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Analysis of hydrogen enriched treble biofuel blended with diesel for performance, emission and combustion characteristics on CI engine

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ABSTRACT

The need of the hour is to look forward to alternative fuels to swipe out the dependence on fossil fuels, as biofuels from various feedstocks are being experimented worldwide. However, it is difficult to implement biodiesel from a single feedstock to replace the existing fossil fuels. It is reliable to obtain biodiesel from local feedstock and to make multiple biodiesel mixtures blended with diesel. The present work relies more on biofuels and acts as a step towards fossil fuel-free engine or at least to snatch the lion's share of the fossil fuels. In this contest, the experiment was carried out by using treble biofuels i.e., WCOBD + PSBD + Bio-hydrogen at different injection pressures (i.e., 200bar, 225bar and 250bar) and compared them with a similar engine that utilised fossil fuel as the stand-alone fuel. The mixture ratios were B10, B20 and B30 and the enrichment of hydrogen was done at 4lpm, 6lpm and 8lpm. The results showed that the brake thermal efficiency of dual biofuel blended diesel decreased as compared to that of the base fuel and increased with hydrogen enriched biodiesel. Hence, the brake specific energy consumption decreased for the hydrogen enriched fuel and the exhaust emissions of CO and CO_2 were reduced, however, NOx showed an increasing trend as usual.

Keywords: Bio-hydrogen, waste cooking oil biodiesel, palm biodiesel, treble blend and injection pressure.

INTRODUCTION

Nowadays, alternative fuels for diesel engines is an emerging topic among researchers due to decreasing petroleum reserve and hazardous health and environmental effects of engine exhaust gases. Edible-based biodiesel sources pertaining to food chain are not considered feasible due to price fluctuation, and land limitation, also, they are contrary to the current social movement and energy policies, therefore, their industrial expansion has been limited [1]. Biomass sources, particularly vegetables oils, have attracted much attention as alternative energy sources due to easy availability, renewable and cleaner burning than fossil fuels [2, 3]. In addition, biodiesel has lower sulphur and aromatic contents and net carbon dioxide (CO_2) emission. Biodiesel can be used immediately in diesel power generators without many modifications as it can be mixed at any proportion with diesel [3]. Besides that, biodiesel cost is a major concern for its commercialisation. Biodiesel produced from vegetable oil or animal fat is 10-15% more expensive than petroleum-based diesel fuel. The feedstock cost comprises approximately 70-95% of total operating costs of a biodiesel plant [2]. Locally available biofuel should be an alternative source for petroleum and able to be made in any local area [4]. Waste cooking oil (WCO) is one of biodiesel sources, unlike the high speed diesel (fossil fuel) that may cause harm in future. WCO is a renewable fuel extracted from the residual waste of used cooking oil. It is very cheap, non-volatile, safe to store, releases comparatively less carbon dioxide and has a cleaner exhaust. Depending on its source and availability, WCO costs less than neat vegetable oils. Hotels and other public eateries are the major contributors to WCO production. Over cooked WCO can cause adverse health issues like cataracts, liver damage and jaundice and can damage the immune system in children. Recycling is the best way to use WCO properly without compromising its adverse effects. Animal feed production is a major part of recycled WCO and a small portion is used to manufacture soaps and biodegradable lubricants. Consumption of food of animal origin like milk, meat, poultry and other products may cause undesirable contaminants to enter the human body and pose serious long term health hazards. Therefore, a major portion of the recycled WCO is available to be used as an alternative fuel in compression ignition (CI) engines after suitable modifications in the fuel properties [5, 6]. Palm oil is semi-solid at room temperature (20^oC). The liquid part may be physically separated from the solid part of palm oil via fractionation method. After fractionation, it is known as palm olein, which is commonly sold as cooking oil, while the solid fat portion is known as palm stearin, which is normally used to formulate trans-free fats such as margarine, soap, shortening and vegetable ghee.

