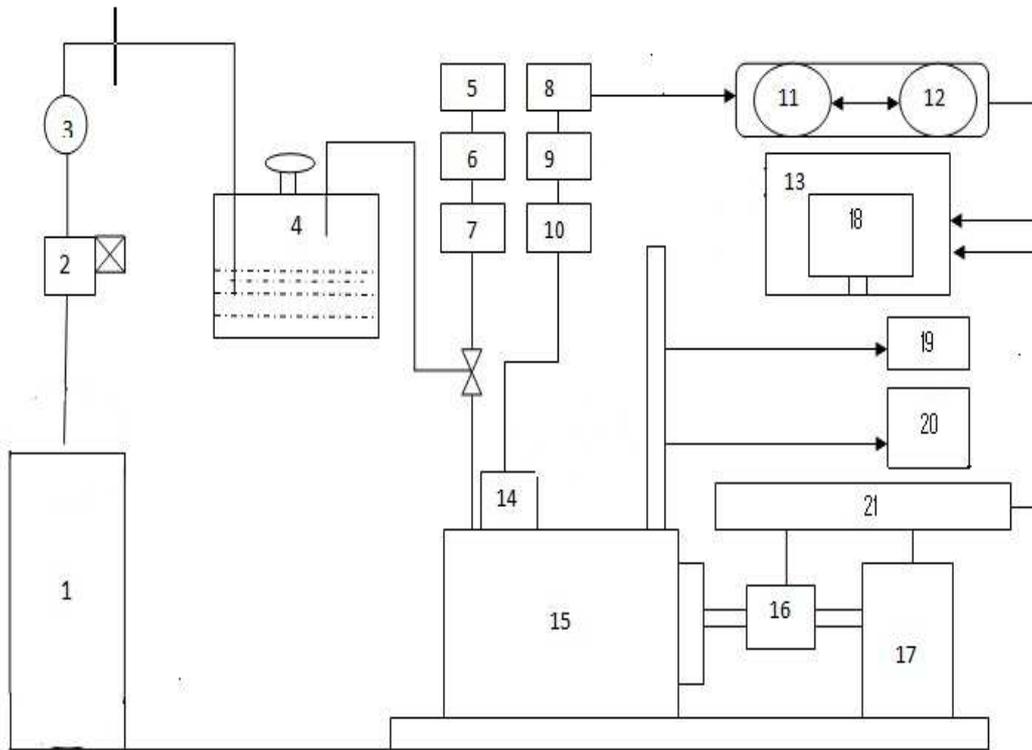


Fig 2. Photographic view of experimental set up



1.Hydrogen cylinder	8.Fuel tank	15. Engine
2.Pressure regulator	9.Fuel filter	16. Alternator
3.Flashback arrester	10.Fuel ump	17.Dyanamometer
4.Flame Trap	11.Fuel sensor	18. Computer
5.Air filter	12.Burette	19.Exhaust gas Analyzer
6.Air box	13. DAS	20.Smoke meter
7.Airflow sensor	14 Injector	21.control panel

Fig 3. Schematic layout of experimental set up

3.3. Error Analysis

Uncertainties and some errors are arises during instrument selection for conducting experiment. Depend upon the condition, calibration, environment, observation, some uncertainties in the experimental results occurred. Therefore error analysis is required to check the accuracy of the experiments [33]. The percentage uncertainties of various parameters like brake power and brake thermal efficiency were calculated using the percentage uncertainties of various instruments given in Table 5. An error analysis was performed by using equation 6.

The total percentage of uncertainty of various instruments in this experiment is calculated.

$$Y = \sqrt{\{(Uncertainty\ of\ TFC\)^2 + (Uncertainty\ of\ BP\)^2 + (Uncertainty\ of\ BSFC)^2 + (Uncertainty\ of\ BTE\)^2 + (Uncertainty\ of\ CO)^2 + (Uncertainty\ of\)^2}}$$

$$\text{CO}_2)^2 + (\text{Uncertainty of UBHC})^2 + (\text{Uncertainty of NO}_x)^2 + (\text{Uncertainty of Smoke})^2 + (\text{Uncertainty of EGT})^2 + (\text{Uncertainty of pressure Pickup})^2 \dots\dots\dots(6)$$

Table 5. List of instruments range, accuracy and percentage uncertainties

Sl. no.	Instruments	Range	Accuracy	Percentage uncertainties
1	Gas Analyzer	NO _x 0-5000ppm HC CO CO ₂	±20 ppm ±15 ppm ±0.02 % ±0.03%	±0.2 ±0.2 ±0.2 ±0.15
2	Smoke level measuring instrument	BSN 0-10	±0.2	±1.0
3	EGT sensor	0-1000 °C	±1°C	±0.15
4	Load indicator	0-100 kg	±10 rpm	±1.0
5	Burette for fuel measurement	-	±0.2 cm ³	±0.15
6	Manometer	-	±1 mm	±1.0

So by inserting the values of percentage uncertainties of various instrument in equation 6, the total percentage of uncertainties was found to be:

$$Y = \sqrt{\{(1.5)^2 + (0.2)^2 + (1.5)^2 + (1)^2 + (0.2)^2 + (0.15)^2 + (0.2)^2 + (0.2)^2 + (1.0)^2 + (0.15)^2 + (1.0)^2\}}$$

$$Y = \pm 2.77\%$$

3.4. Energy share between hydrogen and main fuels

In the present study, the hydrogen flow rate was kept constant at about 4 lit/min. So mass flow rate of hydrogen at all the loads in terms of kg/hr is calculated as 0.01968kg/hr.

Energy share of hydrogen (kW) = mass flow rate of hydrogen (kg/sec) × Lower calorific value of hydrogen (kJ/kg)

Energy share of hydrogen at all loads was calculated as 0.656 kW.

Similarly energy share for main fuel was calculated by using the formula;

Energy share (kW) = mass flow rate of main fuel (kg/sec) × lower calorific value (kJ/kg).

The energy share of hydrogen and the main fuels (UTO40 and UTO100) are shown in the table 5 and table 6 respectively.

