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EXPERIMENTAL INVESTIGATIONS ON THE EFFECT OF HYDROGEN INDUCTION ON PERFORMANCE AND EMISSION BEHAVIOUR OF A SINGLE CYLINDER DIESEL ENGINE FUELLED WITH PALM OIL METHYL ESTER AND ITS BLEND WITH DIESEL

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Abstract

Internal combustion engines are an integral part of our daily lives, especially in the agricultural and transportation sector. With depleting fossil fuel and increasing environmental pollution, the researchers are foraying into alternate sources for fuelling the internal combustion engine. Vegetable oils derived from plant seeds is one such solution, but using them in unmodified diesel engine leads to reduced thermal efficiency and increased smoke emissions. Hydrogen if induced in small quantities in the air intake manifold can enhance the engine performance running on biodiesel. In this work, experiments were performed to evaluate the engine performance when hydrogen was inducted in small quantities and blends of esterified palm oil and diesel was injected as pilot fuel in the conventional manner. Tests were performed on a single cylinder, 4 - stroke, water cooled, direct injection diesel engine running at constant speed of 1500 rpm under variable load conditions and varying hydrogen flow. At full load for 75D25POME (a blend of 75% diesel and 25% palm oil methyl ester by volume), the results indicated an increase in brake thermal efficiency from 29.75% with zero hydrogen flow to a maximum of 30.17% at 5lpm hydrogen flow rate. HC emission reduced from 34 to 31.5 ppm, by volume at maximum load. Whereas, CO emission reduced from 0.09 to 0.045 % by volume at maximum load. Due to higher combustion rates with hydrogen induction, NOx emission increased from 756 to 926 ppm, at maximum load.

Keywords: CI engine, Dual fuel, Hydrogen, Palm oil, Palm oil methyl ester.

Abbreviations

BSEC	Brake Specific Energy Consumption
BTE	Brake Thermal Efficiency
CI	Compression Ignition
CO	Carbon Monoxide
HC	Unburned Hydrocarbon
HRR	Heat Release Rate
NOx	Oxides of Nitrogen
POME	Palm Oil Methyl Ester
TMI	Throttle Manifold Injection
TPI	Throttle Port Injection

1. Introduction

Diesel engines have been used in transportation sector, agriculture sector and as power backups where there is acute shortage of electricity. They are highly popular because of their high brake thermal efficiency, highly reliable and ease of maintenance. However, they suffer from rising fuel prices, fossil fuel depletion and stricter emission norms. This has triggered an intensive research by the scientists all over the world to foray into alternative fuel resources [1-3]. The best alternative fuel source for compression ignition (CI) engines is vegetable oil. Researchers have extracted oil from the seeds of plants like jatropha, karanji, rubber, honge, sesame, and poon and from edible plants like peanut, palm, soyabean, rapeseed and cottonseed [4-12]. In India, these seeds are readily available in large quantities such that their usage in CI engine as fuel can reduce the dependency on petroleum imports.

Vegetable oils when used in diesel engines produce almost same power, with a slight decrease in thermal efficiency and increase in emissions. Researchers also found that engine's long term durability is adversely affected due to high viscosity, low volatility and reactivity of unsaturated hydrocarbon chains. High viscosity is a pre dominant factor as it causes excessive carbon deposits and ring sticking [2]. Transesterification and dual fuel operation methods have been found suitable for using vegetable oils in diesel engines [2, 13]. Transesterification process reduces the viscosity of oil so that the problems of atomizing the fuel and mixing of fuel with air can be reduced [1]. Operation of diesel engines in dual fuel mode reduces smoke and increases brake thermal efficiency [13].

An engine can be used as a dual fuel engine, without major modifications. The dual fuel mode is achieved by injecting a secondary volatile liquid fuel or gaseous fuel into the inlet manifold which is ignited by diesel or vegetable oil or blend of diesel and vegetable oil as main fuel [14-17]. Hydrogen is front-runner in dual fuel operation as it is less polluting and renewable. Hydrogen has been adapted as both SI and CI engine fuel by various researchers [13, 18, 19]. Hydrogen has high flammability limit and it burns in air at a concentration of 4-75% by volume (Table 1). Hence, wide range of fuel air mixtures is used for combustion in hydrogen engine. Hydrogen has higher burning velocity which helps in overcoming lower combustion rate of vegetable oils in dual fuel mode. It can also help in reducing the emissions because of near complete combustion of the charge [14].

Table 1. Properties of fuels.