Many refined virgin vegetable oils, such as palm, canola, soybean and corn, have been used to produce biodiesel to substitute petroleum diesel. Due to the high cost of cooking oils, palm stearin (PS) may become a promising alternative feedstock for biodiesel production. PS is the solid fraction obtained by fractionation of palm oil after crystallisation at a controlled temperature. It is not used directly for edible purposes due to its high melting point that ranges from 44 to 56 ^oC [7] . The physical characteristics of PS differ significantly from those of palm olein. The high degree of saturation of PS poses problems in edible fats manufacturing as it confers low plasticity to the end product, thus, limiting the commercial exploitation of the material [7]. Renewable fuels are those produced from renewable resources in nature. Examples include biofuels e.g., ethanol and methanol from clean energy, vegetable oil used as fuel, carbon dioxide or biomass, biodiesel and hydrogen fuel (when produced with renewable processes). An important future application of hydrogen could be as an alternative for fossil fuels, only once the oil deposits are depleted. However, this application relies on the storing techniques development to enable a proper storage, effective distribution and good hydrogen combustion. If the cost of hydrogen production and distribution decreases, then end-user technologies could pick up and hydrogen fuel could be entering the market in 2020 [8].

Fossil energy source cannot be regenerated and will be exhausted with increasing fossil fuel consumptions. Hydrogen energy is a new energy source with abundant reserves and does not depend on fossil fuel. Moreover, hydrogen energy conforms to the requirement of the worldwide environmental protection, thus, receives more attention all over the world. Hydrogen may be produced in biosystem, which includes two ways of light-drive process and anaerobic fermentation, the former is theoretically a perfect process that transforms solar energy into hydrogen by photosynthetic bacteria. However, due to low utilisation efficiency of light and difficulties in designing light reactor, this method is hard to be applied in practice. The latter carries out anaerobic fermentation by hydrogen, which has many advantages, such as rapid, simple, easy operation and hydrogen production by renewable resources and organic waste [9]. Compared to the light-drive reactor, anaerobic fermentative hydrogen-production is easier to conduct and suitable for the demands of sustainable development strategy. At present, the yield and rate of hydrogen production are still low. With the rapid development of molecular biological technology, the directional heredity reconstruction for microbe becomes the new research hotspot, which can radically change microbial biological properties and metabolic modes to cultivate superior microbial strains more beneficial to bio-hydrogen production, economise costs and increase production efficiency and yield, and provide more efficient pathways for the exploitation and popularisation of hydrogen energy sources [10]. The objective of the paper is to experimentally analyse the performance, emission and combustion characteristics of diesel engine that runs on treble biofuels blended with diesel. Among them is hydrogen, that will boost the combustion due to its high calorific value and flame velocity.

MATERIALS AND METHODS

Engine Specifications

A performance test was carried out in a research engine test rig as shown in Figure 1 and the specification is tabulated in Table 2. The uncertainties in the measured parameters in the present study are given in Table 1.

Table 1. Uncertainties in measured experimental variables.

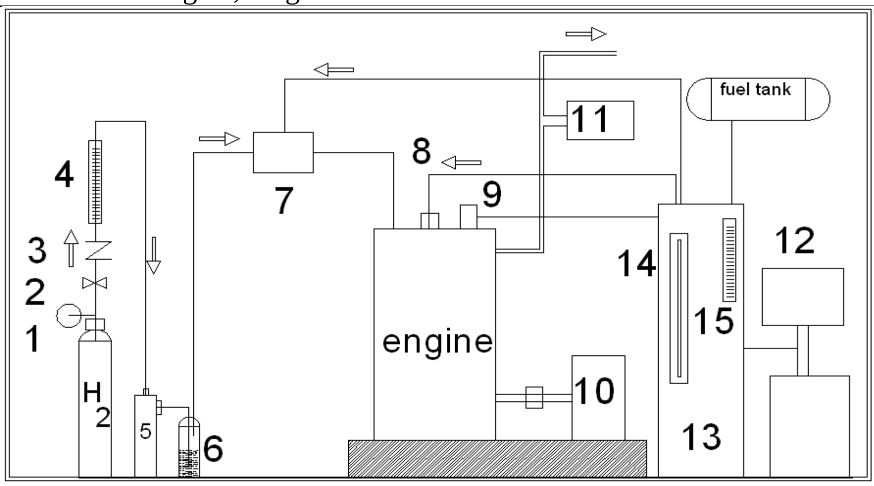
Make	Kirloskar
Number of cylinder	1
Number of stroke	4
Fuel	Diesel
Cooling Type	Water
Model	TV1
Stroke length	110 mm
Bore diameter	87.5 mm
Volume	661 cc
Power	3.5 kw
Speed	1500 rpm
Compression ratio	17
Injection pressure	Variable injection pressure
Range	200bar to 250bar
Loading unit	Eddy current
Dynamometer type	Eddy current & Water cooled

Variation of Injection Pressure

The experiment was conducted at various injection opening pressures (IOPs) to find the optimum injection pressure at which a good engine performance can be obtained. Three different injection pressures i.e., 200bars, 225bars and 250bars were set by rotating the compression spring load screw until the associated pressure sensor displayed the desired value on the monitor.