Table 5. Energy share between hydrogen and UTO40

Load	Energy share by UTO40(kW)	Energy share by hydrogen(kW)	Total energy share(kW)	% Energy share by UTO40	% Energy share by hydrogen
0	2.4458	0.656	3.1018	78.85	21.14
1000	2.6787	0.656	3.3347	80.32	19.67
2000	5.4739	0.656	6.1299	89.92	10.70
3000	8.1526	0.656	8.8086	92.55	7.44
3750	9.7832	0.656	10.4392	93.71	6.28

Table 6. Energy share between hydrogen and UTO

Load	Energy share by UTO(kW)	Energy share by hydrogen(kW)	Total energy share(kW)	% Energy share by UTO	% Energy share by hydrogen
0	2.934	0.656	3.590	81.72	18.27
1000	3.912	0.656	4.568	85.63	14.36
2000	5.542	0.656	6.198	89.41	10.58
3000	8.150	0.656	8.806	92.55	7.45
3750	10.649	0.656	11.305	94.19	5.80

CHAPTER 4

RESULTS AND DISCUSSION

CHAPTER 4

RESULTS AND DISCUSSION

In the present work, hydrogen gas- air mixture is used for compression ignition engine where UTO40, UTO100 respectively is used as a main fuel for. The performance, emission and combustion characteristics of UTO40, UTO100 respectively with and without hydrogen are compared with diesel operation.

4.1. Performance Parameters

4.1.1. Brake Thermal Efficiency

The variation of brake thermal efficiency with brake power is shown in Fig 4. The brake thermal efficiency for hydrogen with UTO40 is 42.14% at full load with a flow rate of hydrogen is 4lpm. Whereas that of UTO40 is 32.01% and that of diesel is 28.64%. UTO100 exhibits the brake thermal efficiency of 31.72% at full load, and that get enhanced after supplying hydrogen to 38.91%. Higher brake thermal efficiency is due to better mixing of hydrogen with air which results in better combustion and also due to wider ignition limit and high burning velocity [9]. The brake thermal efficiency of both the fuel UTO40 and UTO100 is found to be 10% more after supplying hydrogen compared to baseline diesel.

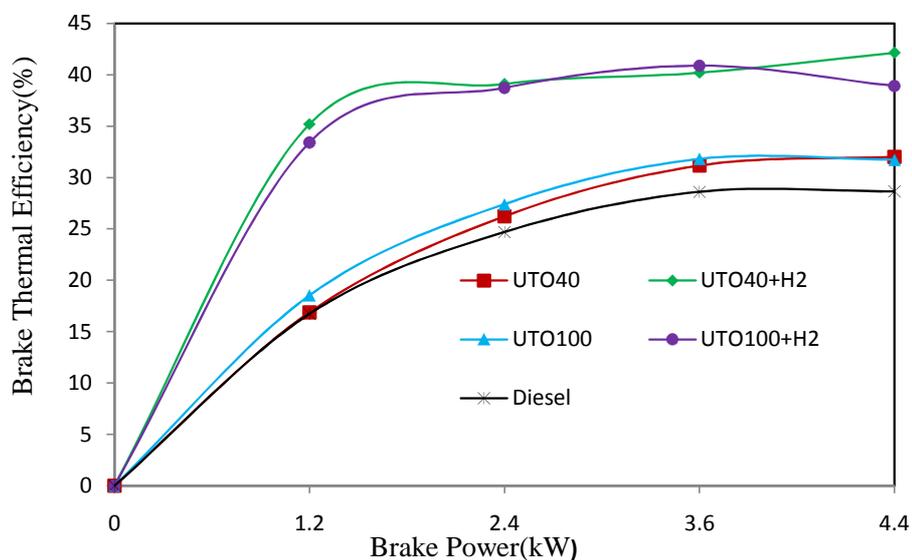


Fig 4. Variation of brake thermal efficiency with brake power

4.1.2. Brake Specific Energy Consumption

Fig 5. Shows the variation of brake specific energy consumption with the brake power. The specific energy consumption of UTO40 and UTO100 with hydrogen induction is found to be lower compared to UTO40 ,UTO100 without hydrogen and baseline diesel fuel. The lower specific energy consumption is due to the better mixing of hydrogen with air, results in complete combustion of the fuel[32]. The specific energy consumption of UTO40 with hydrogen is found to be 8.5411 MJ/kW–hr which is lower compared to 11.2443MJ/kW-hr for UTO40 without hydrogen at full load. The diesel shows the maximum energy consumption at all the loads.

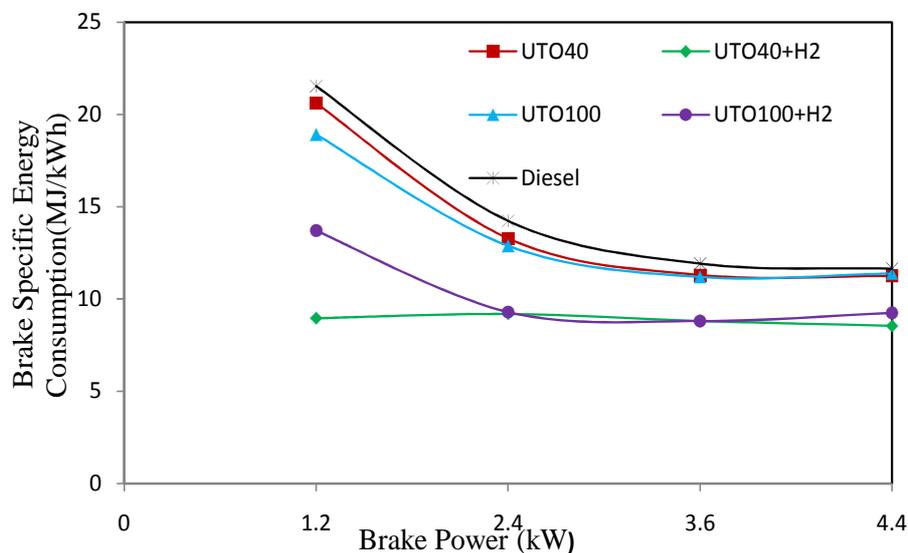


Fig 5. Variation of brake specific energy consumption with brake power

4.1.3 Exhaust Gas Temperature

The variation of exhaust gas temperature with brake power is shown in Fig 6. The exhaust gas temperature of UTO40 with hydrogen is 365°C at full load while that of UTO40 is 325°C and that of diesel is 269.54°C while the exhaust gas temperature of UTO100 with hydrogen is 375°C at full load while that of UTO100 is 360°C . The exhaust gas temperature of UTO100 with hydrogen is more compared to UTO40 with and without hydrogen and also with baseline diesel. The reason is may be due to high auto ignition temperature of hydrogen. It requires high temperature to ignite. Therefore the residence time is more for the hydrogen.