Property	Gasoline	Diesel	Hydrogen
Density at 1 atm. & 15°C (kg/m^3)	721-785	833-881	0.0898
Stoichiometric A/F	14.8	14.5	34.3
Flammability Limits (Vol.% in air)	1.4 - 7.6	0.6 - 7.5	4 - 75
Auto Ignition Temperature (°C)	246 - 280	210	585
LCV at 1 atm. & 15°C (kJ/kg)	44500	42500	120,000

Saravanan [20] studied a direct injection dual-fuel diesel engine with hydrogen fuel using carburetion technique, Timed Port Injection Technique (TPI) and Timed Manifold Injection (TMI). The author observed that the engine was unstable during late injection (30° after gas exchange TDC) especially at higher loads, with 90°CA injection duration and engine started knocking at hydrogen flow rates greater than 25lpm. Smoke emissions increased at full load with hydrogen flow rate greater than 20lpm in port and manifold injection. The BTE and peak HRR were high for both port and manifold injection modes. BTE for carburetion mode was found to be lower, as compared to neat diesel operation. BSFC was found to decrease. NOx was found to be higher for both timed port injection (TPI) and timed manifold injection (TMI) modes. HC, CO, CO_2 and smoke emissions were reduced with all the three modes. Kose et al. [13] used a four cylinder, 3.9 litre, turbocharged diesel engine to study the effect of inlet manifold induced hydrogen on the engine performance and emission. The author observed increase in brake thermal efficiency and exhaust gas temperature due to higher flame speed resulting in complete combustion. Decrease in unburned hydrocarbon and carbon monoxide emission was also observed.

Dual fuel operation in a diesel engine with hydrogen induction using vegetable oil is one of the ways to reduce emissions from the diesel engine and also increase the thermal efficiency of the engine. Senthil Kumar et al. [15] used waste cooking oil and waste cooking oil emulsion as primary fuel in a hydrogen inducted dual fuel diesel operation. The authors concluded that by inducting small quantities of hydrogen along with air improved the engine performance and reduced emissions, but there were no advantages of adding hydrogen at low power output. Edwin Geo et al. [16] used rubber seed oil for dual fuel operation with hydrogen. The authors observed reduction in HC, CO and smoke levels at all loads. With increase in hydrogen energy content brake thermal efficiency, exhaust gas temperature were found to increase. At higher loads cylinder pressure and maximum rate of pressure rise were higher due to hydrogen's high flame velocity leading to improvement in combustion of vegetable oils. Senthil Kumar et al. [17] also studied the effect of inducting hydrogen in a jatropha oil fuelled diesel engine. The authors reported improvement in brake thermal efficiency and reduction in HC and CO emission, smoke.

In the present work, the performance of palm oil methyl ester (POME) and its blend with diesel in a CI engine is improved using hydrogen induction. Oil palm is an oleaginous tropical plant, which has the highest oil productivity per unit land (Table 2). Palm oil is edible oil that is used to cook; in industry, it is used to produce soap, lubricants, detergents and plastics, and it is used in steel making, textile industry and pharmacology [21].

Table 2. Sources of fuels of plant origin and their yields in oil.

Source	Fuel	Yield (kg oil/hectare)
Babassu palm	Oil	240
Oil palm	Oil	5000
Castor plant	Oil	1600

Locally available commercial diesel fuel was selected for base readings. Esterified palm oil (POME) was blended with diesel in the laboratory to operate a diesel engine. The ratio of blends of palm oil diesel selected were 0% (base reading), 25%, 50%, 75% and 100% on volume basis of palm oil biodiesel in a palm biodiesel - diesel fuel mixture. They are referred to as Diesel (100% diesel fuel - 0% palm oil biodiesel), 75D25POME (75% diesel fuel - 25% palm oil biodiesel), 50D50POME (50% diesel fuel - 50% palm oil biodiesel), 25D75POME (25% diesel fuel - 75% palm oil biodiesel) and 100POME (0% diesel fuel - 100% palm oil biodiesel) respectively. These abbreviations are used throughout the study. The study was conducted in two phases: In the first phase, blends of palm oil biodiesel and diesel were tested on a diesel engine for the measurement of emission and performance parameters. In the second phase, the engine was modified for dual fuel operation using hydrogen as inducted fuel and palm oil biodiesel blends, neat diesel and neat POME as pilot injected fuel. Performance and emission characteristics at 25%, 50%, 75% and 100% load were evaluated with various hydrogen flow rates. Results of dual fuel operation with neat palm oil biodiesel and its blend with diesel and neat diesel are discussed.

