



A Comparative study on Diesel Engine Performance operating with Biodiesel (with & without Hydrogen as an Inductive fuel) and Diesel

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Abstract: The main objective of this research is to compare the performance of diesel engine operating with diesel; biodiesel and biodiesel enriched with hydrogen as the inducted fuel to overcome the problems created by Biodiesel. Analysis was carried out for various parameters like Performance, Emission and Combustion emission parameters. The brake thermal efficiency was increased with the utilization of Biodiesel enriched with hydrogen. And brake specific energy consumption fuel decreased as hydrogen enrichment increased. Peak combustion temperature increases and the carbon monoxide emission decreases with increase in hydrogen addition. All the hydrogen enriched fuel shows less ignition delay. The maximum thermal efficiency was recorded with hydrogen enrichment. Finally the comparative study proves that use of Biodiesel fuel with hydrogen as inductive fuel is more efficient than diesel fuel and Biodiesel without hydrogen enrichment.

Index Terms— Biodiesel; Hydrogen; Emissions; Efficiency; Combustion; Inductive Fuel

1. INTRODUCTION

In recent years, due to reduction of finite petroleum resources, and both environmental pollution criteria, researchers give to particularly a distinct importance on the usage of alternative fuels in internal combustion engines (ICEs). Emission from engine exhaust is serious problem for environment point of view. For that search for alternative fuel is encouraged. In view of the fast depletion of fossil fuel, the search for alternative fuels has become inevitable, looking at huge demand of diesel for transportation sector, captive power generation and agricultural sector, the biodiesel is being viewed a substitute of diesel.

The main problems with the use of Bio diesel in engines are higher smoke levels, higher viscosity 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 Bio 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 with different quantities of hydrogen being inducted.

Compression Ignition engines have become an indispensable part of modern life style because of their role in transportation and mechanized agriculture sector. The dwindling sources of conventional fossil fuels, their ever increasing demand and prices have prompted the scientists and researchers to find alternate fuels for diesel engines. Known crude oil reserves are estimated to be exhausted in less than 50 years at present rate of consumption. Consequently, countries lacking such resources are facing foreign exchange crisis, mainly due to the import of the fuels [1]. A number of alternative fuels such as ethanol, methanol, hydrogen, Compressed Natural Gas (CNG), liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Dimethyl-ether (DME) and vegetable oils have been used as alternative fuels, however biodiesel has received a considerable attention to be used as a substitute fuel for conventional petroleum.

Biodiesel has already been commercialized in the transport sector and can be used in diesel engines with little or no modification [2]. Biodiesel and its blends with conventional diesel are environment friendly and their use in diesel engine results in reduced exhaust pollutants as compared to conventional diesel fuel [3]. It is well known that biodiesel is a carbon –neutral fuel and its global use will result in diminution of green house gas emission [4]. Rudolf Diesel, the inventor of diesel engine, is the first who used peanut oil as alternative fuel for diesel engine at the 1900



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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 times as important as petroleum and the coal tar products of present times" [5]. However, the undesirable injection and combustion problems caused by the higher viscosity of neat vegetable oils were the main obstacles in their use as alternative fuel. This issue has been resolved by using some suitable techniques like dilution, pyrolysis, transesterification, preheating and emulsion to get methyl esters of such oils [6]. These methyl esters of animal and vegetable oils are called biodiesel, and are being investigated for use as fuel for modern diesel engines due to their cleaner burning tendency and environmental benefits.

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

Properties	Diesel	Vegetable oil
Viscosity at 30 °C	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

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 anaerobically to obtain a gaseous fuel called bio gas.

VEGETABLE OILS AS ALTERNATIVE FUELS IN CI ENGINES

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 to 18 whereas vegetable oil molecules are triglycerides generally with no branched chains of different lengths and different degrees of saturation. It may be 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.

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.

Comparative properties of Vegetable oil and Diesel

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.

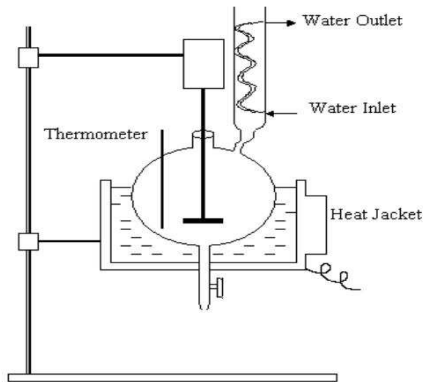


Fig . Experimental set up of biodiesel production

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.

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.

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.

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.

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

EXPERIMENTAL INVESTIGATION

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.

