

Effect of Hydrogen Enrichment on the Performance Emissions and Combustion Parameters of A Complete Biofueled Diesel Engine

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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National Institute of Technology, Rourkela
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Under the supervision of

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CERTIFICATE

This is to certify that the thesis entitled, **“Effect of hydrogen enrichment on the performance emissions and combustion parameters of a complete biofueled diesel engine”** Submitted By **Mr. Gandhi Pullagura** In Partial fulfillment of the requirements for the award of **Master of Technology** Degree in **“Mechanical Engineering”** with specialization in **“Thermal Engineering”** at the National Institute of Technology, Rourkela (India) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

ROURKELA

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Place : Rourkela

ACKNOWLEDGEMENT

First and foremost I offer my sincerest gratitude and respect to my supervisor, **Dr. S. Murugan**, Associate professor, Department of Mechanical Engineering, for his invaluable guidance and suggestions to me during my study. I consider myself extremely fortunate to have had the opportunity of associating myself with him for one year. This thesis was made possible by his patience and persistence.

After the completion of this Thesis, I experience feeling of achievement and satisfaction. Looking into the past I realize how impossible it was for me to succeed on my own. I wish to express my deep gratitude to all those who extended their helping hands towards me in various ways during my short tenure at NIT Rourkela.

I express my sincere thanks to **Professor R. K. Sahoo, HOD, Department of Mechanical Engineering, NIT Rourkela** for providing me the necessary facilities in the department.

I would like to thank The Department of Mechanical Engineering has provided the support and equipment I have needed to produce and complete my thesis. I greatly appreciate & convey my heart full thanks to my colleagues' flow of ideas, dear ones & all those who helped me in completion of this work.

I am especially indebted to my parents for their love, sacrifice, and support. They are my first teachers after I came to this world and have set great examples for me about how to live, study, and work.

GANDHI PULLAGURA

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ABSTRACT

Emission from engine exhaust is series problem for environment point of view. For that search for alternative fuel is encouraged. The main problems with the use of neat vegetable oils in diesel engines are higher smoke levels and lower thermal efficiency as compared to diesel. The problem can be tackled by inducting a gaseous fuel in the intake manifold along with air. In this investigation, hydrogen is used as the inducted fuel. It is expected that, the problems associated with vegetable oil fueled engine like smoke and hydrocarbon emissions can be brought down by supplying hydrogen in small quantities along with air. Experiments were conducted to evaluate the performance emission and combustion parameters in a compression ignition engine primarily fuelled with an emulsion of bio-oil produced from pyrolysis of biomass source and methyl ester of karanja with different quantities of hydrogen being inducted. The brake thermal efficiency was 28.64% and 32.02% with diesel and WPO-MEK oil without hydrogen operation respectively at full load. MEK oil has less viscosity and better volatility compared to diesel which causes better injection, mixing and evaporation characteristics results in a increasing in brake thermal efficiency. The brake thermal efficiency was 36.57%, 38.5% with 2lpm and 4lpm hydrogen enrichment at full load. The high flame velocity of hydrogen contributed to better mixing of methyl ester oil with air which leads to improvements in thermal efficiency. The maximum thermal efficiency was recorded with 4lpm hydrogen enrichment. However, the dual fuel operation reduces the HC and CO emissions considerably. Since hydrogen has no carbon, burning of hydrogen different flow rates along with wpo10 is reduced HC and CO emissions compared to wpo10 without hydrogen.

Keywords: methyl ester of karanja oil; pyrolysis; Hydrogen; Emissions;

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ABBREVIATIONS

WPO	wood pyrolysis oil
KME	methyl ester of karanja oil
DF	Diesel fuel
WPO10	10% wood pyrolysis oil blended with 90% methyl ester of karanja oil
BP	Brake power
BSFC	Brake specific fuel consumption
BSEC	Brake specific energy consumption
BTE	Brake thermal efficiency
EGT	Exhaust gas temperature
TFC	Total fuel consumption
NO _x	Oxides of nitrogen
HC	Unburned hydrocarbon
CO	Carbon monoxide
CO ₂	Carbon dioxide

ID	Ignition delay
HRR	Heat release Rate
TDC	Top dead centre
BDC	Bottom dead centre

INTRODUCTION

General

Biodiesel production from karanja oil

Production of bio-oil from pyrolysis process.

Hydrogen

INTRODUCTION

1.1. GENERAL

The world is presently confronted with the twin crisis of fossil fuel depletion and environmental degradation. Indiscriminate extraction and lavish consumption of fossil fuels have led to reduction in underground based carbon resources. The search for an alternative fuel, which promises a harmonious correlation with sustainable development, energy conservation, management, efficiency, and environmental preservation, has become highly pronounced in the present context. For the developing countries of the world, fuels of bio-origin can provide a feasible solution to the crisis. The fuels of bio-origin may be alcohol, vegetable oils, bio mass, and biogas. Some of these fuels can be used directly while others need to be formulated to bring the relevant properties close to conventional fuels. The power used in the agricultural and transportation sector is essentially based on diesel fuels and it is, therefore, essential that alternatives to diesel fuels be developed. Hydrogen is an obvious alternative to hydrocarbon fuels such as gasoline. It has many potential uses, is safe to manufacture, and is environment friendly.[1] Today many technologies can use hydrogen to power cars, trucks, electric plants, and buildings – yet the absence of an infrastructure for producing, transporting, and storing large quantities of hydrogen prevents its practical use.

1.2. ENERGY FROM BIO MASS

Biomass is organic matter produced by plant, both terrestrial (those grown on land) and aquatic (those grown in water) and their derivatives. It includes forest crops and residues, crops grown especially for their energy content on ‘energy farms’ and animal manure. Unlike coal oil, and natural gas, which takes millions of years to form, biomass can be considered a renewable energy source because plant life renews and adds to itself every year. It can also be considered a form of solar energy as the latter is used indirectly to grow these plants by photosynthesis.

As the word clearly signifies; biomass means organic matter and photo-chemical approach to harness solar energy means harnessing of solar energy by photosynthesis. Solar energy is stored in the form of chemical energy.

Hence

Solar energy →Photosynthesis-→Biomass→Energy generation

Out of several sources of renewable energy like solar, wind, ocean thermal energy, tidal wave energy, geothermal energy, nuclear energy, energy through biomass are important feature in our country[2]. Bio mass resources fall into to three categories:

One is Biomass in its tradition solid mass (wood and agriculture residue). Second one is biomass in non- traditional form (converted into liquid- fuels). The first category is to burn the biomass directly and get the energy. In 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 biomass an aerobically to obtain a gaseous fuel called bio gas.

1.2.1 BIO-FUELS

The energy stored in dry biomass like wood and straw is most easily released by direct combustion –although dry materials can also be converted into liquid and gaseous fuel (for later combustion) by a variety of techniques. Biomass that is wet, or has moisture content like sewage sludge and vegetable matter can be dried and burn. However, it required considerable energy to drive off the water, and this diminishes the value of the biomass as fuel. It is usually more appropriate to convert wet organic matter directly into premium fuels by a wet process like digestion or fermentation.

Fuel derived from biomass are easily handled and burnt, whereas raw biomass is often wet and of inconsistent quality or variable composition. Most importantly, refined bio fuels can be used in existing fuel systems, often with little or no modification, and are compatible with current patterns of energy use [3]. This improves their economic potential and the speed with which they can be introduced. Refined bio fuels have high calorific values, and can be stored for long periods without deterioration. By contrast, untreated biomass readily absorbs water and rots.

1.2.2. SOLID

There solid bio fuels – wood, straw and refuse are being burnt on an increasing scale in many countries to provide useful heat.

1.2.2.1 WOOD

In the form of cut logs, wood chips and sawdust is currently used for domestic heating and to provide process heat in the timber and furniture industries.

1.2.2.2 STRAW

Straw-burning stoves and furnaces are becoming increasingly common in many countries. They burn various sizes of baled or chopped and compressed straw, and provide heat for crop drying and space and water heating. For grain drying on the farm there is a good match between supply and demand; this minimizes storage costs.

Table 1. The heat content of various fuels

State	Fuel	Value	Unit
Gas	Hydrogen	12	MJ/m ³
	Fuel gas	5-20	MJ/m ³
	Biogas	20-25	MJ/m ³
	Methane	38	MJ/m ³
Liquid	Methanol	21	GJ/t _e
	Ethanol	27	GJ/t _e
	Crude oil	44	GJ/t _e
Solid	Refuse	9	GJ/t _e
	Straw	16	GJ/t _e
	Wood	12-15	GJ/t _e
	Char	20	GJ/t _e
	coal	22-32	GJ/t _e

1.2.3. LIQUID FUELS

Alcohols and vegetable oil are now replaced petrol and diesel as transport fuels in several countries and this process is likely to accelerate as oil prices rise. Other liquid bio fuels are being investigated such as hydro-carbons from euphorbia plants that can be grown in desert regions. Euphorbias are related to rubber trees; their latex is rich in petroleum-like compounds.

1.2.4. GASES

The production of biogas from dung and agricultural wastes is now extensive in some developing countries. Surprisingly, its potential in the industrial World has only recently been recognised.

1.2.5. FUEL GAS

Is produced by the thermal degradation of bio mass. Its main combustible component is carbon monoxide and hydrogen, but its composition and calorific value according to the way it is produced and the raw material used. Fuel gas from an air-blown gasifier.

1.3 BIOMASS CONVERSION TECHNOLOGIES.

A wide variety of conversion technologies is available for manufacturing premium fuels from biomass Some are simple and well understood like digestion and fermentation; others like gasification have been tested in large pilot plants and are now being commercialised[4]. Each bio mass resource → wood, dung, vegetable waste can be treated in many different ways to provide a wide spectrum of useful products.

Biomass conversion, simply by conversion can take many forms: (1) direct combustion, such as wood waste, (2) thermo chemical conversion, and (3) biochemical conversion.

1.4 VEGETABLE OILS AS ALTERNATIVE FUELS IN CI ENGINES

1.4.1 HISTORICAL PERSPECTIVE

The inventor of the diesel engine, Rudolf diesel, in 1885, used vegetable oil (peanut oil) as a diesel fuel for demonstration at the 1900 world exhibition in Paris. Speaking to the engineering society of St. Louis, Missouri, in 1912, diesel said, ‘the use of vegetable oils for engine fuels may seem insignificant today, but such oils may become in course of time as important as petroleum and the coal tar products of the present times’ [5]. The ideal diesel fuel molecules are saturated non-branched hydrocarbon molecules with carbon number ranging between 12 to18 whereas vegetable oil molecules are triglycerides generally with no branched chains of different lengths and different degrees of saturation. It may noticed that vegetable oil contain a substantial amount of oxygen in their molecules structure. Fuel properties for the combustion analysis of vegetable oil can be grouped conveniently into physical, chemical, and thermal properties.