2. Experimental Setup

2.1. Biodiesel production

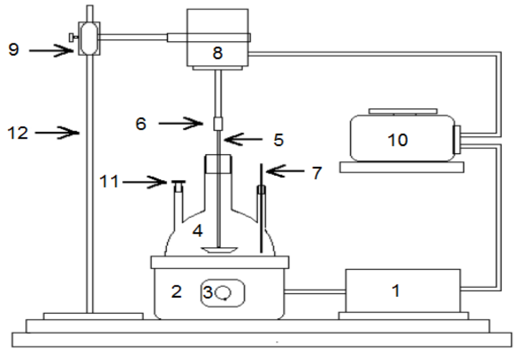
Palm oil biodiesel was produced in the laboratory from raw palm oil using a batch type reactor. 1 Litre of palm oil was added to the batch type reactor (Fig. 1) which is a three necked round bottom flask. A stirrer, which is connected to a DC motor, was placed in the centre neck to stir the reactants. A thermometer was also placed in the reactor to continuously monitor the temperature of the reactants. The reactor was placed on a heating jacket for heating the oil and maintaining the desired temperature of the oil. 14.6 gram of potassium hydroxide was dissolved in 100 ml of methanol separately in a beaker and then it was added to the reactor under constant stirring and the temperature was maintained at 65 - 70°C for 45 minutes. After the completion of the reaction, the mixture was allowed to settle for 12 - 24 hours. Upper layer consists of biodiesel, alcohol, and some soap, which was formed as a result of side reaction saponification - free fatty acids are converted to soap. Lower layer consists of glycerine, excess alcohol, catalyst, impurities, and traces of un-reacted oil. Later a separating funnel was used to separate the methyl ester and respective glycerides. Purification of POME was done by water washing of the separated layer. The biodiesel yield was nearly 85% from raw palm oil; the cost analysis is given in Table 3. Characterized fuel properties, of the obtained biodiesel are shown in Table 4.

Table 3. Cost analysis for 850 ml of POME production.

Type of cost	INR
Palm Oil	40/litre
100 ml Methanol	2
14.6 gm Potassium Hydroxide	8.76
15 ml of conc. H_2SO_4	12
Electricity Cost	4
Total Cost for 850 ml POME oil	66.76

Table 4. Fuel properties.

Fuel property	Diesel	Palm oil	POME
Density @ 15.5^{0}C kg/m^3	840	960	885.2
Kinematic Viscosity @ 40^{0}C cSt	2 - 6	45.7	10.7
Pour Point ^{0}C	-15 to 10	-6	-6
Flash Point ^{0}C	130	253	253
Fire Point ^{0}C	68	273	261
Gross Calorific value in MJ/kg	44.8	41.7	42.4
Acid Content in mg KOH/gm	0.8%	0.17%	0.15%
Calculated Cetane Index (CCI)	47	42	45



1. Power Supply; 2. Heater; 3. Thermostat; 4. Round Bottom Flask; 5. Stirrer; 6. Connector; 7. Thermometer; 8. Stirrer Motor; 9. Slider; 10. Speed Controller; 11. Cap; 12. Stirrer Stand.

Fig. 1. Setup for biodiesel production.

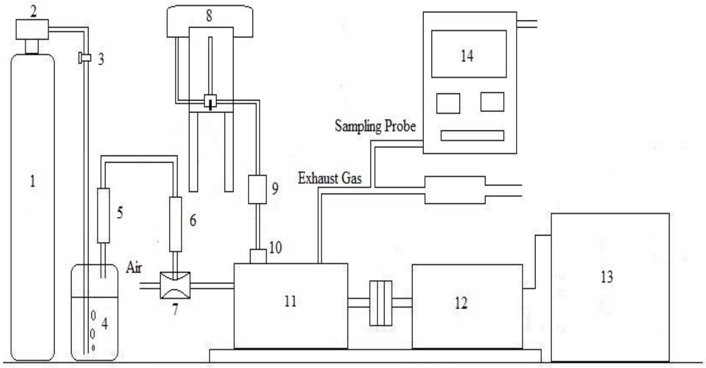
2.2. Engine test setup

A single cylinder, 4 - stroke, water-cooled, direct injection, constant speed, compression ignition engine developing a power output of 3.6 kW at 1500 rpm was used for this work. Schematic of the experimental setup is shown in Fig. 2 and the test engine specification is given in Table 5. An electrical dynamometer was used for loading the engine. A pipe was used to connect hydrogen tank to a specially designed Venturi type gas carburettor placed in the intake manifold. The pipe passed through a water filled flame trap and a dry type flame arrester. Hydrogen flow rate was controlled manually by using a flow control valve. The quantity of hydrogen inducted was measured using a gas flow meter. The carbon monoxide (CO), unburnt hydrocarbon (HC) and oxides of nitrogen (NOx) emissions were measured using a NOVA Model-7465 exhaust gas analyser. Diesel flow rate was measured using a burette and a stopwatch.

The experiments were first conducted on the engine using diesel and blends of diesel with POME as baseline data. The engine performance was evaluated in terms of brake thermal efficiency, brake specific energy consumption and emission characteristics like CO, HC and NOx. Experiments were then conducted by inducting hydrogen in the intake manifold along with air. The engine was loaded from no load to full load in the increments of 25%. The experiments were performed using two fixed hydrogen flow rate of 5 litre per minute (lpm) and 10lpm. Low flow rate of hydrogen was used because with higher flow rates, the probability of engine knocking is more. Also with high flow rate of hydrogen the volumetric efficiency of the engine will reduce thus negating the effect of improvement in efficiency because of hydrogen addition.