The high viscosity and more residence time are responsible for increase in exhaust gas temperature [30]. Due to this the heat that is generated due to the compression stroke gets shifted its direction toward the exhaust side and increases the exhaust gas temperature.

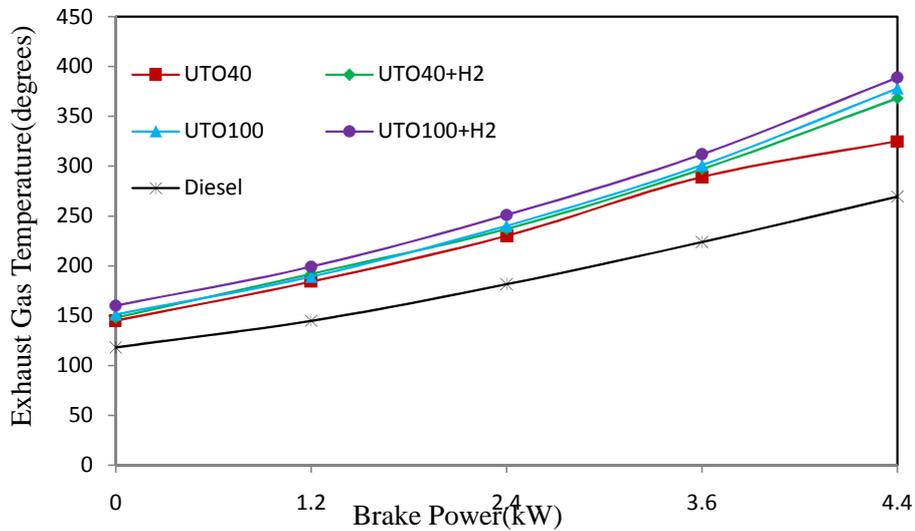


Fig 6. Variation of exhaust gas temperature with brake power

4.1.4. Volumetric Efficiency

The variation of volumetric efficiency of fuels is shown in the Fig 7. The volumetric efficiency of the engine is found to be less when hydrogen is inducted with the main fuels. The reason for low volumetric efficiency is because of the high velocity of hydrogen tends to displace the air. The volumetric efficiency is calculated as the ratio of actual volume of air passed into the engine to the swept volume. The UTO40 and UTO100 with hydrogen shows lower volumetric efficiency of 10.94 and 11.38% respectively while UTO40 and UTO100 without hydrogen shows more volumetric efficiency. The diesel fuel possesses the volumetric efficiency of 12.81% at full load, intermediate of UTO40 and UTO100 with and without hydrogen.

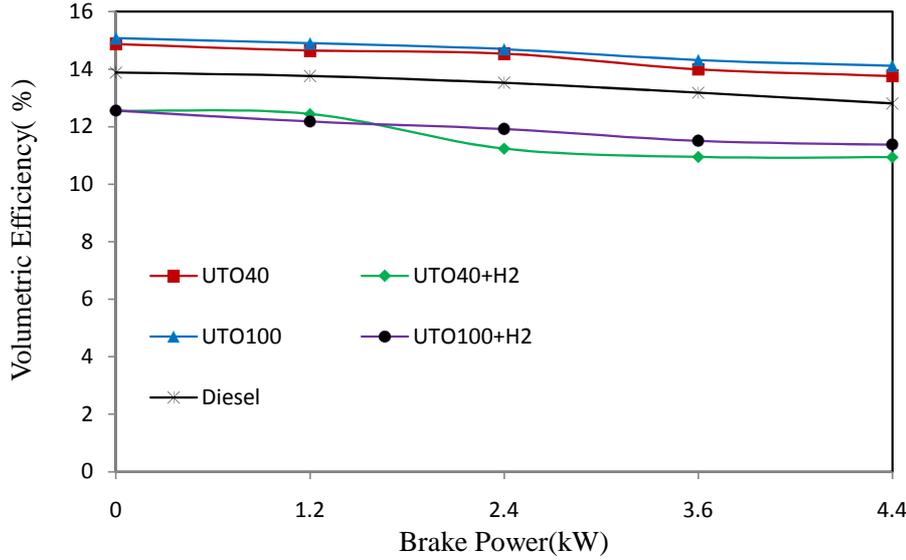


Fig 7. Variation of volumetric efficiency with brake power

4.2. Emission Parameters

4.2.1. CO Emission

Carbon monoxide is formed due to deficiency of oxygen during combustion [34]. Due to deficiency of oxygen the carbon present in fuel does not contribute fully in combustion process and coming out in the form of CO from the engine exhaust. The variation of Carbon monoxide with brake power is given in the Fig. 8. The carbon monoxide emission of UTO40 and UTO100 with hydrogen is lower compared to baseline diesel and UTO40 and UTO100 without hydrogen. The carbon monoxide emission is lower may be due to the absence of carbon atoms present in the hydrogen structure [9]. Some CO emission is present because of the combustion of lubricating oil and also due to the carbon present in the structure of UTO40 and UTO100. The CO emission for UTO40 and UTO100 without hydrogen was found to be 0.008% and 0.012 % respectively while that after supplying hydrogen was found to be 0.004 % and 0.006 % respectively at full load. The diesel shows more CO emission of 0.01% at full load. For a complete combustion of fuel, two step processes are involved. The formation of carbon monoxide is the first step. This carbon monoxide gets oxidized into carbon dioxide in the second step. Less carbon monoxide emission indicates a proper combustion of the fuel. Utilizing the heat of hydrogen, carbon present in UTO and UTO40 gets oxidized properly and emits very less CO emission.