Table 2. Engine specification.

Particulars	Specifications	Uncertainty
Dynamometer	Eddy current dynamometer of Model AG10, Make Saj Test Plant Pvt. Ltd.	Speed ±1% and torque ±0.4%
Load sensor	Make Sensortronics, Model 60001.	±0.2%
Air flow transmitter	Make Wika, Model SL1 Range 0- 25mbar	± 0.5%
Fuel flow transmitter	Differential pressure type-Make Yokogawa – Model EJA110E-S1-JMS5J-912NN Made in Japan.	±0.065%
Piezo Sensors	Make PCB Piezotronics, Model SM111A22 Diaphragm stainless steel type & hermetic Sealed Range 0-350 bar	±0.1%
Crank angle sensor	Make Kubler-Germany, Model 8.3700.1321.0360.	± 0.2%
Temperature sensor	Make Radix, Type RTD, PT100 measures engine water inlet temperature, engine water outlet temperature, calorimeter water inlet temperature and calorimeter water outlet temperature Range 0-250 ºC	±1%
	Make Radix, Thermocouple type K (Chromel /Alumel) measures Exhaust gas temperature at calorimeter inlet and outlet Range 0-400ºC	±0.8%
Rotameter	Eureka model PG-1 to 21 For Calorimeter, range from 25-250 LPH, For Engine, range from 40-400 LPH	±2%



1. Hydrogen cylinder with pressure gauge
2. Pressure regulating valve
3. Non return valve
4. Hydrogen flow meter
5. Flash back arrester
6. Flame trapper
7. Mixing box
8. Fuel injector
9. Cylinder pressure sensor
10. Eddy current dynamometer
11. Exhaust gas analyser
12. Computer interface
13. Control panel
14. Manometer
15. Burette

Figure 1. Schematic diagram of the experimental setup.

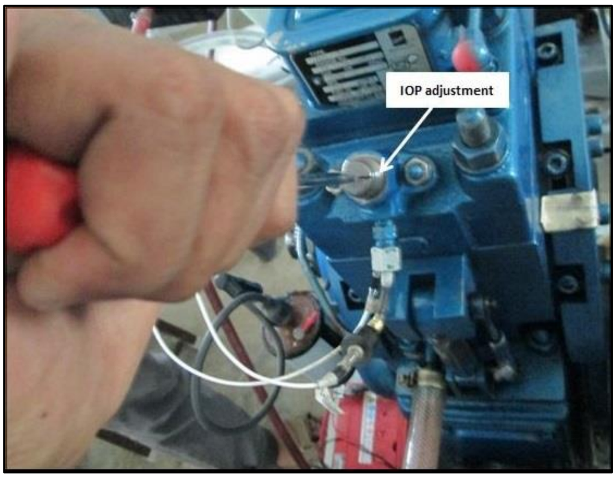


Figure 2. Physical experimental setup for variation in Injection Opening Pressure (IOP).

Mixing of Hydrogen with Air

Figure 3 shows the modified engine for direct induction of hydrogen through the inlet manifold and the hydrogen pressure was controlled directly by the pressure regulator provided at the hydrogen cylinder opening. The constant speed operation diesel was controlled by the governor mechanism provided in the engine.

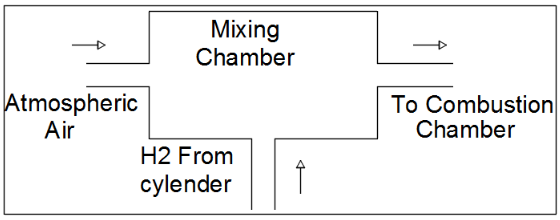


Figure 3. Mixing chamber of hydrogen and air.