Table 5. Test engine specification.

Make	**Kirloskar**
Type	Single Cylinder, CI, 4 - stroke
Brake Power	3.6 kW
Type of Cooling	Water Cooled
Compression Ratio	17.5:1
Bore/Stroke	87.5/110 mm
Cubic Capacity	661.5 cm^3



1. Hydrogen Cylinder; 2. Regulator; 3. Needle Valve; 4. Flame Trap; 5. Flame Arrester; 6. Rotameter; 7. Venturi; 8. Fuel Tank; 9. Fuel Pump; 10. Fuel Injector; 11. Engine; 12. Electrical Dynamometer; 13. Resistance Bank; 14. Emission Analyser.

Fig. 2. Engine test setup.

2.3. Uncertainty in experiment and instrument

Errors and uncertainties in experiments can arise from instrument selection, its condition, and calibration and during observing the readings. Its analysis is needed to prove the accuracy of experiments. Uncertainties were evaluated using Eq. (1).

$$\frac{U_Y}{Y} = \sum_{i=1}^{n}\left(\frac{1}{Y}\frac{\partial Y}{\partial X_i}U_{x_i}\right)^{2^{1/2}} \qquad (1)$$

Here Y is the physical parameter that is dependent on the parameters, x_i. The symbol U_y denotes the uncertainty in Y. By using the above equation the uncertainty of experiments was obtained as 3.05%. The error analysis for the experimental data is given in Table 6.

Table 6. Name of instrument and their uncertainties.

Instrument	Range	Accuracy	Percentage Uncertainty
Load Indicator	0-5kW	±0.08	±0.2
Temperature Indicator	0-900°C	±1°C	±0.15
Speed Sensor	0-10000rpm	±10rpm	±0.1
Burette	0-30cc	±0.1cc	±1
Digital Stop Watch		±0.6s	±0.2
Manometer		±1mm	±1
Exhaust Gas Analyser			
NO (ppm)	0-5000ppm	±10ppm	±0.2
CO (%)	0-10%	±0.02	±0.2
HC (ppm)	0-10000ppm	±20ppm	±0.2

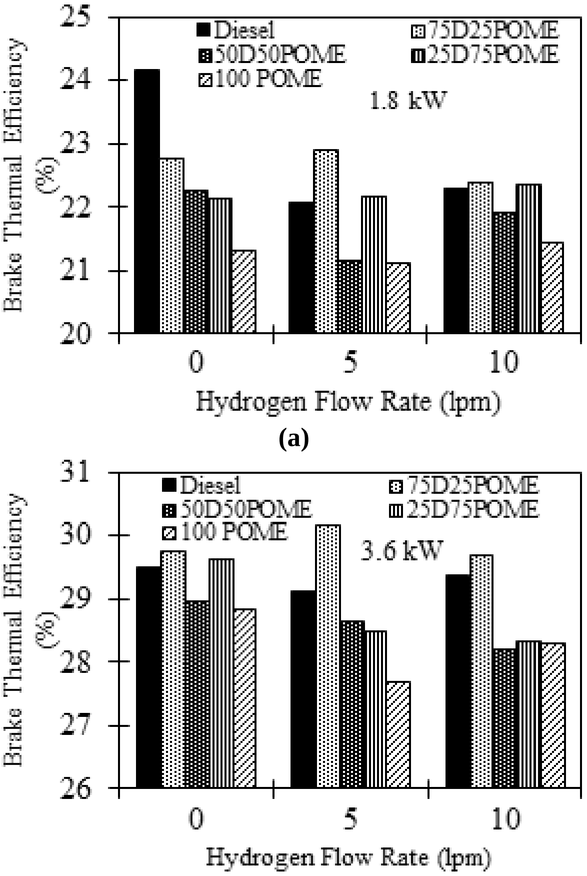
3. Results

3.1. Brake thermal efficiency

The variation of brake thermal efficiency of diesel, 75D25POME, 50D50POME, 25D75POME and 100POME with hydrogen flow rate is shown in Fig. 3. With the addition of POME to diesel, decrease in thermal efficiency was observed. Higher density and viscosity of biodiesel results in poor atomization and mixture formation leading to lower combustion efficiency. At full load, 75D25POME blend engine operation lead to maximum thermal efficiency. By replacing diesel with POME up to 25%, the increase in amount of oxygen due to biodiesel addition increases the combustion efficiency. Further increase in biodiesel content does not help in increasing efficiency because higher density and viscosity of biodiesel overcomes the effect of high oxygen content.