Physical properties include viscosity, density, cloud point, pour point, flash point, boiling range, freezing point, chemical properties comprise chemical structure, acid value, saponification value, iodine value, ash and sulphur content, The characteristics of the variety of available vegetable oil fall within a fairly narrow band and are close to those of diesel oil. Vegetable oil has about 10 percent less heating value than diesel oil due to the oxygen content in their molecules. The kinematic viscosity is, however, several times higher than that of diesel oil. However, higher viscosity is responsible for various undesirable combustion properties of neat vegetable oils. Various vegetable oils, either edible or inedible, of considerable calorific value and comparatively lower viscosity can be used as a substitute for diesel or used in addition to diesel in compression ignition engines.

1.4.2. ADVANTAGES OF VEGETABLE OILS AS FUELS

The merits of using the vegetable oils as alternative fuels are given below;

1. Augment the limited reserves of fossil fuels
2. Renewable energy source
3. Sulphur free fuel
4. Better performance with respect to certain characteristics
5. It is a fuel that can be made from agricultural crops and or other feed stocks that are considered as waste
6. Low aromatic content
7. Non competing as food or fodder source
8. Can grow in poor climatic and soil conditions

1.4.3. DISADVANTAGES OF VEGETABLE OILS AS FUELS

The demerits of using the vegetable oils as alternative fuels are given below;

1. High viscosity
2. Low volatility
3. Gumming
4. Carbon residue

1.4.4 METHODS TO REDUCE THE VISCOSITY OF VEGETABLE OILS

The major limitations of vegetable oil are that they have high viscosity and poor ignition characteristics which impose a negative impact on the engine performance, emissions durability. Many investigations have reported operational and durability problems such as injector nozzle coking, lubrication oil thickening, abnormal engine wear and ring sticking. The higher viscosity of vegetable oils can be addressed by various viscosity reduction techniques. The above mentioned disadvantages make the use of straight vegetable oils (SVO) as fuel less viable. So certain approaches are used to modify these SVOs to use then as alternative fuels in compressive ignition engine. Due to higher viscosity of the vegetable oil, it produces coarse spray when it is injected as fuel into the combustion chamber of a diesel engine and this creates lot of problems like injector coking, carbon deposits, wear and tear etc that results in poor durability of the engine reduces the life of the engine components. Therefore, before using them as fuels the viscosity of the vegetable oils have to be reduced. The different methods to reduce the viscosity of the vegetable oils and also to improve the spray formation so as to use them in the compression ignition engines are (i) Blending (ii) Higher fuel nozzle opening pressures (iii) Preheating (iv) Transesterification (v) Pyrolysis and thermal cracking. The methods are discussed below;

a) Blending

The SVOs are blended with alcohols or diesel to reduce their viscosity. But the problems like carbon formation and polymerisation still occur.

b) Higher fuel nozzle opening pressures

Fuel injectors are employed in internal combustion engines for delivering a precisely metered amount of fuel to the combustion chamber at pre-selected intervals. In case of compression ignition in diesel fuel engines, the fuel is injected into the combustion chamber at relatively high pressures. With increasing demands on greater fuel economy and cleaner emission, even higher fuel pressures are anticipated for future generations of diesel fuel injector designs.

c) Preheating

Preheating and mixing with diesel are some of the methods adopted to reduce the viscosity of vegetable oil. The SVO can be heated with the help of preheating setup before admitting into the injector of the diesel engine. Preheating reduces the viscosity of the SVO.

d) Transesterification

In recent year biodiesel, a fuel derived from vegetable oil by a chemical process known as transesterification has attracted several researchers. Transesterification was known as early as 1864, when rochleder described glycerol preparation through ethanolsis of castor oil. Transesterification is a chemical reaction that aims at substituting the glycerol of the glycerides with three molecules of monoalcohol such as methanol thus leading to three molecules of methyl ester of vegetable oil. The idea of chemically altering vegetable oil was noted ever before World War 2. Walton wrote in 1938 ‘to get the utmost value from vegetable oil as fuels it is academically necessary to split the glycerides and to run on the residual fatty acid’ because ‘the glycerides are likely to cause an excess of carbon in comparison’. The process of utilizing biodiesel in the IC engines for transport as well as other applications, is gaining momentum recently. IEA has recognized biodiesel as an alternative fuel for the transportation sector. The European commission proposed a 12 percent market share for bio fuels by the year 2020 [7]. Kaltschmitt et al. conducted a study, which shows that bio energy carriers offer some clear ecological advantages over fossil fuels such as conserving fossil energy resources or reducing the green house effect [8]. It is a chemical process in which the triglyceride structure of the oils is broken down by reaction with methanol/ethanol in presence of catalyst (NaOH/KOH) to form a mixture of mono alkyl esters and glycerol.

e) Pyrolysis and thermal cracking

Pyrolysis means conversion of one substance to another by application of heat. Catalysts are used to speed up the process. Different products can be obtained from the same material depending on different path of reaction and this makes pyrolytic chemistry difficult. Pyrolysis of vegetable oil gives different lower hydrocarbons that can be used as fuel.

1.5. KARANJA OIL

The Karanja tree- *Pongamia Glabra* - is widely distributed in tropical Asia. The tree is hardy and drought resistant. The 'Pongam' tree is commonly found in India and grows to a height of about 1 m. The oil of the Karanja or Pongam is used in pharmacy and in agriculture. Like, neem oil, it is excellent for skin and hair and used in the manufacture of soaps, creams, lotions and other skin and hair care products.[6] A mixture containing equal amounts of neem and karanja oil is very effective on animals for skin problems. Karanja tree (*Pongamia glabra*) is wonderful tree almost like neem tree. In south part of the indian peninsula the karanja oil / cake are also used same like neem oil and neem cake. This Can be considered same like neem oil and neem cake in pest and fertilizer management in organically.



Fig 1 karanja seed.

Pongamia pinnata (Karanja), The seed oil has been used by the natives of India for hundreds of years. It is used in Ayurvedic and Siddha traditional medicine systems to treat various skin conditions from eczema and psoriasis to leprosy, and for skin protection, as it is believed to

enhance the UV absorbing properties of conventional sunscreens.[7] A paste made of Karanja and lime is used to relieve rheumatic pain, and Karanja infused baths are used for cleaning skin ulcers and sores.

Pharmaceutical preparations based on Karanja Oil are used for treating skin diseases including acne, herpes, rosacea and leucoderma (partial or total loss of skin pigmentation, often occurring in patches, also known as vitiligo.). In Sri Lanka, promising studies have been conducted on the effects of Karanja Oil on keloid scars. Roots of the tree are used for cleaning gums, teeth, and ulcers. Bark is used internally for bleeding piles. Juices from the plant, as well as the oil, are antiseptic.

1.5.1. CHARACTERISTICS OF BIODIESEL FROM KARANJA OIL

Karanja (*Pongamia pinnata*) is a non edible plant whose oil is dark and has an odour. Our sample used is a methyl ester of the karanja oil. Karanja (*Pongamia Pinnata*) is (a tree) grown in parts of India and Australia. The seed gernels contain 27-39 per cent of oil. The potential availability of the oil is estimated to be 55,000 t/y. The seed oil is extracted and sold for non-edible purposes. Currently it is used in soap making and in the leather industry.

The composition of the sample was determined by GC-MS analysis and the results were given in Table 3.

Table 3. Analysis of Methyl Ester

S.No	Name of Component	% Composition
1	hexadecanoic acid,methyl ester	10.34
2	n-hexadecanoic acid	0.50
3	9,12octadecadienoic acid (z,z)-,methyl ester	14.90
4	Methyl cis-7-octadecenoate;7-Octadecenoic acid,methyl ester,(Z)-	40.00
5	Octadecanoic acid ,methyl ester	8.45
6	9,12-Octadecadienoic acid (Z,Z)-	0.79
7	octadec-9-enoic acid	4.34
8	9-oxa-cis(1,8),cis(2,7),trans(7,8)-tricyclo[6.3.0,0(2,7)]undeca-3,5,10-trie	1.22
9	Octadecanoic acid	0.99
10	cis-11-Eicosenoic acid,methyl ester	0.74
11	eicosanoic acid,methyl ester	1.51
12	docosanoic acid,methyl ester	3.34
13	2,2-dimethyl-7-hydroxy-6-[(2'-phenylethenyl)carbonyl]-(benzo-2h-pyran	0.50
14	2-Phenyl-4anilino-6[1H]-pyrimidinone	2.29
15	2-[5-(2-methyl-1,3-benzoxazol-7-yl)-1h-pyrazol-3-yl]phenol	2.14
16	Oleoyl chloride	5.45
17	Tetracosanic acid, methyl ester	0.85
18	hexadecanoic acid,methyl ester	10.34
19	n-hexadecanoic acid	0.50
20	9,12octadecadienoic acid (z,z)-,methyl ester	14.90
21	Methyl cis-7-octadecenoate;7-Octadecenoic acid,methyl ester,(Z)-	40.00
22	Octadecanoic acid ,methyl ester	8.45
23	9,12-Octadecadienoic acid (Z,Z)-	0.79
24	octadec-9-enoic acid	4.34

1.5.2. PROPERTIES OF KARANJA OIL

The physical properties of karanja oil are compared with diesel and given in Table 2.

Table 2. Comparative properties of karanja oil

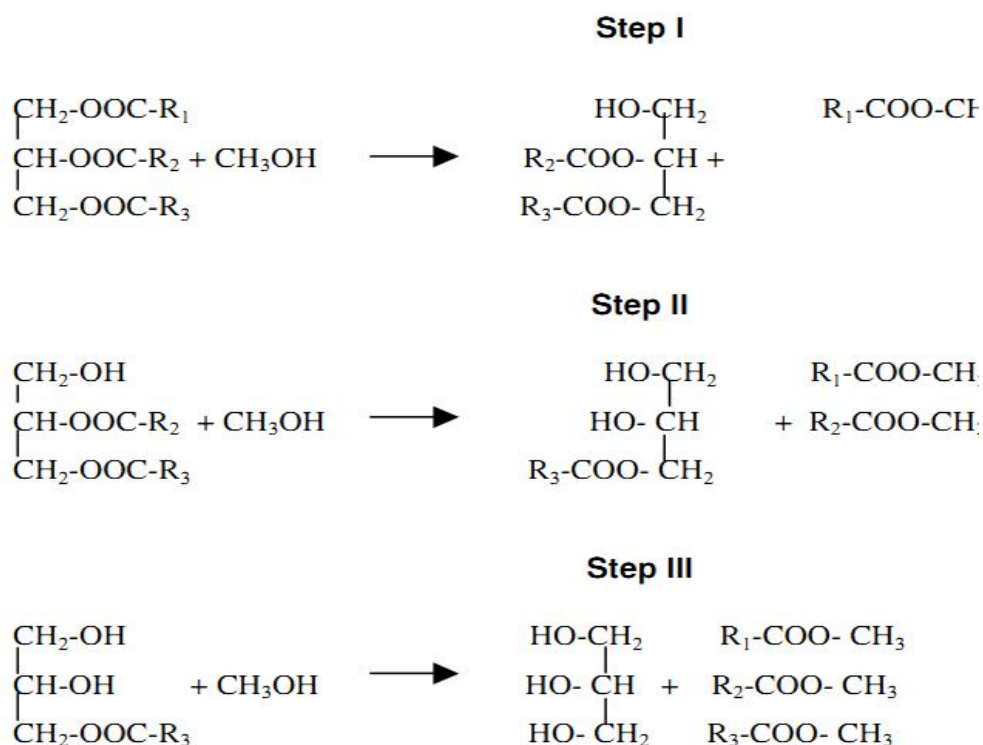
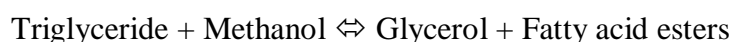
Properties	Diesel	Karanja oil
Viscosity at 30 °C (cSt)	3.06	69.6
Density (kg m ⁻³)	860	911
Flash point (°C)	76	230
Pour point (°C)	-16	-3
Cloud point (°C)	-10	0
Carbon residue (%)	0.1	0.71
Ash content (%)	0.01	0.04
Sulphur content (%)	0.05	–
Calorific value (kJ/kg)	42,490	38,416
Cetane number	50	39