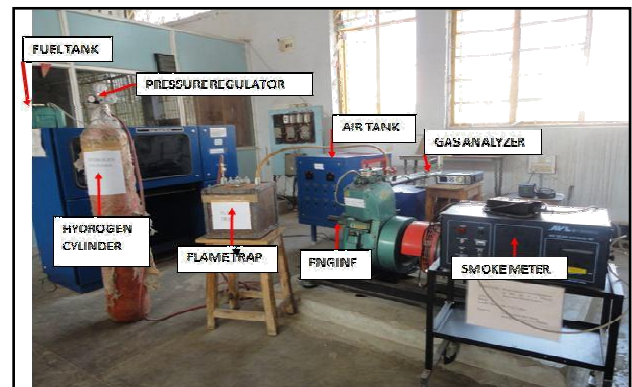


Fig : Schematic representation of the engine experimental set up
Test engine specification

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.

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

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	200-205



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- c. Inlet Connection: 5/8" BSP (M) LH
- Outlet Connection: ¼ inches OD Tub
- d. Gas Service: Hydrogen

3750 12.24 0.328 12.568 97.3 2.6

FLAME TRAP

Flame traps are used in a internal combustion engines. The flame trap is jest 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.

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).

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 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).

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).

Energy share between hydrogen 1bar WPO-MEK (kw)

Load	Energy by fuel	Energy share by hydrogen	Total energy share	%Energy share 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

Energy share between hydrogen 2 bars and WPO-MEK

Load	Energy by fuel	Energy share by hydrogen	Total energy share	%Energy share fuel	% Energy share by hydrogen
0	2.136	0.656	2.792	76.5	23.4
1000	4.272	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

RESULTS & DISCUSSION:

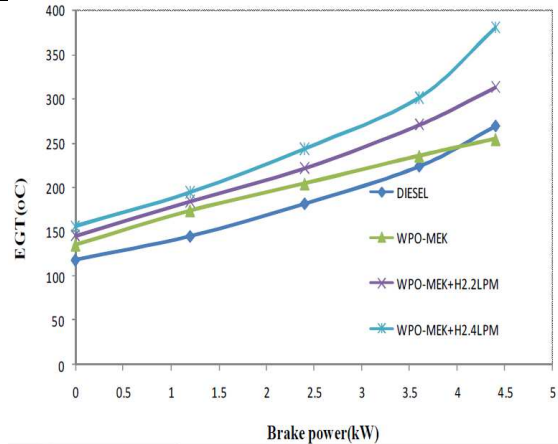
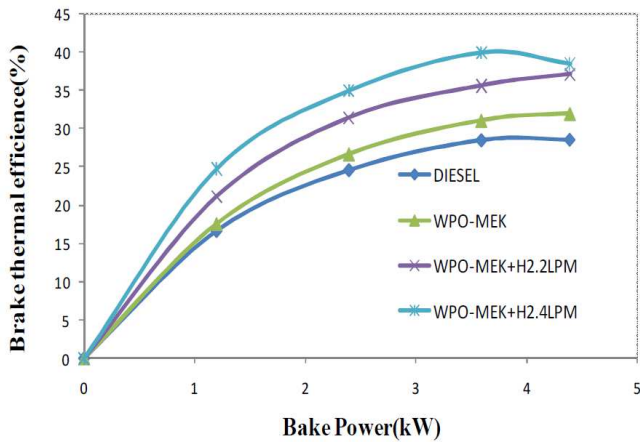
In the present work, hydrogen gas- air mixture was used in the compression ignition engine where WPO10-methyl ester of karanja oil respectively was used as a main fuel in the operation. The performance, emission and combustion characteristics of WPO10 - methyl ester of karanja oil with hydrogen enrichment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

PERFORMANCE PARAMETERS

BRAKE THERMAL EFFICIENCY

The Variations of brake thermal efficiency with brake power shown in Fig . The brake thermal efficiency was 28.64% and 32.02% with diesel andWPO10 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.

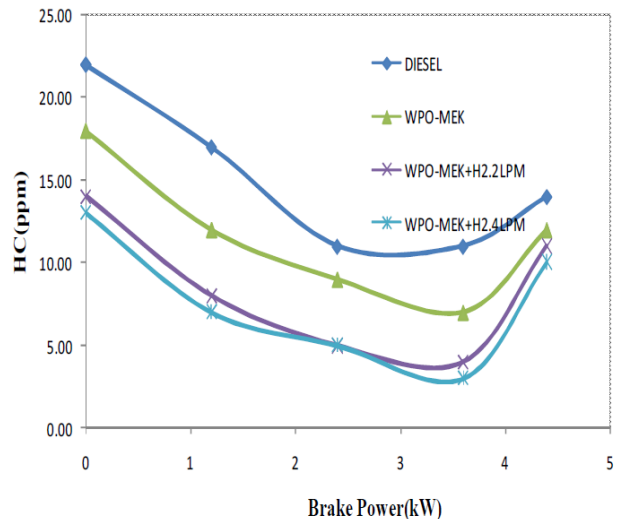
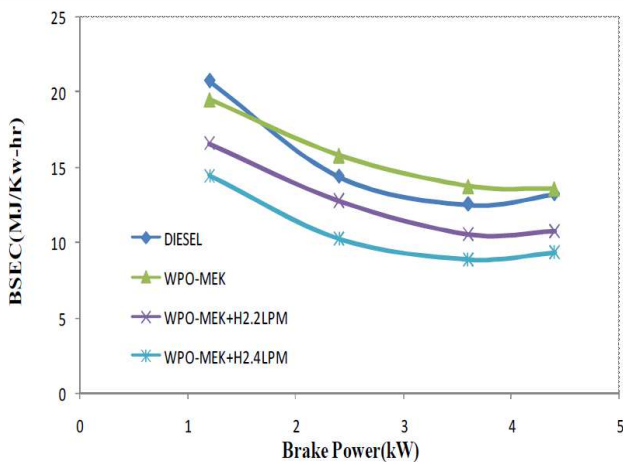