Hydrogen induction, lead to decrease in brake thermal efficiency with diesel engine operation. In the carburetion technique hydrogen flows continuously into the intake manifold even though the engine is not suction stroke, this leads to loss of fuel through intake manifold and also reduction of volumetric efficiency as air is replaced by fuel. The flow is continuous because hydrogen is stored at a higher pressure and the cylinder valve is open during the entire running of engine [22]. However, by inducting hydrogen during POME and its blend, engine operation resulted in appreciable rise in thermal efficiency at 1.8 kW and 5lpm hydrogen flow rate. The thermal efficiency was observed to be 22.1%, 21.13%, 22.9%, 21.16% and 22.17% for diesel, 75D25POME, 50D50POME, 25D75POME and 100POME, respectively. Increase in hydrogen flow rate (10lpm) lead to further increase in engine efficiency. The increase in efficiency is a result of improvement in combustion rate due to high flame velocity of hydrogen [16].

At 3.6 kW load and 5lpm hydrogen flow rate, the thermal efficiency was observed to be 29.12%, 27.7%, 30.17%, 28.65% and 28.48% for diesel, 75D25POME, 50D50POME, 25D75POME and 100POME, respectively. However, at 10 lpm hydrogen flow rate, decrease in thermal efficiency was observed. At higher hydrogen flow rate, a good amount of hydrogen gas is present in the combustion chamber. Also the amount of pilot fuel injected is high resulting in more ignition centres and rapid combustion which may lead to lower thermal efficiency. This decrease is because rapid combustion leads to heat release in short duration which is not utilised to generate power but discarded as heat loss to the chamber walls.



(a)

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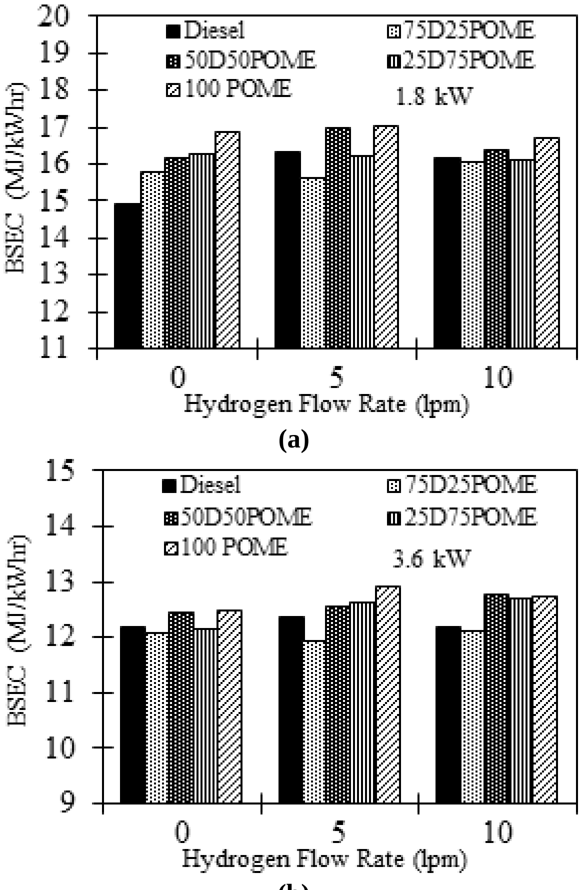
Fig. 3. Brake thermal efficiency vs. hydrogen flow rate at various loads.

3.2. Brake specific energy consumption

The variation of BSEC at different loads with different hydrogen flow rate for diesel, 75D25POME, 50D50POME, 25D75POME and 100POME is given in Fig. 4. BSEC is calculated using the Eq. (2). Without hydrogen induction, diesel fuel operation gave the lowest energy consumption, with increase in POME content in diesel an increase in BSEC is observed. Lower calorific value of biodiesel compared to diesel resulted in the increase in BSEC, since more fuel is required to produce the same power. The other probable reason could be higher viscosity and density of POME, which would result in higher energy consumption. Addition of hydrogen increases the BSEC at all loads.

At 1.8 kW load, BSEC increases by 9.4% and 8.32% for diesel at 5lpm and 10lpm hydrogen flow rate. It decreases by 0.94% and increases by 1.77% for 75D25POME at 5lpm and 10lpm hydrogen flow rate. It increases by 5.2% and 1.5% for 50D50POME at 5lpm and 10lpm hydrogen flow rate. It decreases by 0.18% and 0.86% for 25D75POME at 5lpm and 10lpm hydrogen flow rate. For 100POME, it increases by 1% and decreases by 1% at 5lpm and 10lpm hydrogen flow rate. At full load increase of 1.31% in BSEC for diesel at 5lpm is observed. For 75D25POME, a decrease in BSEC of 1.24% and increase of 0.24% at 5lpm and 10lpm hydrogen flow rate is observed. For 50D50POME, increase of 1.04% and 2.65% in BSEC is observed at 5lpm and 10lpm hydrogen flow rate. For 25D75POME, increase of 4.03% and 4.53% in BSEC is observed at 5lpm and 10lpm hydrogen flow rate. For 100POME, increase of 3.28% and 1.84% in BSEC is observed at 5lpm and 10lpm hydrogen flow rate.

$$BSEC = \frac{Fuel\ Consumed}{Brake\ Power} \times Calorific\ Value \qquad (2)$$



(a)

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Fig. 4. Brake specific energy consumption vs. hydrogen flow rate at various loads.