1.6 BIODIESEL PRODUCTION FROM KARANJA OIL

Biodiesel is an alternative diesel fuel made from vegetable oil and animal fats. It can act both as substitute and an additive to diesel fuel. European Union has set an objective to replace its 5 percent of total motor fuel consumption with biodiesel in 2005.[9] Similarly the US department of energy estimated that up to 50 per cent of the diesel fuel could be replaced with biodiesel. Importance of biodiesel increases due to (1) Increasing petroleum prices, (2) Limited fossil fuel reserves, and (3) Environmental benefits of biodiesel.

1.6.1 TRANSESTERIFICATION:

Transesterification is a kind of organic reaction where alcohol group in ester is substituted. It can also be reaction of vegetable oil/fat to give ester and glycerol. The applicability of transesterification is not restricted to laboratory. Several relevant industrial processes use this reaction to produce different types of compounds. An example is the production of PET (polyethyleneterephthalate), which involves a step where dimethylterephthalate is transesterified with ethylene glycol in the presence of zinc acetate as catalyst. Furthermore, a large number of acrylic acid derivatives are produced by transesterification of methyl acrylate with different alcohols, in the presence of acid catalysts. Transesterification works by cracking the vegetable oil molecules splitting the triglycerides from the hydrocarbons and shortening the carbon chain. The chain reaction equation is given below.



1.6.2 TRANSESTERIFICATION OF VEGETABLE OILS:

In transesterification of vegetable oils, a triglyceride reacts with three molecules of alcohol in the presence of catalyst, producing a mixture of fatty acids alkyl esters and glycerol. The overall process is a sequence of three consecutive reactions, in which di- and monoglycerides are formed as intermediates. [9] Transesterification is a reversible reaction thus; excess alcohol is used to increase the yields of the alkyl esters and to allow its phase separation from the glycerol formed.

Conversion of vegetable oil to biodiesel is effected by several parameters namely

- (i) Time of reaction,
- (ii) Reactant ratio (Molar ratio of alcohol to vegetable oil),
- (iii) Type of catalyst,
- (iv) Amount of catalyst, and
- (v) Temperature of reaction.

1.6.3 EXPERIMENTAL SETUP:

Reaction or transesterification was carried out in a system in system. Reactor consisted of spherical flask, which was put inside the heat jacket. Oil was used as medium of heat transfer from heat jacket to the reactor.

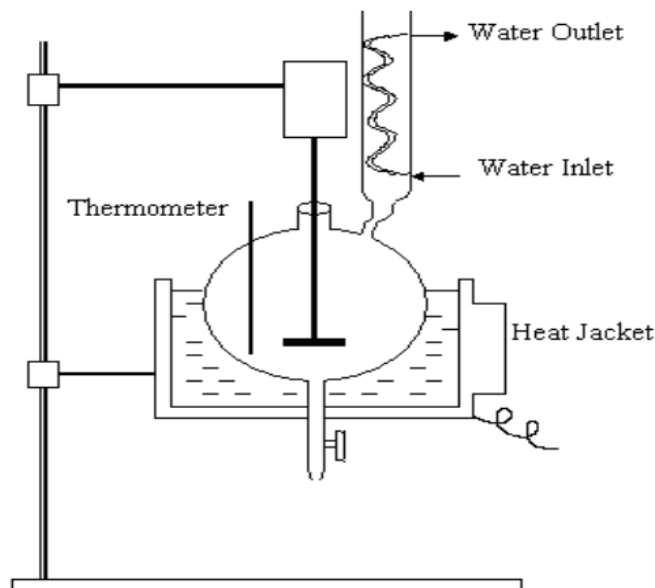


Fig 2. Experimental set up of biodiesel production

Thermostat was a part of heat jacket, which maintained the temperature of oil and in turn the temperature of the reactants at a desired value. The reaction was carried out at around 65-70 °C. Spherical flask consisted of four openings. The centre one was used for putting stirrer in the reactor[10]. The motor propelled the stirrer. Thermometer was put inside the second opening to continuously monitor the temperature of the reaction. Alcohol being volatile vaporized during the reaction so the condenser was put in the third opening. To reflux the vapors back to the reactor to prevent any reactant loss. Fourth opening was used for filling reactants to the reactor.

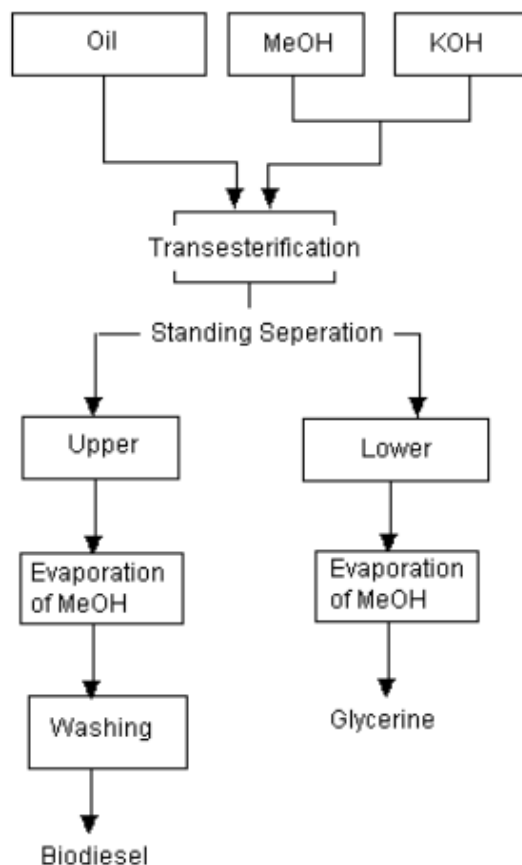
1.6.4 EXPERIMENTAL PROCEDURE:

A known quantity of karanja oil (100ml for each run) was taken inside the reactor and heated at about 70 °C. This temperature was maintained throughout the reaction by the thermostat inside the heat jacket. Preheating was used to remove unwanted moisture present in the oil. The transesterification was carried out in basic medium and to achieve it, KOH was used as a catalyst. Catalyst was dissolved in alcohol (MeOH)[9]. Once the oil temperature reached 70 °C, alcohol solution (containing dissolved catalyst) was added to the reactor and an equilibrium temperature was maintained. During the reaction the alcohol gets vaporized. To prevent any reactant loss condenser was used to condense the alcohol vapor and reflux it back into the reactor. Condenser was also helpful in maintaining the atmospheric pressure inside the reactor.

Once the reaction was over the products were taken out through the outlet in the lower side of the reactor and put in the separating funnel. Two phases (having different density) are formed as a result of transesterification. Separation was done using a separating funnel (separation took around two hours) . Upper layer consisted of biodiesel, alcohol, and some soap (formed as a result of side reaction saponification – free fatty acids get converted to soap). Lower layer consisted of glycerin, excess alcohol, catalyst, impurities, and traces of unreacted oil.

Purification of upper layer (to obtain biodiesel) was done in two steps.

- (i) Removal of alcohol – by keeping mixture at elevated temperature ~ 80 Celsius.
- (ii) Removal of saponified products – by washing with warm water. Water is immiscible with biodiesel, hence can be easily separated from biodiesel.



1.7. PRODUCTION OF BIO-OIL FROM PYROLYSIS PROCESS

In this study pyrolysis oil was obtained through vacuum pyrolysis process. Thick wood obtained from packing container box taken as sample, cut into small chips, washed, dried. The schematic diagram of the pyrolysis process for deriving wood pyrolysis oil was given in figure 1. This chips were fed into an externally heated mild steel reactor unit. The fed chips were heated up in the reactor unit in the absence of oxygen. The reactor used for production of wood pyrolysis oil is cylindrical in shape with inner diameter 200mm and outer diameter 250mm and a height of 250mm. The reactor is fully insulated by glass wool with thickness 50mm and refractory lining. The heat input to the electrical heater was 3kW. The temperature of the reactor was measured by the help of a temperature indicator provided in a temperature controller unit. The temperature of the reactor was controlled by a PID controller. In pyrolysis process for deriving wood pyrolysis oil was carried out at 500°C.

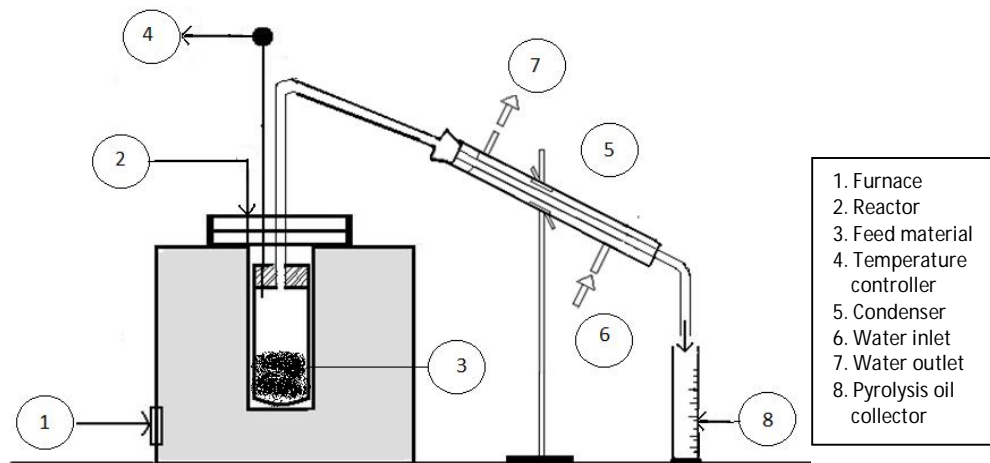


Fig 3 Schematic diagram of pyrolysis setup

The products of pyrolysis in the form of vapour were sent to a water cooled condenser and the condensed liquid was collected in a container. The pyrolysis oil has a high oxygen content burn smoothly and cleanly and has the potential for alternative source. But pyrolysis oil contains many reactive components that can form higher molecular weight species. So these reactions result in an increase in viscosity and decrease in volatility.