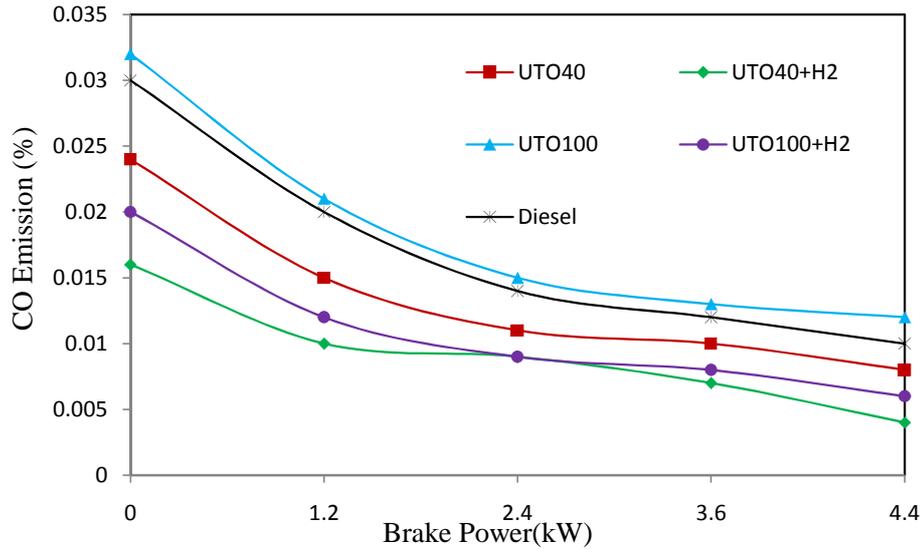


Fig 8. Variation of CO emission with brake power

At zero load the CO emission is found to be more and because of coarse spray formation of main fuels at zero load and it decreases with the increase in load due to high temperature achieved after combustion, CO get oxidized into CO₂.

4.2.2. HC Emission

Unburned hydrocarbon emissions result from incomplete combustion of hydrocarbon fuels. The unburned hydrocarbons and their derivatives that readily vaporize are termed as volatile organic compounds (VOCs). The VOCs react with oxides of nitrogen in the presence of sunlight to form oxidants and photochemical smog [34]. This emission arises when a part of the fuel inducted into the engine escapes combustion. During ignition delay period, fuel air mixtures becomes too rich to ignite and combust contribute to HC emissions [34]. Fig 9. Shows the variation of hydrocarbon emission with brake power. The HC emission is lower for UTO40 and UTO100 with hydrogen compared with the other fuels without hydrogen and baseline diesel. The HC emission of UTO40 with hydrogen is about 3ppm at full load compared to diesel 5.6 ppm while UTO100 with hydrogen exhibits 4.8 ppm at full load. UTO40 and UTO100 without hydrogen shows more unburnt hydrocarbon emission and this value gets lowered after supplying hydrogen fuel. The reason is due to the absence of carbon in hydrogen and also because of high cylinder temperature the carbon particles, present in lubricating oil and main fuel, gets oxidises and converted into CO₂.

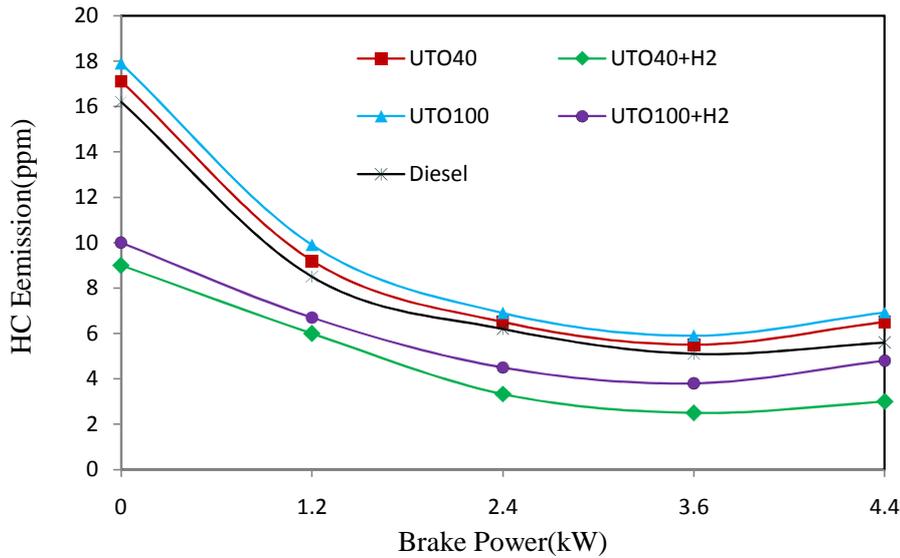


Fig 9. Variation of HC emission with brake power

4.2.3. CO₂ Emission

The variation of carbon dioxide with brake power is shown in Fig 10. As due to high temperature achieved during combustion of hydrogen, the CO get oxidized and converted into CO₂. Basically a two step process may approximate complete combustion of hydrocarbon fuel to form finally the carbon dioxide. First step is the conversion of hydrocarbons to CO. During this step, several oxidation reaction occur involving formation of intermediate species like smaller hydrocarbon molecules, aldehydes, ketones etc. The second step is the conversion of CO into CO₂ provided sufficient oxygen is available [34]. As CO emission is found to be low signifies that it get oxidized into CO₂. Therefore the carbon dioxide emission increases with increase in load but very less compared to UTO40 and UTO100 without hydrogen and diesel. At full load the carbon dioxide emission is 1.3% for UTO40 with hydrogen and 1.4% for UTO100 with hydrogen while that of UTO40 and UTO100 without hydrogen shows 2% and 1.8% CO emission respectively and that of diesel is 1.7% at full load.