3.3. Exhaust gas temperature

The variation of exhaust gas temperature with hydrogen substitution for different fuels and different loads is shown in Fig. 5. A K- type thermocouple was used to measure the exhaust gas temperature. When no hydrogen is inducted, biodiesel blends have a higher exhaust gas temperature as compared to neat diesel. At full load, it is about 302°C, 393°C, 397°C, 391°C and 387°C for diesel, 75D25POME, 50D50POME, 25D75POME and 100POME respectively. Biodiesel has higher molecular weight, poor volatility and higher viscosity which would burn only during the diffusion phase of combustion resulting in higher exhaust gas temperature.

Induction of hydrogen leads to further increase in exhaust gas temperature. At 1.8 kW and 3.6 kW the exhaust gas temperature increase to 277°C, 279°C at 5lpm and 10lpm hydrogen flow rate and it increased to 410°C and 421°C at 5lpm and 10lpm hydrogen flow rate for diesel. By using a blend of 75D25POME for engine operation, at 1.8 kW and 3.6 kW exhaust gas temperature increased to 288°C and 291°C at 5lpm and 10lpm hydrogen flow rate and it increased to 409°C and decreased to 396°C at 5lpm and 10lpm hydrogen flow rate, respectively. For other blends also an increase in exhaust gas temperature was observed. The increase in exhaust temperature can be attributed to good mixing of hydrogen with air resulting in near complete combustion of fuel and also faster combustion rate of the inducted fuel.

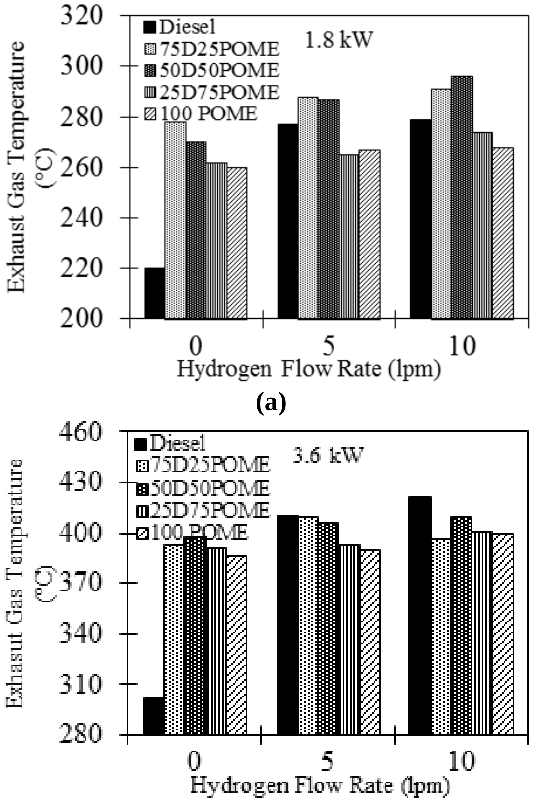

Fig. 5. Exhaust gas temperature vs. hydrogen flow rate at various loads.

3.4. Carbon monoxide emission

Carbon monoxide emission without hydrogen induction, as shown in Fig. 6, is higher for diesel and it goes on decreasing with the increase in percentage of POME in diesel, for 100POME lowest CO emission is observed. The reduction in CO emission is mainly due to oxygen content present in the biodiesel, which results in complete combustion of fuel. However, with the increase in load increase in CO emission is observed. Induction of hydrogen into the inlet manifold along with air reduces the CO emissions. At 1.8 kW and 3.6 kW it reduced to 0.3% at 10lpm hydrogen flow rate for 75D25POME. For 100POME it reduced to 0.2% and 0.1% at 1.8 kW and 3.6 kW and 10lpm hydrogen flow rate. The high flame velocity and high temperature kinetics due to hydrogen enrichment, improves the combustion. Hydrogen also replaces the injected liquid fuel thus reducing carbon emission as hydrogen itself is carbon free.