Experimentation

The mass flow rate of the blended fuel was calculated via volumetric basis by using a burette and a stop watch. The exhaust gas temperature was measured by using a thermocouple attached with a digital temperature indicator, while the pressure was recorded by using a piezo pressure sensor fitted in the head of the engine cylinder.

Experimental Procedure

In the first step of experiment, the engine was operated with pure diesel and its performance and emission characteristics were calculated for three different injection opening pressures. In the second step of experiment, the engine was operated to run with emulsions made with 5WCOBD5PSBD90D, 10WCOBD10PSBD80D and 15WCOBD15PSBD70D for three different injection opening pressure ratios. The 10WCOBD10PSBD70D blend was optimal among those tested in terms of BTE and BSFC. In the third step of experiment, the engine was operated to run with optimal emulsion of the above said biodiesels blended with diesel and compressed hydrogen gas (to further enhance combustion) introduced by induction through the intake manifold at three different flow rates of 4lpm, 6lpm and 8lpm as shown in Table 3. The performance results and emission parameters were compared.

Table 3. Composition of fuel mixtures and test matrix.

Spell of Experiment	Feedstock: % by volume			Cycle of Experiment for different Injection Opening Pressures (IOPs)			H_2 lpm
	Pure diesel	Waste cooking oil biodiesel	Palm Stearin Biodiesel	A	B	C	
1	100	-	-	200bar	225bar	250bar	-
	90	5	5	200bar	225bar	250bar	
2	80	10	10	200bar	225bar	250bar	-
	70	15	15	200bar	225bar	250bar	
				200bar	225bar	250bar	4
3	80	10	10	200bar	225bar	250bar	6
				200bar	225bar	250bar	8

Table 4. Fuel properties for pure diesel, biodiesels and diesel blend of dual biodiesel

Property	Diesel	WCOBD	PSBD	B30 (15WCOBD+15PSBD+70D)
Density (kg/m^3)	832	878	898	848.8
Viscosity at 40˚C (mm^2/s)	2.6	3.35	4.12	2.94
Calorific value (MJ/Kg)	46.049	45.080	39.507	44.922

Table 5. Energy equivalent and energy share.

Strategy of Experiment	Load % age	Energy Equivalent of diesel KW	Energy Equivalent of WCOBD KW	Energy Equivalent of PSBD KW	Energy Equivalent of H_2 KW	Diesel Energy Share (%)	WCOBD Energy Share (%)	PSBD Energy Share (%)	H_2 Energy Share (%)
225 bar									
10WCOBD	50	8.406	1.763	1.545	0.655	67.9	14.2	12.4	5.2
+10PSBD	75	9.611	2.016	1.766	0.655	68.4	14.3	12.5	4.6
+80D+ $H_2$4lpm	100	11.2	2.351	2.060	0.655	68.8	14.4	12.6	4.0
10WCOBD	50	7.081	1.485	1.301	0.983	65.2	13.6	11.9	9.0
+10PSBD	75	8.406	1.763	1.545	0.983	66.2	13.8	12.1	7.7
+80D+ $H_2$6lpm	100	9.611	2.016	1.766	0.983	66.8	14.0	12.2	6.8
10WCOBD	50	6.728	1.411	1.236	1.31	62.9	13.2	11.5	12.2
+10PSBD	75	8.406	1.763	1.545	1.31	64.5	13.5	11.8	10.0
+80D+ $H_2$8lpm	100	10.350	2.171	1.902	1.31	65.7	13.7	12.0	8.3

The calorific value of diesel is higher than its diesel blends due to high oxygen content than fossil diesel [11]. Two main factors that are responsible for higher viscosity and density of biodiesel are large molecular weight and complex chemical structure [12-15]. Table 4 reveals that PS biodiesel has less calorific value and lower viscosity and density than WCO biodiesel. For different hydrogen flow rates i.e., 4lpm, 6lpm and 8lpm, the mass flow rate of hydrogen at all loads in terms of kg/sec was calculated. Then, the energy share of hydrogen (kW) = mass flow rate of hydrogen (kg/sec) × lower calorific value of hydrogen (kJ/kg). Similarly, the energy share for diesel and biodiesel fuels were calculated by using the formula; energy share (kW) = mass flow rate of main fuel (kg/sec) × lower calorific value (kJ/kg) as shown in Table 5 for 225 bar injection opening pressure.