BRAKE SPECIFIC ENERGY CONSUMPTION

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. 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.

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.

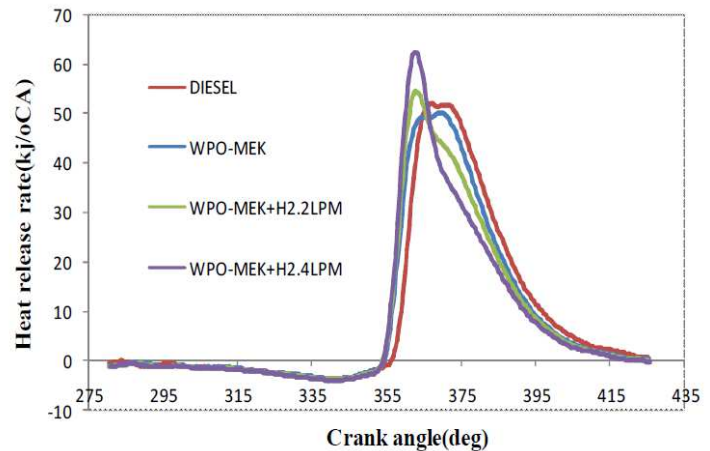
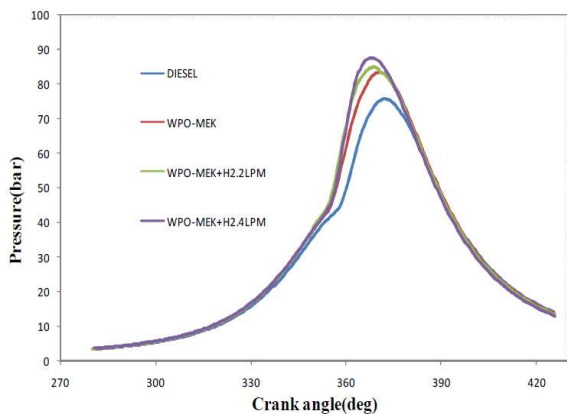


EXHAUST GAS TEMPERATURE

The variation exhaust gas temperature with brake power is shown in fig. 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.

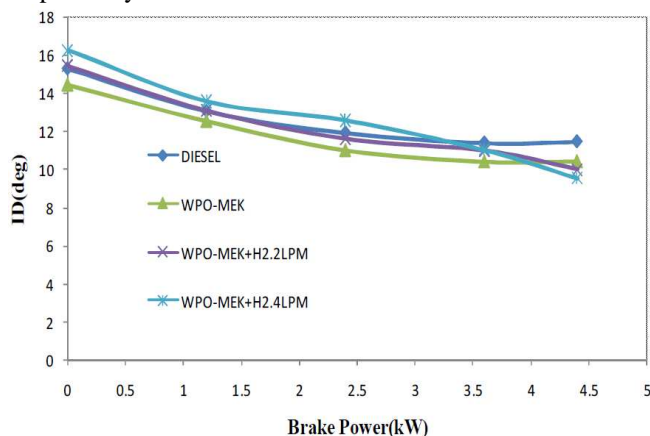
CRANK ANGLE WITH PRESSURE

The fig 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 11 degrees 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,



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.



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

The highest rate of heat release for diesel is 52 J/deg CA. the heat released rate for diesel operation at full load 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 inducing higher heat release rate is achieved in advance due to instantaneous combustion of gaseous fuel

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 diesel, biodiesel with and without hydrogen at different flow rate. The results obtained were compared with diesel fuel.

1. The brake thermal efficiency was 28.64% and 32.02% with diesel and biodiesel operation respectively at full load. 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.
2. 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.
3. It is found that the carbon monoxide was decreased with increase in hydrogen addition. At all loads, the induction of hydrogen lowers the CO levels. The HC emission of Biodiesel is lower compared to diesel and
4. The NO content is 318 (ppm) and 481 (ppm) with diesel and Biodiesel 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.
5. Ignition delay due to high self ignition temperature of hydrogen, all the hydrogen enriched fuel shows less ignition



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delay. At full load the ignition delay was 11.43° , and 10.41° with diesel and Biodiesel

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