Table 4. The properties of wood pyrolysis oil is compared with diesel fuel

Properties	ASTM Standard	Diesel Fuel	WPO
Specific gravity at 15 °C	ASTM D 4052	0.83	1.2
Net calorific value[MJ/kg]	ASTM D 4809	43.8	18
Flash point[°C]	ASTM D 93	50	66
Pour point[°C]	ASTM D 97	30	-27
Kinematic viscosity at 40 °C[cst]	ASTM D 445	2.58	13
pH value	-	-	2.4
Moisture content (wt %)	-	0.025	15-30
Ash (wt%)	-	0.13	0.01

Biomass is one of the important sources of alternative energy. Biomass can be used in internal combustion engine in many ways. One of the methods for deriving fuel from biomass is pyrolysis.

1.8. HYDROGEN

Hydrogen is a high quality carrier which can be used with a high efficiency and zero emissions at the point of use. It has technically demonstrated that hydrogen can be used for transportation, heating, and power generation, Hydrogen has very low density both as gas and as liquid. Hydrogen is also a potential fuel for internal combustion engines. Hydrogen is an attractive alternative fuel due to the fact that it can be produced from fossil fuels. Alternative fuels are available in the form of solid, liquid, and gas. Biomass, biodiesel from different vegetable oils respectively which are commonly used to run the internal combustion engine. Although these fuels are used, they generate considerable pollutants from the internal combustion engines. Hydrogen is largely available and renewable in nature. Hydrogen is clean burning fuel among all other alternative fuels. Hydrogen has high auto ignition temperature and energy density. The higher auto ignition temperature of hydrogen limits its use as a sole fuel in diesel engines. Hydrogen has wide flammability limits which make it to burn in an internal combustion engine over a wide range of air-fuel mixtures [12]. Hydrogen can burn on lean mixture and it is possible to achieve greater fuel economy. Hydrogen also has higher flame speed and mass diffusivity compared to other gaseous fuels. Hydrogen mixed in the intake air in small quantities improves the thermal efficiency and reduce the smoke emissions of a diesel engine.

Table 5. 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
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	-
Boiling point(K)	20.27	436-672
Cetane number	-	40-55
Molecular weight(g/mole)	2.015	170
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

1.8.1. ADVANTAGES OF HYDROGEN AS FUEL FOR I.C ENGINES

The merits of hydrogen as a fuel are given below;

- Hydrogen –air mixture burns early 10 times faster compared to gasoline air mixture. Being burning rate considerably high it is more preferred in high speed engine. As the burning rate are very high, working approaches to instantaneous combustion of an ideal Otto cycle performance.
- Hydrogen ignition limits are much wider. So it can burn easily and give considerably higher efficiency.
- Its clean exhaust is the most attractive feature of all. As it does not produce carbon dioxide, there is no green house effect.
- The exhaust heat can be used to extract hydrogen from the hydride reducing the load on engine.
- Less cyclic variations are encountered with hydrogen than with other fuels even for very lean mixture operation. This leads to a reduction in emissions, improved efficiency, and quieter and smoother operation.

1.8.2 DISADVANTAGES OF HYDROGEN AS FUEL FOR I.C ENGINE

The demerits of hydrogen as a fuel are given below;

- Hydrogen engines have been in the danger of back fire during combustion. Therefore flame trappers are necessary in hydrogen fuelled engines.
- Hydrogen fuelled engine are having low pollution level but produce toxic emission of NO_x .
- The handling of hydrogen is more difficult and storage requires high capital and running cost particularly for liquid H_2 .
- It can detonate.

1.8.3. METHODS 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 [13]. There are basically five different techniques of hydrogen induction that were carried out in the last few decades by the researchers. They are;

- Carburetion technique
 - Continuous manifold injection (CMI)
 - Low pressure direct cylinder injection (LPDI)
 - High pressure direct cylinder injection (HPDI)
 - Timed manifold injection (TMI)
- The above five points are the techniques to optimize the basic procedure of induction of hydrogen on diesel engines

1.8.4. SAFETY AND MANAGEMENT

Since hydrogen is a highly flammable gas, it must be handled with care in special equipment designed for safety. The extensive use of H_2 on the grounds is dangerous. Natural gas and gasoline are also hazardous materials, yet they are in common daily use. The danger of fire or explosion can be minimized by taking proper precaution with hydrogen [13]. Larger quantities of the gas and liquid have been carried by pipeline, road and rail for use in industry and in space vehicles in many respects, hydrogen gas is no more, and possibly less, hazardous than natural gas. The lower flammability limit of hydrogen is 4 percent in air, whereas that of methane in natural gas is 5 percent. However, hydrogen will escape from a leak of fixed size about three times as fast as natural gas; hence, in a closed space, the flammability will be reached soon with hydrogen. On the other hand, the energy contained in the space at the lower flammability limit is about one fourth that for natural gas. Because of its low density, hydrogen disperses more readily in an open space, and it would therefore take a much longer time for the flammability limit to be reached. The chief danger from hydrogen gas is associated with the very low ignition energy,

which is less than a tenth than of natural gas. Consequently, a spark that is too weak to ignite a flammable air-natural gas mixture may ignite an air-hydrogen mixture. In handling hydrogen, special care is to be taken to avoid flames and prevent spark formation.

Hydrogen is used on a large scale today in industry, especially the chemical industry, where the safe handling of hydrogen is an established technique. Now any essential problems to be expected in this area of use in future. However, in considering the possible future public use of hydrogen as an energy vector. 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. 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.

CHAPTER -2

Literature Survey

LITERATURE SURVEY

M.Senthil Kumar et al. did experiments to evaluate the performance while using small quantities of hydrogen in a compression ignition engine primarily fuelled with a vegetable oil, namely Jatropha oil. Results indicated an increase in the brake thermal efficiency from 27.3% to a maximum of 29.3% with 7% of hydrogen mass share at maximum power output. Smoke was reduced from 4.4 to 3.7 BSU at the best efficiency point. There was also a reduction in HC and CO emissions from 130 to 100 ppm and 0.26–0.17% by volume respectively at maximum power output. With hydrogen induction, due to high combustion rates, NO level was increased from 735 to 875 ppm at full output. Ignition delay, peak pressure and maximum rate of pressure rise were also increased in the dual fuel mode of operation. Comparison was made with diesel being used as the pilot fuel instead of vegetable oil. At the optimum hydrogen share of 5% by mass, the brake thermal efficiency went up from 30.3–32%. Hydrocarbon, carbon monoxide, smoke emission and ignition delay were also lower with diesel as compared to vegetable oil. Smoke level decreased from 3.9 to 2.7 BSU with diesel as pilot at the optimum hydrogen share. Concluded that induction of small quantities of hydrogen can significantly enhance the performance of a vegetable (Jatropha) oil/diesel fuelled diesel engine.

G. Nagarajan, and B. Nagalingam: The main problems with the use of neat vegetable oils in diesel engines are higher smoke levels and lower thermal efficiency as compared to diesel. The problem can be tackled by inducting a gaseous fuel in the intake manifold along with air. In this investigation, hydrogen was used as the inducted fuel and rubber seed oil (RSO), rubber seed oil methyl ester (RSOME) and diesel was used as main fuels in a dual fuel engine. Dual fuel operation of varying hydrogen quantity with RSO and RSOME results in higher brake thermal efficiency and significant reduction in smoke levels at high outputs. The maximum brake thermal efficiency is 28.12%, 29.26% and 31.62% with RSO, RSOME and diesel at hydrogen energy share of 8.39%, 8.73% and 10.1%, respectively. Smoke was reduced from 5.5 to 3.5 BSU with

RSOME and for RSO it was from 6.1 to 3.8 BSU at the maximum efficiency point. The maximum hydrogen energy share that can be tolerated with knock limit was highest with diesel (12.69%) and decreases with RSOME (11.2%) and RSO (10.76%) at full load. There was a reduction in the HC and CO levels at all loads with the induction of hydrogen for all injected fuels.

G. Sankaranarayanan and J. Jayaraj The objective of the present work was to improve the performance of mahua oil fuelled diesel engine using hydrogen enriched air. Hydrogen enriched air was supplied at different flow rates through a gas carburettor. Mahua oil combustion with varying gravities of hydrogen 10lpm,20lpm,30lpm,40lpm and 50lpm enriched air resulted in improvement in brake thermal efficiency and reduction in smoke density. Hydrogen enrichment was found to increase the combustion rate of mahua oil. The NO concentration was higher for mahua oil operation with hydrogen enrichment but lower than diesel. The engine produced severe knock with 50lpm hydrogen induction at full load operation condition. With 40lpm hydrogen enrichment the engine brake thermal efficiency reached a maximum of 23% at 75% full load. The noise level increased with increased in hydrogen admission, the smoke density was reduced significantly with the addition of hydrogen

L.M.Das studied that the mixture formation method plays an 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 were 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. 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 give a better performance compared to carburetion technique. The knock can occur at high flow rate of hydrogen. It was concluded the optimum hydrogen enrichment with diesel was 30% by volume.

N. Saravanan et al. Investigated the combustion analysis on a direct injection DI diesel engine using hydrogen with diesel and hydrogen with diethyl ether as ignition source. Hydrogen injected 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. Did experiment by using hydrogen as a sole fuel and then hydrogen mixed with petrol and hydrogen diesel oil mixed fuel. Their 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 brought 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.

L.M. Das] studied the nature and formation mechanism of different types of pollutants emitted from 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. did experimental investigation on a hydrogen fuelled diesel engine to measure the performance characteristics through charge diluents. The results show 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 was found that the engine started knocking when the hydrogen flow rate was 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 gave the best thermal efficiency and power output when its percentage was 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.

M. Senthil Kumar, and A. Ramesh, did investigation on hydrogen will be used as the inducted fuel. Investigation was done on the problems associated with vegetable oil fueled engine like smoke and hydrocarbon emissions can be brought down by supplying hydrogen in small quantities along with air. The brake thermal efficiency of the hydrogen enriched engine fueled with vegetable oil will get increase. Experiments were conducted to evaluate the performance in a compression ignition engine primarily fuelled with a vegetable oil with different quantities of hydrogen being inducted. The vegetable oil was injected into the engine in the conventional way. The problem of high NO emission when fueled with hydrogen can be should be reduced by adopting Exhaust Gas Recirculation (EGR) technique.

T. Lakshmanan and G.Nagarajan Studied on a single cylinder, air cooled DI diesel engine by inducting acetylene gas at different flow rates in dual fuel mode. The diesel acted as an 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.

T.Lakshmanan and G.Nagarajan Studied the possibility of utilizing the acetylene gas fuel in a dual fuel mode. Diesel was used 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 angle.