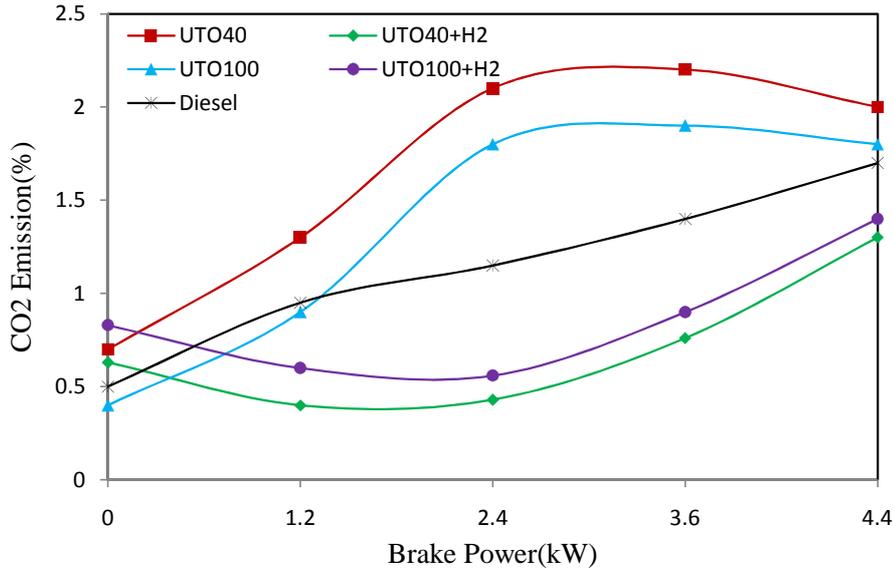


Fig 10. Variation of CO₂ emission with brake power

4.2.4. NO_x Emission

Oxides of nitrogen which occur in the engine exhaust are a combination of nitric oxide (NO) and nitrogen dioxide (NO₂). The Variation of NO emission with brake power is shown in Fig 11. The NO emission of UTO100 and UTO40 with hydrogen is found to be higher compared to UTO100 and UTO40 without hydrogen and also baseline diesel. The reason is due to the high viscosity, availability of oxygen and more residence time associated when hydrogen is supplied. Due to high auto ignition temperature of hydrogen, it takes more time to ignite. Therefore the phenomenon called rapid combustion takes place which contribute to increase the inside cylinder temperature. More the inside cylinder temperature, the NO emission will be more. Also the availability of oxygen in UTO100 and UTO40 is another factor for NO emission. Nitrogen and oxygen react at relatively higher temperatures. Therefore, high temperature and oxygen availability are the two main reasons for the NO emission. When the proper amount of oxygen is available the higher the peak combustion temperature the more is the NO formed. The NO_x is formed in the atmosphere as NO oxidizes [10]. The UTO100 with hydrogen shows more NO emission of 490 ppm at full load while UTO40 with hydrogen is found to be 465 ppm. The baseline diesel shows lower NO emission of about 318 ppm. The NO emission of UTO40 and UTO100 without hydrogen was found to be 380 ppm and 430 ppm respectively at full load. The high NO formation of

UTO40 and UTO100 with hydrogen can be reduced by adopting exhaust gas recirculation technique or by adding some charge diluents like helium, water, nitrogen etc.

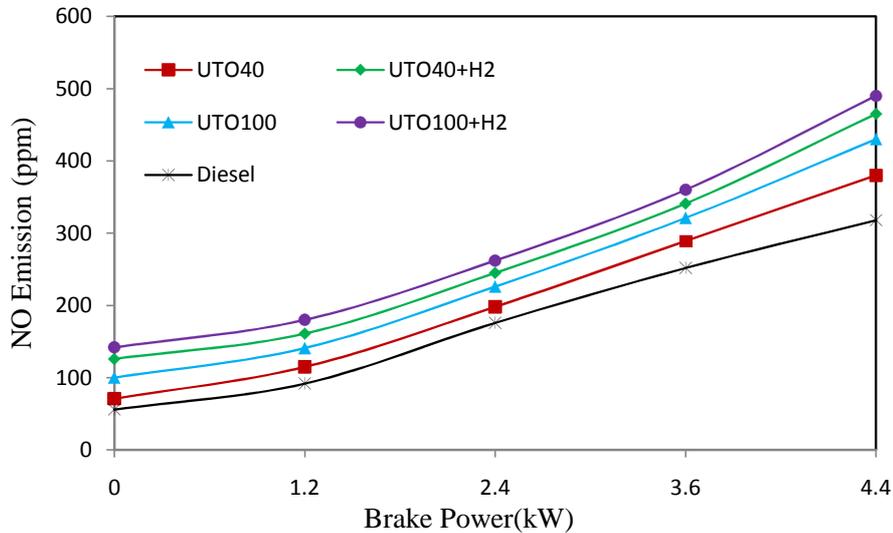


Fig 11. Variation of NO emission with brake power

4.2.5. Smoke Emission

The variation of smoke intensity with brake power is shown in Fig 12. Sole used transformer oil shows higher smoke emission due to coarse spray formation and poor mixing with air [23]. At full load the smoke emission for UTO100 was found to be 25.5 % which is much higher than diesel 19.2% at full load. UTO40 shows 18.1%. However smoke emission was reduced after supplying hydrogen. UTO40 in addition of hydrogen shows lower smoke emission of 15.1% at full load while UTO100 shows 15.7%. The reduction in smoke emission after inducing hydrogen is because the combustion of hydrogen does not contribute to the formation of smoke due to the absence of carbon in hydrogen. The proper mixing of hydrogen and air improves the combustion of used transformer oil and their blends with diesel and reduced the smoke intensity. It was found that at all the loads the smoke density was lower in case of hydrogen induction.