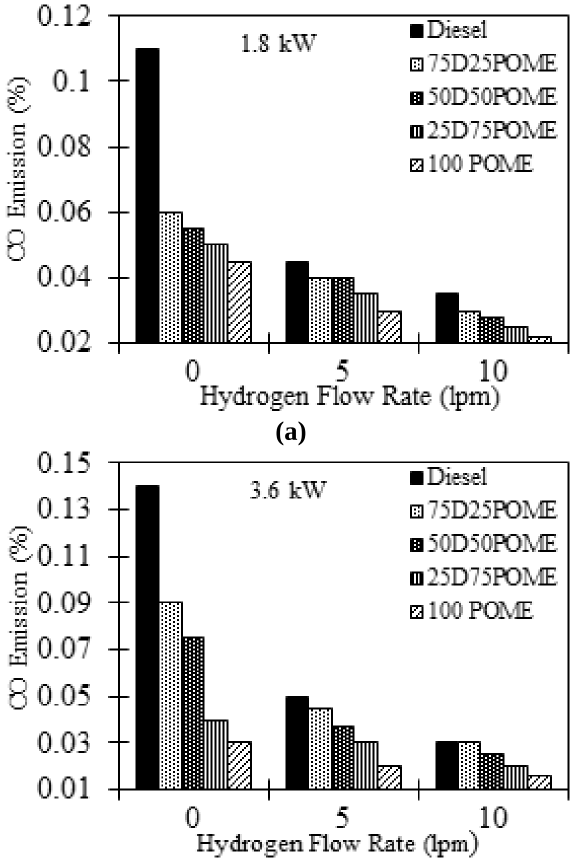

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Fig. 6. Carbon monoxide emission vs. hydrogen flow rate at various loads.

3.5. HC emission

Figure 7 shows HC emission at different loads with different hydrogen flow rates for diesel, 75D25POME, 50D50POME, 25D75POME and 100 POME. Without hydrogen induction, hydrocarbon emission for diesel is observed to be the lowest as compared to blends of diesel and POME. 75D25POME showed higher HC emission as compared to other blends, this trend is consistent with the result obtained by Sharon et al. [9]. With increase in load, increase in unburned hydrocarbon emission is observed for all the tested fuels. The increase in emission can be attributed to high viscosity and density of blends which resulted in improper mixing of blends with air.

Hydrogen enrichment further increased HC emission for diesel and POME blends with diesel. At 5lpm flow rate of hydrogen a huge spike in emission is observed at all loads, with further increase in hydrogen flow rate the HC emission was found to decrease, similar trend is observed for blends of POME and biodiesel.

The results shown are similar to the results of Sandalci et al. [14] and Zou et al. [23]. Guo et al. [24] suggested that hydrogen induction will enhance the high temperature kinetics of combustion but it will slow the low temperature kinetics of combustion of the diesel/biodiesel blend. Thus increasing the unburned hydrocarbon emissions. When hydrogen is added, the oxidation of hydrocarbon depends upon key radicals, like OH, H etc. and it may be related to amount of hydrogen added. Such that higher levels of hydrogen addition can contribute to reduction of HC emission. Due to the presence of oxygen in POME and diesel blends further reduction in HC emission is observed at higher hydrogen flow rate.

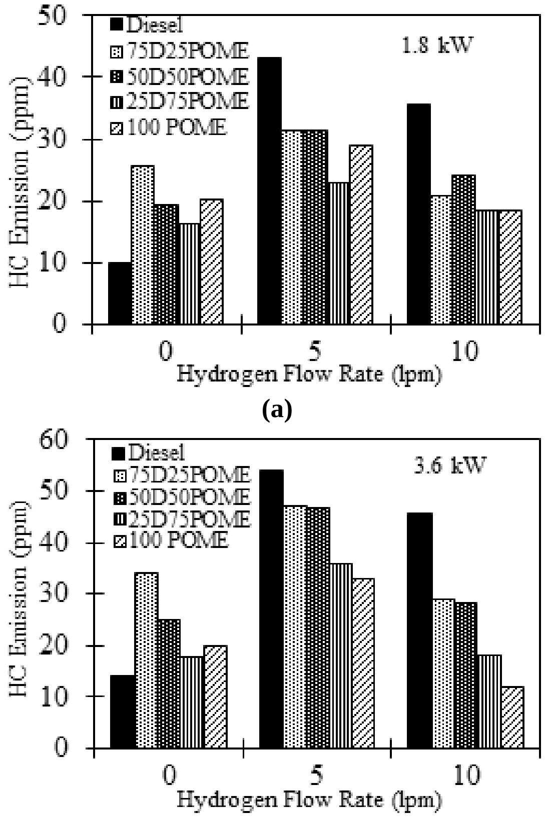

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Fig. 7. Unburned hydrocarbon emission vs. hydrogen flow rate at various loads.

3.6. NOx emission

NOx emission from diesel, 75D25POME, 50D50POME, 25D75POME and 100 POME at different loads and different hydrogen flow rates can be seen in Fig. 8. With no induction of hydrogen, emissions increased with increase in load, but it decreased with the increase in percentage of POME in the blend. The formation of NOx can be correlated to the exhaust gas temperature, as shown in Fig. 5, the higher is the exhaust gas temperature higher will be the NOx emission.