Reduction in all type of emission was noticed except smoke. There slightly increase in smoke emission.

R.G.Papagiannakis et al. Conducted experiment on duel fuel mode on a single cylinder, air cooled direct injection diesel engine having bowl in piston type combustion chamber. Attempts were 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.

T.Lakshamanan et al. in their paper he studied the performance and emissions characteristics of acetylene fuelled engine at different flow rates by using timed manifold injection technique. They reveal that optimum condition in manifold injection technique is 10° ATDC with injection duration of 90° crank angle and results a marginal increase in brake thermal efficiency is noticed for all gas flow rates. NO_x emission decreased according to flow rates and slight increase in smoke levels. Reduction in HC, CO, CO₂ emissions are observed.

John W.H. Price. In his paper considers the explosion of an acetylene gas cylinder, which occurred in 1993 in Sydney. The failure caused severe fragmentation of the cylinder and resulted in a fatality and property damage. The paper describes the failure and the circumstances surrounding it, examines the nature of the explosion which occurred and seeks an explanation of the events. He had given more information to prevent accidents regarding while using acetylene and the reactions take place in combustion and safety precautions.

G.A.Rao et al studies are with LPG in Diesel engine in dual fuel mode.LPG carburetor is incorporated on the intake side of the engine. The LPG energy substitution could be done up to 50% at lower loads and up to 20% at higher loads. The engine performance is better on pure diesel up to engine loads of about 35%.at higher loads; the dual fuel mode is superior to the pure diesel mode of operation, compared to that of pure diesel operation.

CHAPTER -3

EXPERIMENTAL INVESTIGATION

Experimental Procedure

Devices installed for hydrogen admission

Energy share between hydrogen and main fuel

EXPERIMENTAL INVESTIGATION

3.1. EXPERIMENTAL PROCEDURE

The engine used for the present investigation is a single cylinder, four strokes, air cooled, direct injection, diesel engine. The schematic diagram of the experimental setup is shown in Fig 1 and the engine specification is given in Table 3. Initially the engine was operated with neat diesel and the performance, emission parameters were evaluated. Then the engine was allowed to run with a emulsion made with WPO10 (wood pyrolysis oil) - methyl ester of karanja oil. The compressed Hydrogen gas was introduced by induction technique through the intake manifold. The performance, combustion and emission parameters were measured and compared with that of diesel baseline readings. The hydrogen gas was introduced in two different flow rates like 2lpm and 4lpm respectively.

Hydrogen fuel, at a constant flow rate of 2lpm and 4lpm were supplied through a flame arrester and flame trap and finally it was admitted into the intake pipe (at a distance of 40 cms from the intake manifold) where it mixed with air and this hydrogen- air mixture was inducted into the engine cylinder. 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 was used to control the outlet pressure. Wood pyrolysis oil 10% blended with methyl ester of karanja oil 90% without hydrogen on volume basis was introduced from the fuel tank into the engine cylinder by direct injection. Then engine was allowed to run for different loads. And also the engine was run with wood pyrolysis oil 10% blended with methyl ester of karanja oil 90% with hydrogen at two different flow rates 2lpm and 4lpm. The performance and combustion parameter is obtained by computer provided into data acquisition system. AVL exhaust gas analyser was used to calculate the emission parameter whereas smoke meter was 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.

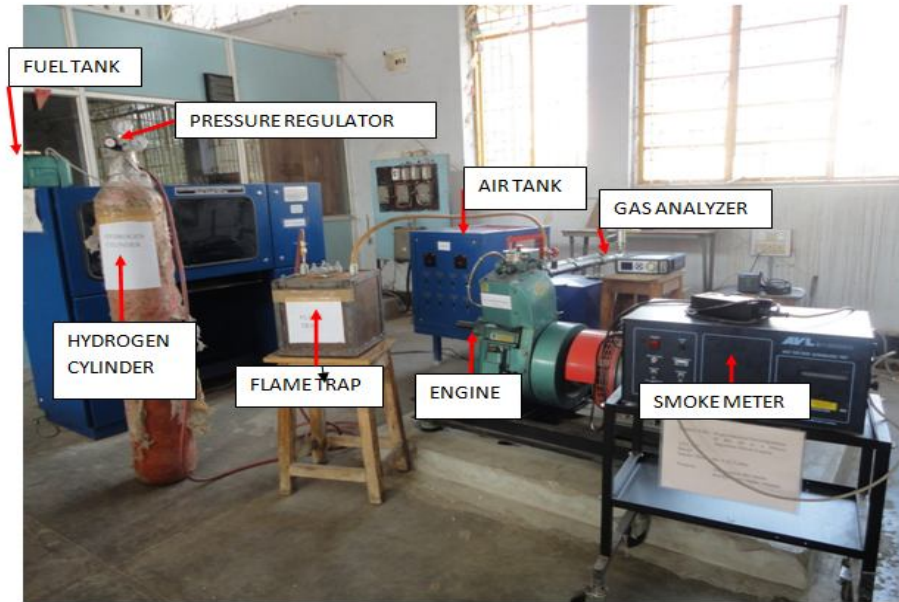


Fig 4 the schematic representation of the engine experimental set up

Table 6. Test engine specification

Make	Kirloskar
Type of Engines	4-stroke cycle, single cylinder, compression ignition engine
Speed(rpm)	1500
Bore	87.5
Stroke	110
Compression ratio	17.5
Method of cooling	Air cooled with radial fan
Injection timing	23deg before TDC
Nozzle opening pressure kg/cm ²	200-205

3.2. DEVICES INSTALLED FOR HYDROGEN ADMISSION

3.2.1. HYDROGEN ADMISSION

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

3.2.2 HYDROGEN SUPPLY

The hydrogen gas is allowed to pass through the intake pipe at an outlet pressure of 1bar and 2bar pressure and at flow rate of 2lpm and 4lpm. The pressure is regulated by a double stage diffusion pressure regulator mounted on to the hydrogen cylinder.

Specification of pressure regulator is given below:

- a. Inlet Pressure Max 0-280 kg/cm²
- b. Outlet pressure Max 0-07 kg/cm²
- c. Inlet Connection: 5/8" BSP (M) LH
Outlet Connection: ¼ inches OD Tub
- d. Gas Service: Hydrogen

3.2.3. FLAME TRAP

Flame traps are used in a internal combustion engines. The flame trap is just a tank filled with water with inlet and outlet openings. The water doesn't allow the flame to the cylinder. Flame trap is a safety feature which is designed to prevent fire from reaching a fuel supply line. This reduces the risk of explosion or fire, making the system safer to operate.



Fig 5 Flame trap

The flame trap extinguishes the fire, ensuring that it cannot come into contact with the raw fuel supply. 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.

3.2.3.1 Specification of flame trap

- 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

3.2.4. FLASH BACK ARRESTER

For flame arresters used as a safety device,

- To stop the spread of an open fire
- To limit the spread of an explosive event that has occurred
- To protect potentially explosive mixtures from igniting
- To confine fire within an enclosed, controlled, or regulated location

A flash back arrestor 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.



Fig 6 Flash back arrester

This can travel back through the line of your gas management system to your gas source if a 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.

3.2.4.1 Use of Flashback Arrestors

The reason for using a protective device such as a flash back arrestor on a fuel gas line or even on a cylinder are

- i) Safety of property and human lives
- ii) The flashback occurs under various conditions.
- iii) The flashback occurs inside the pipeline or vessels.
- iv) The flame moves through a vessel or pipe.
- v) The flame velocity increases as it moves through these pipe or vessels, and if the pipe is long enough the velocity can increase to detonation levels, which are supersonic

3.2.5 PRESSURE REGULATOR



Fig 7 Pressure regulator

3.3. ENERGY SHARE BETWEEN HYDROGEN AND MAIN FUELS

In the present study, the hydrogen 2lpm flow rate. So mass flow rate of hydrogen at all the loads in terms of kg/hr is calculated as 0.00984kg/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 0.328kW.

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).

Table 7. Energy share between hydrogen 1bar WPO-MEK

Load	Energy share by fuel(kw)	Energy share by hydrogen(kw)	Total energy share(kw)	%Energy share by fuel	% Energy share by hydrogen
0	1.475	0.328	1.803	81.8	18.19
1000	2.900	0.328	3.228	89.8	10.16
2000	6.970	0.328	7.298	95.5	4.0
3000	9.646	0.328	9.974	96.7	3.2
3750	12.24	0.328	12.568	97.3	2.6

In the present study, the hydrogen 4lpm flow rate. 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 0.656kW.

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).

Table 8. Energy share between hydrogen 2 bars and WPO-MEK

Load	Energy share by fuel(kw)	Energy share by hydrogen(kw)	Total energy share(kw)	%Energy share by fuel	% Energy share by hydrogen
0	2.136	0.656	2.792	76.5	23.4
1000	4.172	0.656	4.828	86.4	13.5
2000	5.900	0.656	6.556	89.9	10.0
3000	8.240	0.656	8.896	92.6	7.3
3750	10.786	0.656	11.442	94.2	5.7

CHAPTER -4

RESULTS AND DISCUSSION

Performance Parameter

Emission Parameters

Combustion Parameters

RESULTS AND DISCUSSION

In the present work, hydrogen gas- air mixture was used in the compression ignition engine where WPO10-methyl ester of karanja oil respectively was used as a main fuel in the operation. The performance, emission and combustion characteristics of WPO10 - methyl ester of karanja oil with hydrogen enrichment of different flow rate compared with baseline diesel operation.

4.1 PERFORMANCE PARAMETERS

4.1.1 BRAKE THERMAL EFFICIENCY

The Variations of brake thermal efficiency with brake power shown in Fig 8. The brake thermal efficiency was 28.64% and 32.02% with diesel and WPO10 and methyl ester of karanja oil operation respectively at full load. Methyl ester of karanja oil has less viscosity and better volatility compared to diesel which causes better injection, mixing and evaporation characteristics results in a increasing in brake thermal efficiency.

The brake thermal efficiency was 36.7%, 38.5% with 2lpm and 4lpm hydrogen enrichment at full load. The high flame velocity of hydrogen contributed to better mixing of methyl ester with air which leads to improvements in thermal efficiency [25]. Due to better mixing of hydrogen with air, combustion rate gets enhanced results in higher brake thermal efficiency. The maximum thermal efficiency was recorded with 4lpm hydrogen enrichment. The engine noise was observed to be more while the engine was running in dual fuel mode. The noise level increased with increase in hydrogen admission. This was mainly due to rapid combustion of WPO10 and methyl ester of karanja oil in the presence of hydrogen.