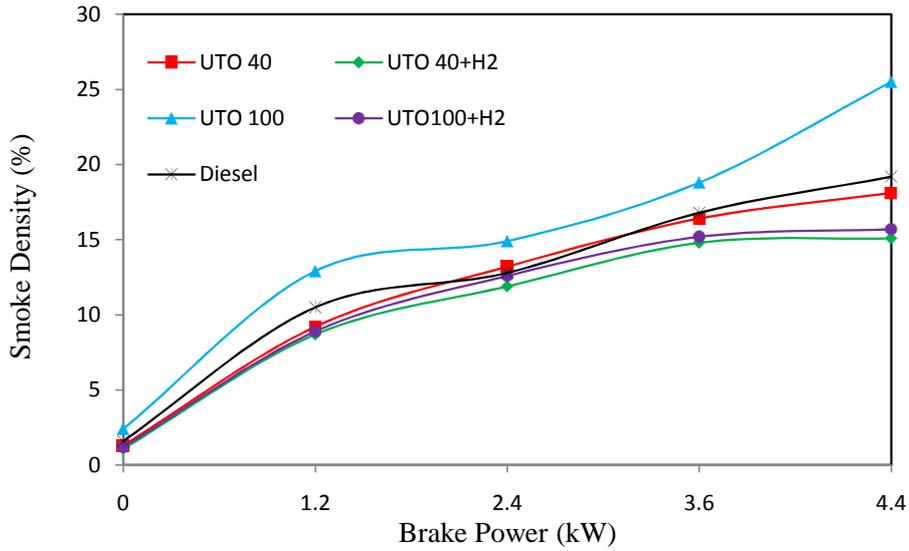


Fig 12. Variation of smoke emission with brake power

4.3. Combustion Parameters

4.3.1. Ignition Delay

The pressure developed for every crank angle gives the way to determine the ignition delay of a particular fuel. The variation of ignition delay with brake power is given in Fig 13.

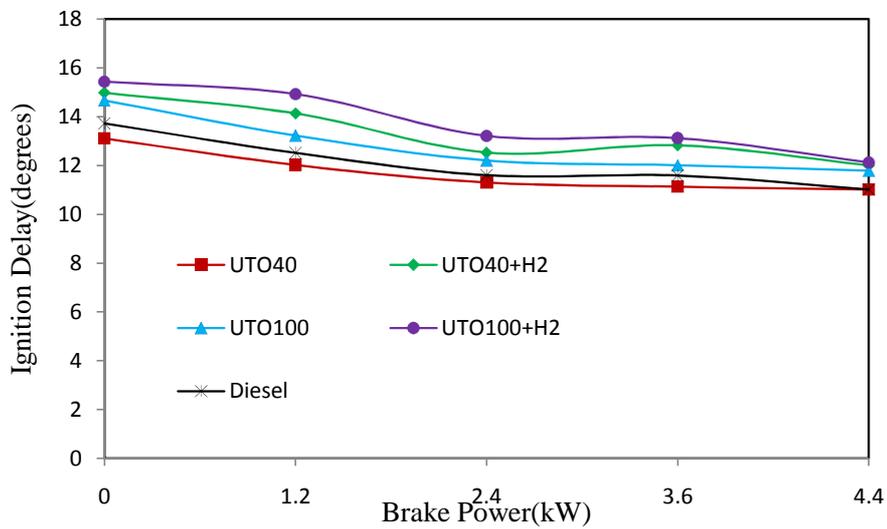


Fig 13. Variation of ignition delay with brake power

The ignition delay is the time difference in crank angle between the start of injection and ignition in compression ignition engines. Due to high self ignition temperature of hydrogen, all the hydrogen enriched fuel shows more ignition delay. The UTO100 with hydrogen exhibits a higher ignition delay of 12.1231°CA at full load followed by 12.0101°CA for UTO40 with hydrogen while that of UTO40, UTO100 without hydrogen shows lower ignition delay of 11.0112° CA and 11.7889° CA respectively.

4.3.2. Pressure – Crank angle diagram

The variation of combustion pressure with crank angle at full load is shown in Fig 14. At TDC of 360° CA the UTO40 with hydrogen shows higher pressure 88 bar followed by UTO100 with hydrogen 86 bar. The unexpected behaviour is found for UTO100 without hydrogen shows lowest peak pressure at full load around 52 bars. The reason for unexpected behaviour of UTO100 is may be due to its high viscosity, the amount of fuel taking part in combustion was less or in other words the quantity of fuel injected into the cylinder through the injector was less.

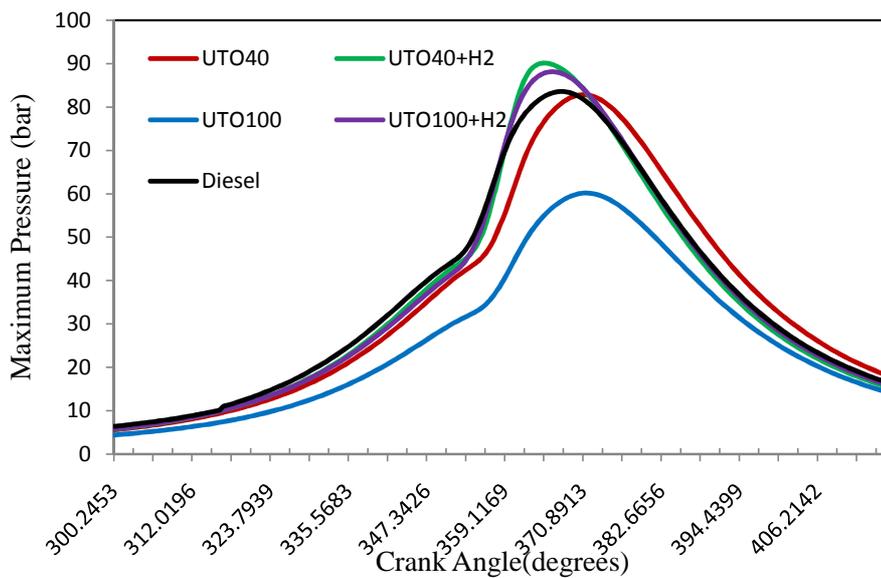


Fig 14. Variation of cylinder pressure rise with crank angle

4.3.3. Maximum Cylinder Pressure with Brake Power

The variation of peak cylinder pressure with brake power is given in Fig 15. The cylinder peak pressure of an engine provides information about the direct utilization of heat into useful work. In a compression ignition engine the peak pressure depends on the combustion rates in the initial stages that are influenced by amount of fuel taking part in the

premixed combustion that is governed by the delay period and also the mixture preparation during the delay period [30]. Thus the fuel exhibits higher ignition delays possess peak cylinder pressure.