With the induction of hydrogen in the intake manifold, further increase in NOx emission is observed. At 1.8 kW and 3.6 kW an increase of 29.5%, 51.2% at 5lpm and 10lpm hydrogen flow rate and an increase of 22.7% and 45.8% at 5lpm and 10lpm hydrogen flow rate for diesel is observed.

By using a blend of 75D25POME for engine operation, at 3.6 kW an increase of 22.5% and 48.2% at 5lpm and 10lpm hydrogen flow rate, respectively is observed. For 100POME it increased by 24.6%, 43.8% at 3.6 kW and 5lpm and 10lpm hydrogen flow rate, respectively.

Hydrogen as compared to diesel has a higher flame velocity and higher calorific value, which would enhance the probability of complete combustion. This results in higher in-cylinder peak pressure, which in turn results in higher in-cylinder temperature. The higher temperature thus culminates into the formation of higher NOx.

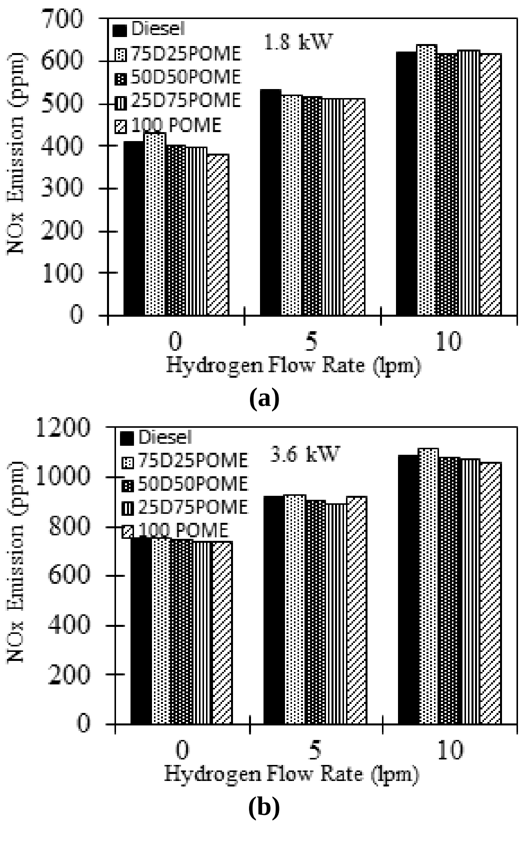

Fig. 8. NOx emission vs. hydrogen flow rate at various loads.

4. Conclusions

Based on the experiments carried out on a single cylinder diesel engine fuelled with diesel and palm oil methyl ester diesel blends with hydrogen induction at different loads, the following conclusions are drawn.

- Induction of hydrogen increases the brake thermal efficiency of the engine for 75D25POME blend at 50% load and full load with 5lpm hydrogen flow rate. For diesel and other blends of POME, addition of hydrogen causes a decrease in thermal efficiency. With increase in hydrogen flow rate, i.e., 10lpm decrease in thermal efficiency was observed for 75D25POME at both the loads. However, for diesel at both loads an increase in thermal efficiency was observed.
- At both loads, brake specific energy consumption was found to decrease with 5lpm hydrogen flow rate for 75D25POME blend. Further increase in hydrogen flow rate and at both loads BSEC was found to increase. At 50% load with 5lpm hydrogen flow rate, an increase in BSEC was observed for other blends of POME, however with increase in hydrogen flow rate decrease in BSEC is observed. At full load the trend is reversed.
- Due to induction of hydrogen in the cylinder drastic reduction in carbon monoxide emission is observed at all loads and both the flow rates of hydrogen. This reduction can be attributed to higher in-cylinder temperature resulting in good combustion. Engine running with 100POME biodiesel lead to highest reduction in CO emission.
- HC emission, was found to drastically increase with the induction of hydrogen at 5lpm but at 10lpm the emission was found to decrease to some extent. At full load and 10lpm hydrogen flow rate the reduction is 15.5%, 7.8%, 9.2%, 23.6% and 45.45% for diesel, 75D25POME, 50D50POME, 25D75POME and 100POME respectively as compared to 5lpm hydrogen flow rate. The engine running with 100POME shows highest reduction in HC emissions.
- NOx emission increases from 29.5% to 51.2% at 1.8kW when the hydrogen flow rate is varied from 5lpm to 10lpm for diesel. When 75D25POME is used as fuel, it increases from 21.4% to 48.37% at 1.8 kW with the increase in hydrogen flow rate from 5lpm to 10lpm. With increase in POME percentage in diesel along with increase in hydrogen flow rate the NOx emission was found to decrease.

It can thus be concluded that induction of hydrogen in the intake manifold along with pilot injection of POME and its blends can improve the engine performance. 75D25POME gave the best engine performance but it also resulted in higher emissions as compared to other blends of POME. 5lpm of hydrogen addition resulted in higher engine efficiency, low CO, HC and NOx emission. Minor modifications in the engine can lead to the reduction of exhaust emissions.

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