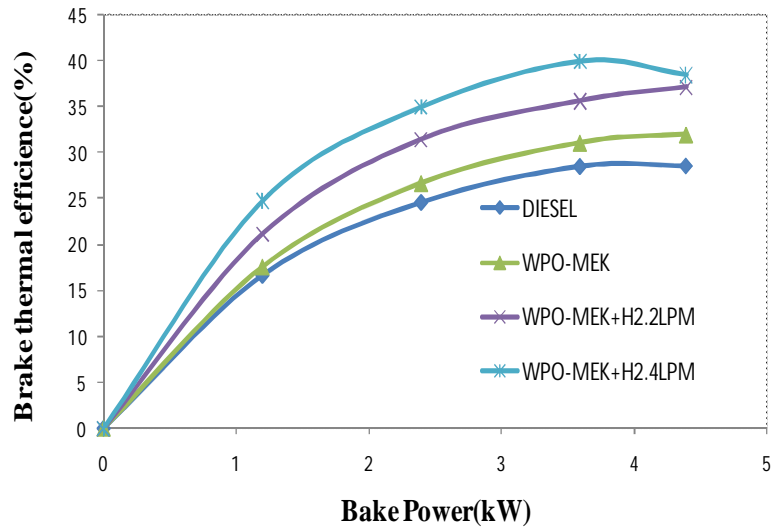


Fig 8 Variation of brake thermal efficiency with brake power

4.1.2 BRAKE SPECIFIC ENERGY CONSUMPTION

It was found that brake specific energy consumption fuel decreased as hydrogen Enrichment increased. The BSEC decreased at high load is due to the premixing of hydrogen fuel with air.

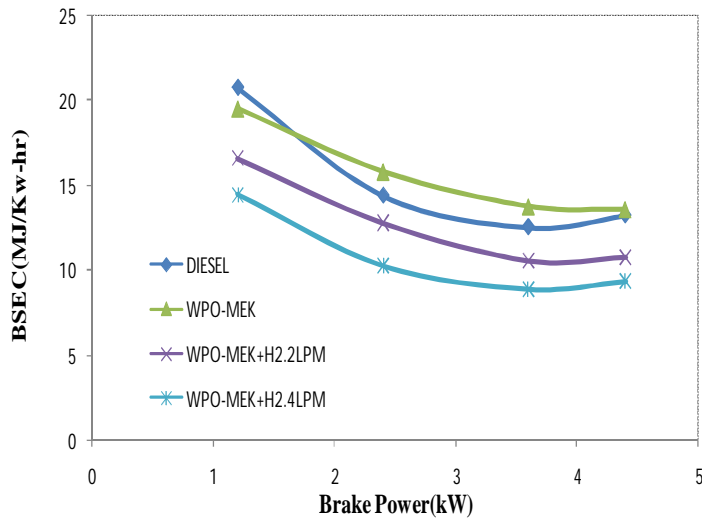


Fig 9 Variation of brake specific energy consumptions with brake power

The BSEC values are 13.23 (MJ/kWh) and 13.57 (MJ/kWh) with diesel and wpo10 operation respectively at full load [16]. The BSEC was 10.75 (MJ/kWh) and 9.35 (MJ/kWh) with 2lpm and 4lpm hydrogen enrichment at full load. The diffusivity and uniform mixing of hydrogen with air leading to near complete combustion of the fuel due to this the fuel consumption gets decreased.

4.1.3 EXHAUST GAS TEMPERATURE

The variation exhaust gas temperature with brake power is shown in fig 10. The trend shows that the EGT increases with increase in brake power. The exhaust gas temperature of 310 °C is reached at 2lpm hydrogen enrichment at full load condition. The exhaust gas temperature of 380 °C is reached at 4lpm hydrogen enrichment at full load condition. The graph shows that a better combustion was taking place after enrichment of hydrogen in to the engine [22]. Because of high residence time associated due to high auto ignition temperature of hydrogen, more charge gets accumulated inside the cylinder contributes to increase the exhaust gas temperature. Due to the increase in peak combustion temperature the exhaust gas temperature of the hydrogen enriched engine is higher than methyl ester of karanja oil and WPO10 and diesel.

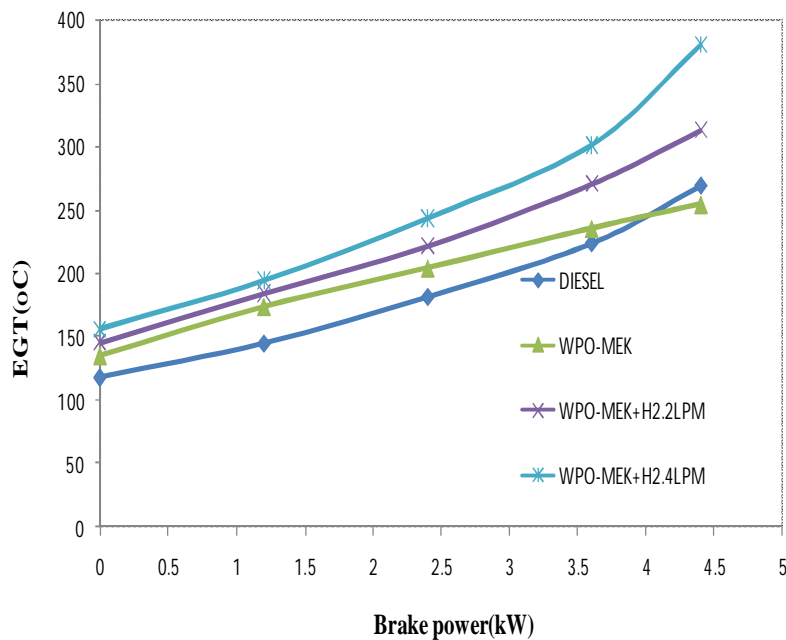


Fig 10 Variations exhaust gas temperature with brake power

4.2 EMISSION PARAMETERS

4.2.1 HYDRO CARBON EMISSIONS

The HC emission of wpo10–methyl ester of karanja oil is lower compared to diesel and wpo10–methyl ester of karanja oil with hydrogen is lower compared without hydrogen [17]. Since hydrogen has no carbon, burning of hydrogen along with wpo10 and wpo10–methyl ester of karanja oil leads to reduced hydrocarbon level. Some HC emission is found because of carbon present in lubricating oil as well as WPO-MEK blend. And also because of high cylinder temperature the carbon particles, present in lubricating oil and main fuel, gets oxidises and converted into CO₂.

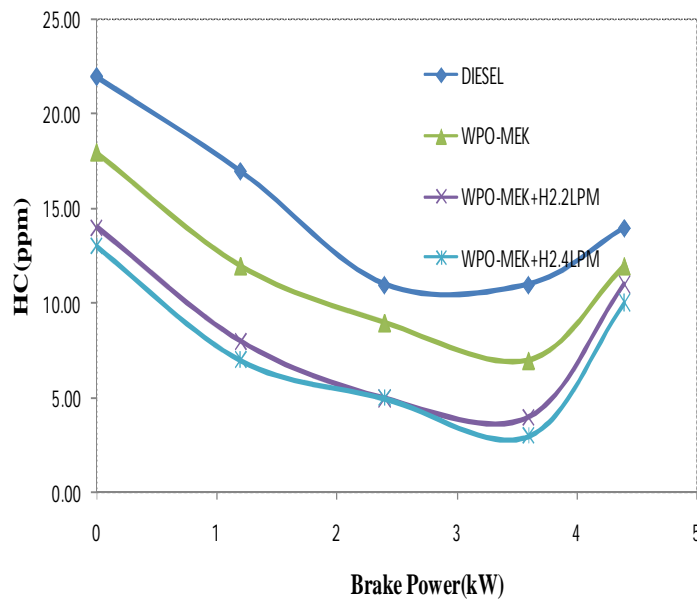


Fig 11 Variation of hydrocarbon emission with brake power

4.2.2 CARBON MONOXIDE EMISSIONS

The variation of the carbon monoxide with hydrogen enrichment at all loads is shown in the fig 12. It is found that the carbon monoxide was decreased with increase in hydrogen addition. At all the loads induction of hydrogen lowers CO levels [18]. At full load the carbon monoxide was 0.01%, and 0.01% with diesel and wpo10–methyl ester of karanja oil. The carbon monoxide was 0.008% and 0.007% with hydrogen enrichment of 2lpm and 4lpm respectively. The reason for lower CO emission is due to absence of carbon atoms in the hydrogen structure.

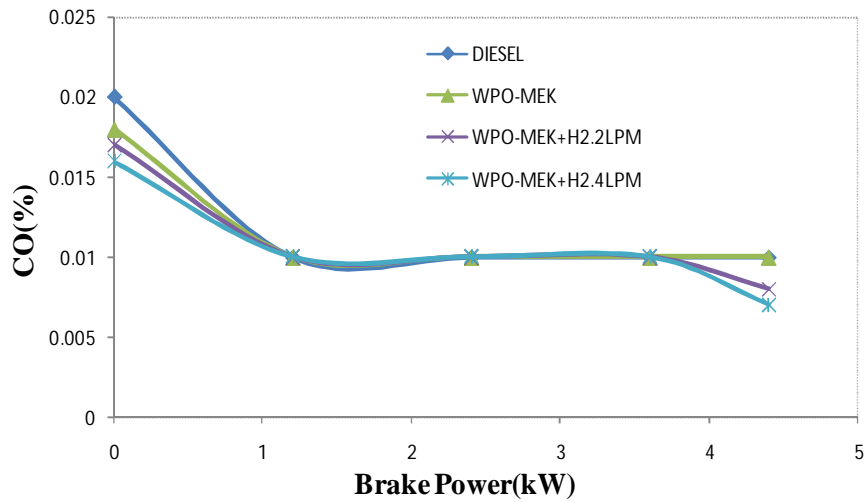


Fig 12 Variation of the carbon monoxide with brake power

4.2.3 CARBON DIOXIDE

The variation of carbon dioxide with brake power is shown in fig 13. While using hydrogen due to high temperature achieved during combustion, the CO get oxidized and converted into CO₂. Therefore the carbon dioxide emission increases with increase in hydrogen flow rate [27] because all CO gets oxidizes and converted into CO₂ after utilizing the heat of hydrogen. At full load the carbon dioxide emission is 0.65% for diesel. And at full load the carbon dioxide emission is 1.9% for wpo10-methyl ester of karanja oil without hydrogen. With hydrogen 2lpm and 4lpm the carbon dioxide emission is 1.78% and 1.6% respectively.

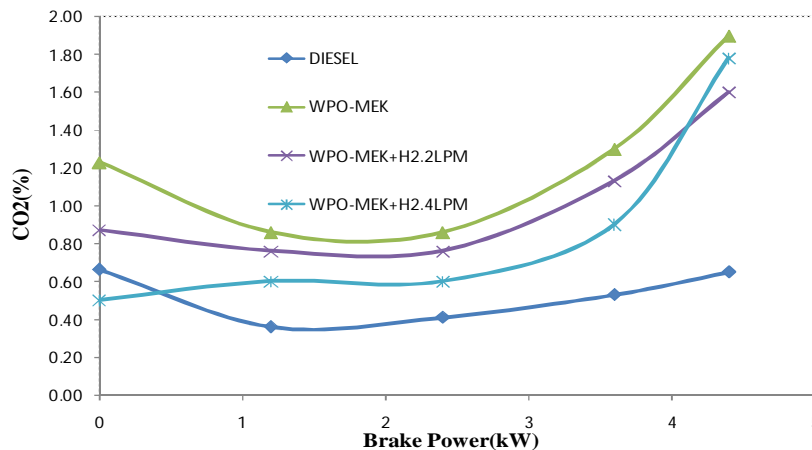


Fig 13 Variation of carbon dioxide with brake power

4.2.4 NO EMISSION

The variation of oxides of nitrogen with respect to the brake power with hydrogen enrichment is shown in fig 14. The formation of oxides of nitrogen is due to the following reasons [20].