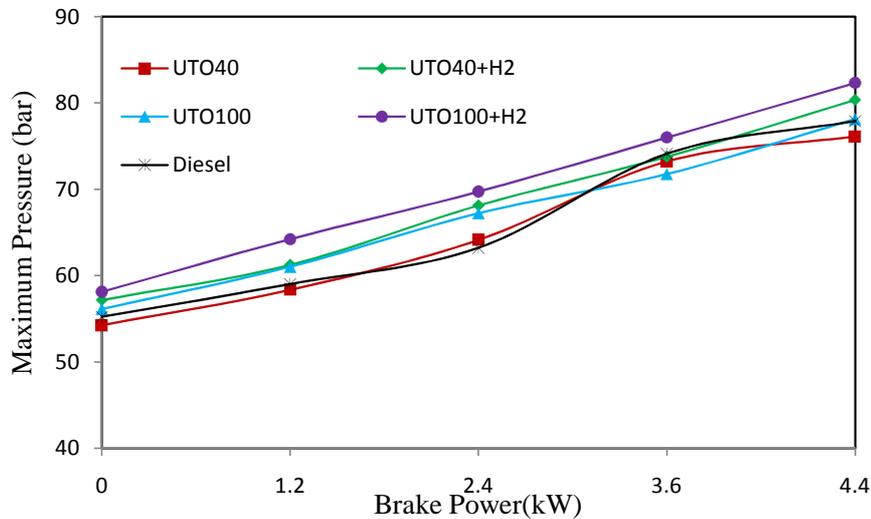


Fig 15. Variation of maximum cylinder pressure with brake power

Due to high self ignition temperature of hydrogen fuel, the mixture takes more time to ignite. During this period, more charge gets accumulated inside the combustion chamber, due to which rapid combustion takes place. The peak pressure is increased from 57 bars from zero loads to 86 bars at full load for UTO40 with hydrogen. While the peak pressure for UTO100 with hydrogen is increased from 58 bars from zero loads to 88 at full load. The supply of hydrogen shows more inside cylinder peak pressure. The unexpected behaviour is found at full load for UTO100 without hydrogen showing decrease in peak cylinder pressure at full load may be due to its high viscosity, less quantity of fuel gets admitted through injector.

4.3.4. Heat release Vs Crank angle

The variation of heat release with crank angle at full load is shown in Fig 16. It is found that the heat release rate for hydrogen inducted fuel increases with increase in crank angle. The heat release rate depends mainly on ignition delay, combustion rate and heat content of the fuel. Due to the higher ignition delay for hydrogen inducted fuels, the rate of pressure rise was also found to be higher. The maximum heat release rate for UTO40 with hydrogen addition was found to be 74J/deg while that of UTO100 with hydrogen shows maximum heat release rate of 63 J/deg. The lower value of UTO100 is due to less participation of fuel quantity inside the combustion chamber because of high viscosity of UTO100. The injector

nozzle restricts the fuel quantity to admit inside the cylinder because of UTO100 high viscosity, not able to flow properly. Some more study is required to evaluate the heat release of UTO with and without hydrogen properly.

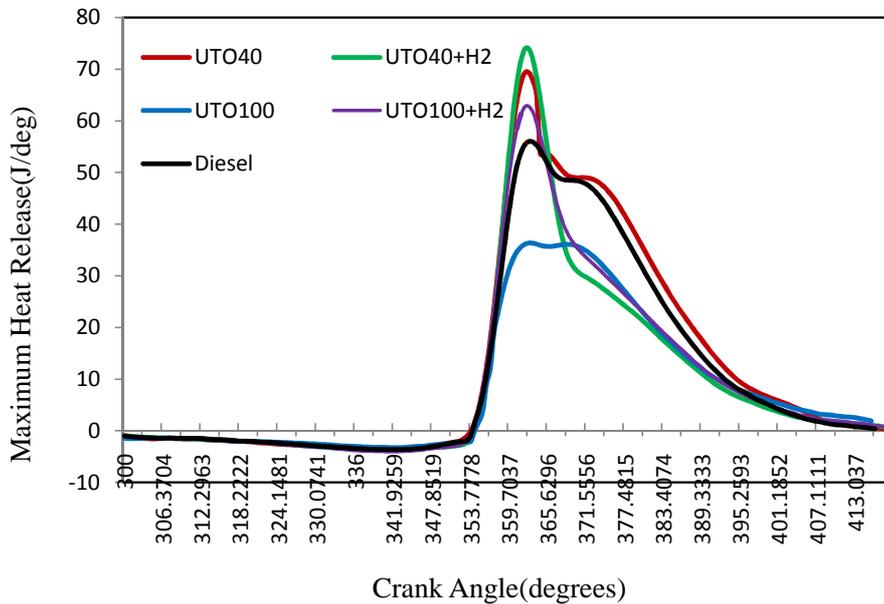


Fig 16. Variation of maximum heat release with crank angle

4.3.5. Maximum heat release with brake power

The trend of maximum heat release with brake power is shown in Fig 17. It is found that the main fuel in addition with hydrogen shows more heat release at full load compared to that of main fuels without hydrogen and neat diesel fuel. The maximum heat release rate for UTO40 with hydrogen addition varies from 52 J/deg crank angle to 74J/deg crank angle at full load while that of UTO100 with hydrogen shows maximum heat release rate of 63 J/deg at full load. The unexpected behaviour of UTO40 and UTO100 in addition of hydrogen at other loads was also observed which needs further evaluation.