- The peak combustion temperature.
- The oxygen concentration in the combustion chamber.
- The residence time of high temperature gas in the cylinder.

The NO values were 318 ppm and 481 ppm with diesel and wpo10-methyl ester of Karanja oil operation respectively at full load. The NO values were 523 ppm and 550 ppm with 2lpm and 4lpm hydrogen enrichment at full load.

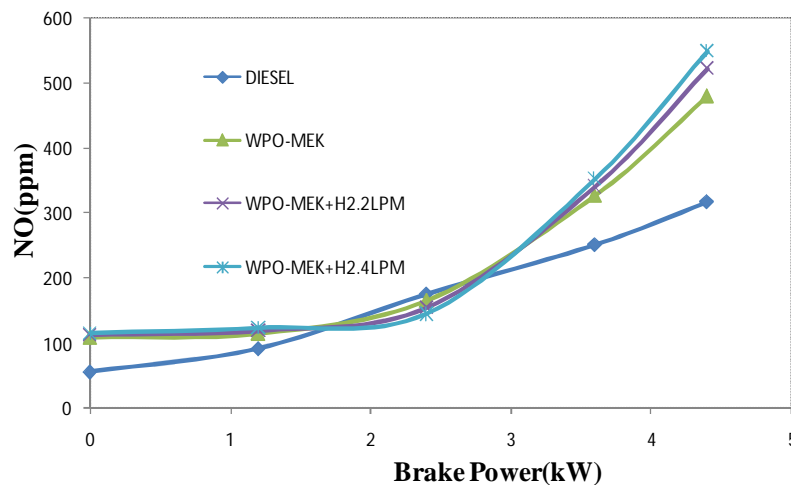


Fig 14 Variation of oxides of nitrogen with the brake power

4.3 COMBUSTION EMISSIONS PARAMETERS

4.3.1. CRANK ANGLE WITH PRESSURE

The fig 15 shows the variation of cylinder pressure with crank angle. Inducting hydrogen compared to that of while Diesel operation. The advantage in attaining peak pressure is due to high rate of pressure rise [19]. The advancement in peak pressures while inducting hydrogen because of instantaneous combustion the peak pressure for diesel operation at full load is 75.7 bar at 12 degrees after TDC. WPO at full load the peak pressure 83.4 bar at 11degrees after TDC.

Peak pressure for WPO-MEK 2lpm hydrogen flow rates are 84.78 bar at 11 degrees after TDC and 4lpm of hydrogen induction, 87.54 bar at 10 degrees after TDC,

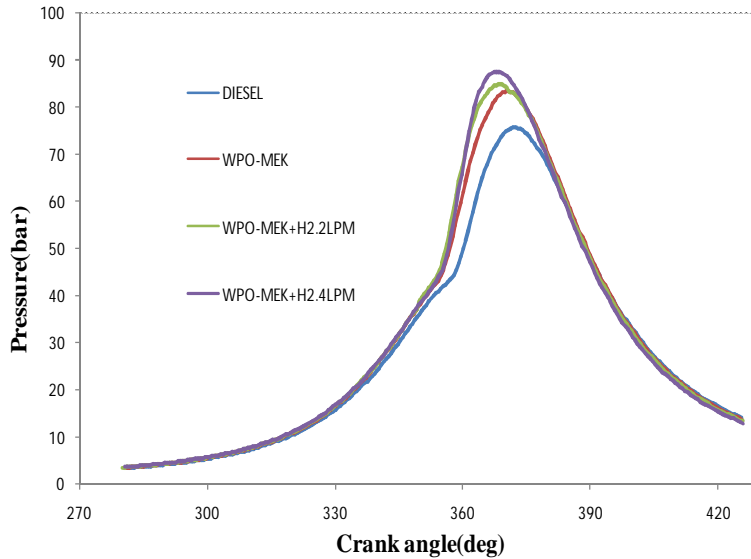


Fig 15 Variation of the crank angle with pressure

4.3.2 IGNITION DELAY

The variation of ignition delay with brake power is given in fig 16. It is found that the ignition delay was decreased with increase in hydrogen addition. The ignition delay is the time difference between the start of injection and ignition in compression ignition engines. Due to high auto ignition temperature of hydrogen, all the hydrogen enriched fuel shows more ignition delay [21]. But at full load the ignition delay for hydrogen enriched fuel is found to be low because high heating value of hydrogen. Once the hydrogen is burned, then there is no problem arises for the further mixture to ignite. Due to its high auto ignition temperature, initially at zero load and part load it takes time to ignite. So at zero load and part load ignition delay is found to be high. At full load the ignition delay was 11.43°CA and 10.41°CA with diesel and wpo10-methyl ester of karanja oil. The ignition delay was 9.97°CA and 9.52°CA wpo10-methyl ester of karanja oil blended with hydrogen enrichment of 2lpm and 4lpm respectively.

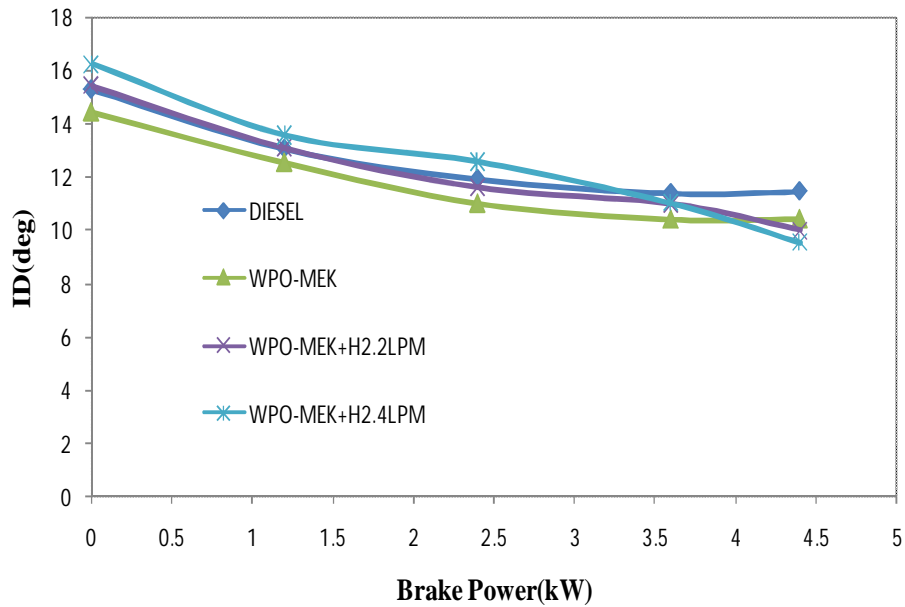


Fig 16 Variation of the ignition delay with brake power

4.3.3 PEAK PRESSURE

The variation of the cylinder peak pressure with hydrogen enrichment at full load is shown in fig 17. It is found that the peak pressure was increased with increase in hydrogen addition. The presence of hydrogen makes WPO10-methyl ester of karanja oil to burn rapidly and increased the peak pressure [26]. At full load the peak pressure was 78.17 bars, and 83 bar with diesel and wpo10- methyl ester of karanja oil blend. The peak pressure of WPO10-methyl ester of karanja oil was 85.45 bar and 87.53 bar with hydrogen enrichment of 2lpm and 4lpm respectively.

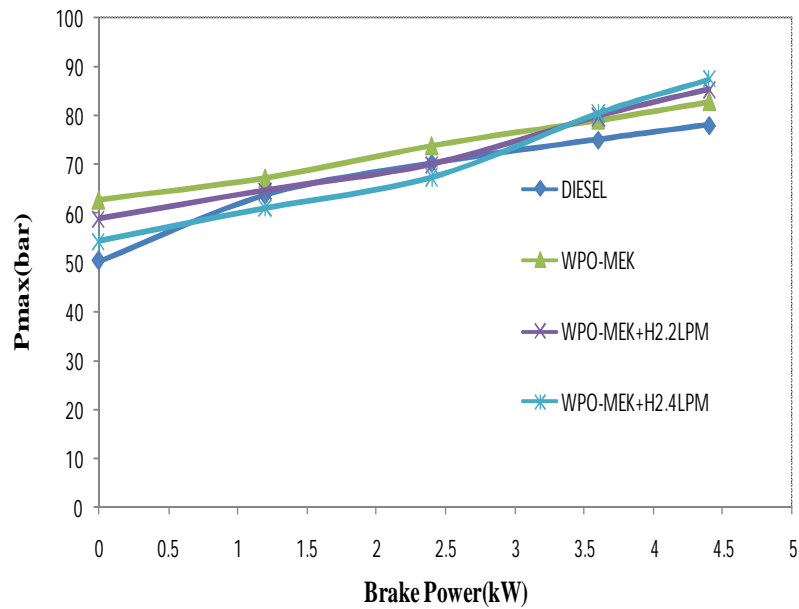


Fig 17 Variation of the cylinder peak pressure with brake power

4.3.4. HEAT RELEASE RATE

The Variation heat release rate shows for hydrogen induction shows a brief premixed combustion phase, followed by slightly higher diffusion combustion phase than diesel fuel [21].

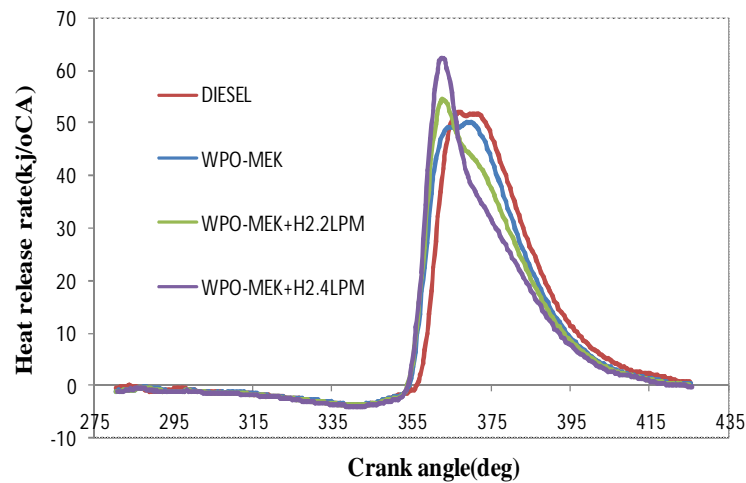


Fig 18 Heat release rate with crank angle

The highest rate of heat release for diesel is 52 J/deg CA. the heat released rate for diesel operation at full load is is 52 J/deg CA. WPO at full load the heat released rate is 50.18 J/deg CA. heat released rate for WPO-MEK WITH hydrogen flow rate at 2lpm is 54.5 J/deg CA. And also 4lpm flow rate of hydrogen the heat release rate is 62.47 J/deg CA while hydrogen inducting higher heat release rate is achieved in advance due to instantaneous combustion of gaseous fuel

CONCLUSIONS AND FUTURE WORK

Conclusions

Future work

5.1 CONCLUSION

The following are the conclusion from the results obtained after experimentations while running single cylinder four stroke, air cooled DI diesel engine fuelled with blending of methyl ester of karanja oil-wood pyrolesses oil respectively with and without hydrogen at different flow rate. The results obtained were compared with diesel fuel.

1. Karanja oil is widely used in soaps, leather tanning and topical liniments. It's utilized agriculturally as well, because it's a good natural pest repellent. Karanja oil is cold pressed from seeds. The oil is reddish brown and rather viscous and non-edible. A truly useful plant, the beautiful karanja has been valued for many centuries in its native India.

3. **BTE** The brake thermal efficiency was 28.64% and 32.02% with diesel and wpo10 and methyl ester of karanja oil operation respectively at full load. MEK oil has less viscosity and better volatility compared to diesel which causes better injection, mixing and evaporation characteristics results in a increasing in brake thermal efficiency. The brake thermal efficiency was 36.5%, 38.5% with 2lpm and 4lpm hydrogen enrichment at full load. The high flame velocity of hydrogen contributed to better mixing of methyl ester oil with air which leads to improvements in thermal efficiency. The maximum thermal efficiency was recorded with 4lpm hydrogen enrichment.

4. **BSEC** It was found that brake specific energy consumption fuel decreased as hydrogen enrichment increased. The BSEC decreased at high load is due to the premixing of hydrogen fuel with air. The BSEC 13.23 (Mj/Kw-hr) and 13.57 (Mj/Kw-hr) with diesel and wpo10 oil operation respectively at full load. The BSEC was 10.75 (Mj/Kw-hr) and 9.35 (Mj/Kw-hr) with 2lpm and 4lpm hydrogen enrichment at full load.

5. EGT The exhaust gas temperature of 310 °c is reached at 2lpm hydrogen enrichment at full load condition. The exhaust gas temperature of 380 °c is reached at 4lpm hydrogen enrichment at full load condition. The graph shows that complete combustion was taking place after enrichment of hydrogen in to the engine. Due to hydrogen enrichment the peak combustion temperature increases.

6. CO It's found that the carbon monoxide was decreased with increase in hydrogen addition. At all loads induction of hydrogen lowers CO levels. At full load the carbon monoxide was 0.01%, and 0.01% with diesel and WPO10. The carbon monoxide was 0.008% and 0.007% with hydrogen enrichment of 2lpm and 4lpm respectively.

7. HC The HC emission of wpo10–methyl ester of karanja oil is lower compared to diesel and wpo10-methyl ester of karanja oil with hydrogen is lower compared without hydrogen. However, the dual fuel operation reduces the hydrocarbon emissions considerably. Since hydrogen has no carbon, burning of hydrogen along with wpo10 and wpo10-methyl ester of karanja oil leads to reduced hydrocarbon level.

8. NO the NO 318 (ppm) and 481 (ppm) with diesel and wpo10-methyl ester of Karanja oil operation respectively at full load. The NO was 523 (ppm) and 550 (ppm) with 2lpm and 4lpm hydrogen enrichment at full load. Due to the oxygen concentration in the combustion chamber. And high peak combustion temperature.

9. Ignition delay Due to high self ignition temperature of hydrogen, all the hydrogen enriched fuel shows less ignition delay. At full load the ignition delay was 11.43°, and 10.41° with diesel and wpo10-methyl ester of karanja oil. The ignition delay was 9.97° and 9.52° wpo10-methyl ester of karanja oil blend with hydrogen enrichment of 2lpm and 4lpm respectively.

10. Peak pressure the presence of hydrogen makes wpo10-methyl ester of karanja oil to burn rapidly and increased the peak pressure. At full load the peak pressure was 78.17 bars, and 83 bar with diesel and wpo10- methyl ester of karanja oil blend. The peak pressure of wpo10-methyl ester of karanja oil was 85.45 bar and 87.53 bar with hydrogen enrichment of 2lpm and 4lpm respectively.

11. A brief premixed combustion phase, followed by slightly higher diffusion combustion phase than diesel fuel. The highest rate of heat release for diesel is 52 J/deg CA. the heat released rate for diesel operation at full load is is 52 J/deg CA. WPO at full load the heat released rate is 50.18 J/deg CA. heat released rate foe WPO-MEK WITH hydrogen flow rate at 2lpm is 54.5 J/deg CA. And also 4lpm flow rate of hydrogen the heat release rate is 62.47 J/deg CA while hydrogen inducting higher heat release rate is achieved in advance due to instantaneous combustion of gaseous fuel.

5.2 SCOPE FOR FUTURE WORK;

- (i) Nitric oxide emission was found more in 4lpm. Therefore, NO emission can be controlled by adopting exhaust gas recirculation method.
- (ii) Different surfactants can be tried to get the emulsion of WPO with karanja methyl ester at higher concentrations.

REFERENCES

LIST OF REFERENCES

- [1]. Gupta,"Hydrogen fuel-Production, storage and transportation", *CRC Press publication Taylor and Francis group, ISBN 978-1-4200-4575-8, pp 1-12.*
- [2] krawczyk, T., 'Biodiesel: alternative fuel makes inroads but hurdles remain,' *inform, 7, pp. 801-81,1996,*
- [3] knothe, G., Dunn, R. O., and bagby, M, O., 'technical aspects of biodiesel standards,' *inform, 7, pp., 827-829,1996*
- [4] van Dyne, D, L., Weber, j. A., 'macroeconomic effect of a community based biodiesel production system,' *Vol...56, pp.1-6, 1996,*
- [5] korbitz, W., biodiesel production in Europe and north America, an encouraging prospect,' *Vol...16, pp., 1078-1083, 1999.*
- [6] Banapurmath NR, Tewari PG, Hosmath RS. Performance and emission characteristics of a DI compression ignition engine operated on honge, jatropha and sesame oil methyl ester. *Renewable energy ;33:1982-1988, 2008.*
- [7]. Suryawanshi JG, deshpanel N. Experimental investigation on a pongaamia oil methyl ester fuelled diesel engine. *SAE paper 2004-28-008;2004.*
- [8].kaltschmitt, M., Reinhardt, G., A., and stelzer , T.,' life cycle analysis of biofuel under different environment aspect,' *Vol..12, pp.121-134, 1997.*
- [9]. Vivek and A K Gupta, biodiesel production from karanja oil, journal of scientific and industrial research *Vol...63, pp 39-47, januvary 2004.*
- [10]. Suresh kumar, Gupta A K and nail S n, conversion of non edible oil into biodiesel, *j sci ind res, 62 pp,124-132, 2002.*
- [11]. Mohamad i. Al-widayam and tashtoush ghasan, utilization of ethyl ester of waste vegetable oil as fuel in diesel engines. *Fuel process technol, 76, pp 91-103, 2002.*
- [12]L.M. Das, "Hydrogen engines: A view of the past and a look into the future", *Int. J. Hydrogen Energy, Vol 15,pp 425-443,1990.*
- [13]L.M. Das, "Safety aspects of a hydrogen fuelled engine system development", *Int. J. Hydrogen Energy, Vol 16,pp 619-624,1991.*
- [14]L.M. Das,"Fuel induction techniques for a hydrogen operated engine", *Int. J. Hydrogen Energy, Vol...15, pp 833-842, 1990.*

- [15].V.Ganeshan,"A textbook on Internal Combustion Engines", 2nd edition, *ISBN 0-07-049457-6*, pp 220-223
- [16]N.Saravanan, G.Nagarajan, S. Narayanswamy,"An experimental investigation of DI diesel engine with hydrogen fuel", *Renewable Energy 33*, pp 415-421, 2008.
- [17]N.Saravanan, G.Nagarajan, K.M.Kalaiselvan, C.Dhanasekaran,"An experimental investigation on hydrogen as a dual fuel for engine system with exhaust gas recirculation technique" *Renewable Energy 33*, pp 422-427, 2008.
- [18]N. Saravanan, G. Nagarajan, "Performance and emission studies on port injection of hydrogen with varied flow rates with diesel as an ignition source", *Applied Energy, Vol.87*, pp 2218-2229, 2010.
- [19]N. Saravanan, G. Nagarajan, G. Sanjay, C. Dhanasekaran, K.M. Kalaiselvan, "Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode", *Fuel 87*,pp 3591-3599, 2008.
- [20]Li Jing-Ding, Lu Ying-Qing and Du Tian-Shen, "Improvement on the combustion of a hydrogen fuelled engine", *Int. J. Hydrogen Energy, Vol 11.No.10*,pp 661-668, 1986.
- [21]J.M.Gomes Antunes, R. Mikalsen, A.P. Roskilly, "An experimental study of a direct injection compression ignition hydrogen engine", *Int. J. Hydrogen Energy Vol 34*,pp 6516-6522,2009.
- [22]L.M. Das, "Exhaust emission characterization of hydrogen operated engine system: Nature of pollutants and their control techniques", *Int. J. Hydrogen Energy, Vol 16*,pp 765-775,1991.
- [23]H.B. Mathur, L.M. Das and T.N. Patro, "Hydrogen fuelled diesel engine: Performance improvement through charge dilution techniques", *Int. J. Hydrogen Energy, Vol. 18*,pp 421-431,1993.
- [24]H.B. Mathur, L.M. Das and T.N. Patro, "Effects of charge diluents on the emission characteristics of a hydrogen fuelled diesel engine", *Int. J. Hydrogen Energy, Vol. 17* ,pp 635-642,1992.
- [25]M. Senthil Kumar, A. Ramesh, B. Nagalingam," Use of hydrogen to enhance the performance of a vegetable oil fuelled compression ignition engine," *Int. J. Hydrogen Energy 28* ,pp 1143-1154, 2003.
- [26]J.Nazar,A.Ramesh and B.Nagalingam,"Experimental investigation on the performance of karanja oil-hydrogen dual fuel engine".Proceedings of the 19th National Conference on I.C. Engines and Combustion, *Annamalai University,Chidambaram*, pp 131-136, 2005.
- [27]G.Sankaranarayanan,J.Jayaraj,N.Saravanan,K.Jeyachandran,"Performance and emission studies on DI diesel engine using madhuca indica oil and hydrogen as dual fuel", Proceedings of the 19th National Conference on I.C. Engines and Combustion, *Annamalai university,Chidambaram*, pp 83-86, 2005.