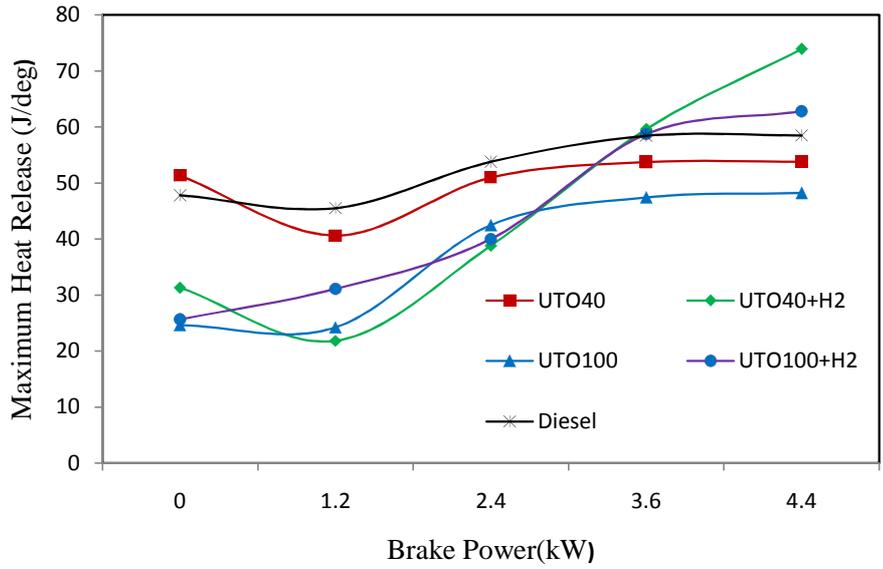


Fig 17. Variation of maximum heat release rate with brake power

CHAPTER 5

SUMMARY

CHAPTER 5

SUMMARY

5.1. Conclusion

A single cylinder, four stroke, air cooled direct injection compression ignition engine was operated successfully using hydrogen gas, supplying at a flow rate of 4 LPM and inducting at a distance of 40 cm from the intake manifold. The performance, emission and combustion parameters of the engine using UTO40 and UTO100 as a main fuel, with and without hydrogen induction were obtained in the investigation are compared with the diesel fuel. The following conclusions are drawn:

1. Experimental results shows UTO40 as the optimum blending compared to all other blending proportion with diesel. The performance, emission and combustion characteristics of UTO40 can be improved further by hydrogen induction along with air. Also with UTO100, the engine was able to run but engine gives high vibration. So by inducting hydrogen on UTO100, the engine was able to run smoother.
2. The brake thermal efficiency for both the main fuel inducted with hydrogen was found to be high, UTO40 with hydrogen is 42.14% and UTO100 with hydrogen addition was 38.91 %, because of proper combustion and high burning velocity.
3. The brake specific energy consumption of UTO40 and UTO100 with hydrogen induction was found to be lower 8.5411MJ/kWh and 9.2498 MJ /kWh respectively compared to 11.2443 MJ/kWh for UTO40 without hydrogen and 11.3803 MJ/kWh for UTO100 without hydrogen at full load.
4. The exhaust gas temperature of UTO40 with hydrogen is 365°C at full load while that of UTO40 is 325°C and that of diesel is 269.54°C while the exhaust gas temperature of UTO100 with hydrogen is 375°C at full load while that of UTO100 is 361°C .
5. The carbon monoxide and hydrocarbon emission of UTO40 and UTO100 with hydrogen induction was lower compared to diesel and UTO40 and UTO100 without hydrogen due to the absence of carbon atoms present in the hydrogen structure. But the carbon dioxide emission increases for UTO40 and UTO100 with hydrogen induction with the increase in load but the concentration is very less compared UTO40 and UTO100 without hydrogen induction.
6. The NO emission of UTO100 and UTO40 with hydrogen is found to be higher compared to UTO100 and UTO40 without hydrogen and also diesel because of high temperature

achieved during combustion when hydrogen was admitted. The UTO100 with hydrogen shows more NO emission of 490 ppm at full load while UTO40 with hydrogen is found to be 465 ppm. The diesel shows lower NO emission of about 318 ppm. The NO emission of UTO40 and UTO100 without hydrogen was found to be 380 ppm and 430 ppm respectively at full load.

7. The smoke level was found to be low at all loads for hydrogen enriched fuels because of proper mixing of hydrogen and air and proper combustion. At full load the smoke emission for UTO100 and UTO40 was found to be 25.5% and 18.1% respectively which gets reduced after hydrogen induction to 15.1% for UTO40 and 15.7% for UTO100 at full load.

8. The UTO100 with hydrogen exhibits a higher ignition delay of 12.1231°C at full load followed by 12.0101°C for UTO40 with hydrogen while that of UTO40, UTO100 without hydrogen shows lower ignition delay of 11.0112° C and 11.7889° C respectively. The higher ignition delay for hydrogen inducted fuel is due to high self ignition temperature of hydrogen and more residence time.

9. Due to high self ignition temperature of hydrogen fuel, and more charge accumulation inside the combustion chamber, hydrogen inducted fuel possess higher peak pressure and high rate of heat release. Due to the high viscosity of UTO100, less quantity of the fuel gets actually admitted results lower heat release rate and also maximum cylinder pressure. More study is required to evaluate the combustion behaviour of the engine inducted with hydrogen.

5.2. Scope for future work

Hydrogen seems to be the future fuel for the automobile but more works are needed on the field of its production, storage and transportation. Also the safety of hydrogen fuelled engine is also an important matter of concern.

As far as the emission is concerned, only NO_x emission is found to be high. The excessive work is required to reduce the NO_x emission from the engine. Also at higher flow rate of hydrogen, the engine starts vibrating, so still scope is there to implement new techniques, so that the engine could perform even better at a higher flow rate,

A detailed research on Used Transformer Oil is also required. Especially the neat used transformer oil (UTO100) needs a high attention of researchers. The unexpected combustion behaviour of UTO100 and UTO100 with hydrogen still needs to be evaluated deeply.

Sole used transformer oil after filtering is utilized on compression ignition engine. Scope is there to work on distilled used transformer oil (i.e. used transformer oil after distillation). It is expected that after distillation, the viscosity of the used transformer oil will get reduce and that may enhance the performance of the engine. The above experimental investigation was carried out at a fixed injection timing and injection pressure. The scope is there to find out the optimized injection timing by adding or removing the shim near fuel pump and also to optimize the nozzle injection pressure. After optimizing all those parameters, hydrogen at different flow rate is need to be supply and to obtain the optimize flow rate of hydrogen. This work is under the progress.

More attention is required to understand the unexpected combustion behaviour of UTO with and without hydrogen induction. Used transformer oil also needs special attention, because UTO has all desirable properties to be treated as fuel.

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