RESULTS AND DISCUSSION

Brake Thermal Efficiency

Brake thermal efficiency is the indication of the engine ability to transform energy input to useful work. Figure 4 and 5 show the brake thermal efficiency of all test fuels at different injection opening pressures (IOPs). BTE for pure diesel was more than the blends. The slight variations in the thermal efficiency of the biodiesel blends were mainly due to the lower calorific value of WCOBD and PSBD when compared with diesel [16, 17]. Furthermore, the higher viscosity and slow vaporisation of biodiesel present in these blends led to inferior combustion of biodiesel which caused the brake thermal efficiency to be low [18-20] . BTE was lower for B10 and increased with the blending ratio of B20, thereafter, it fell with further increase to B30. The optimum blending ratio was B20. For all IOPs, BTE increased with the increase of load until 75%, thereafter, decreased at full load. Hence, the optimum loading was 75%. In Figure 5, the biodiesel blends in diesel were plotted against different IOPs. From the figure, 225bar was the optimum IOP with maximum BTE for baseline fuel and B20 at 27.44% and 24.31%, respectively, which were lower than the baseline fuel i.e., diesel by 12.06%. The optimised values i.e., B20 at 225bar IOP and 75% loading were further tested with hydrogen induction at different rates of admission.

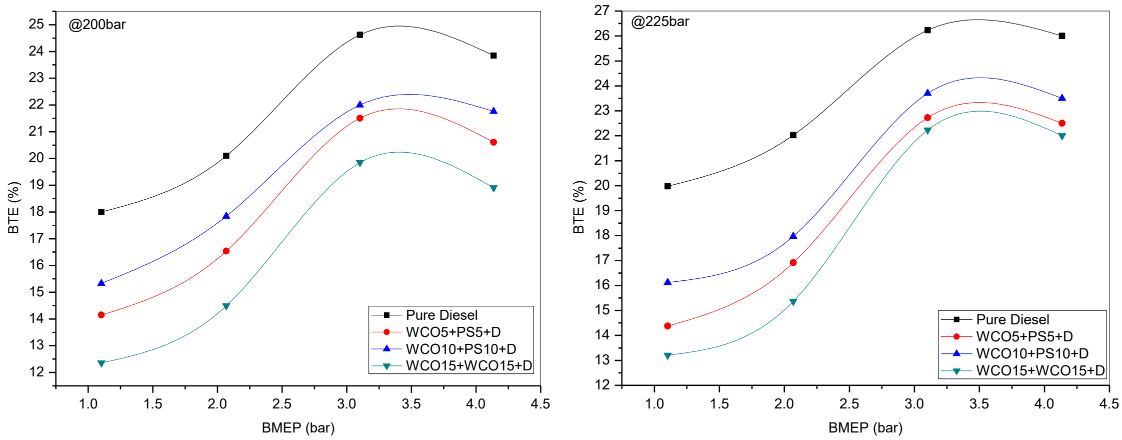


Figure 4. Variation brake thermal efficiency versus brake mean effective pressure at 200 bar and 225 bar injection opening pressures for dual biodiesel blended in diesel.

Figure 6 shows that the peak performance was at 75% load i.e., 31.3% with 6lpm H_2. The engine conditions became unstable at 100% loading conditions with reduction in BTE to 29.8%. Therefore, the optimal loading was 75%, this trend was also experienced by previous researchers [21]. The reduced power production faced by the biodiesel combustion was resolved by hydrogen that assisted dual biodiesel blends of diesel fuel combustion, examined as a promising solution to enhance biodiesel combustion processes [22]. With the induction of hydrogen in dual biodiesel blended with diesel, the brake thermal efficiencies were 29.31%, 31.3%, 30.5% for 4, 6, and 8lpm, respectively, which were 20.56%, 28.75% and 25.46% more compared to biodiesel. Large amount of heat energy was released when the injection pressures were increased in the CI engine, thereby, the ignition delay was reduced and the fuel became completely burnt [23]. Figure 7 shows the increase of brake thermal efficiency from IOP of 200bar to 225 bar. With further increase of injection IOP i.e., to 250 bar, the ignition delay period decreased, which in turn decreased the homogeneous mixing that led to incomplete combustion and less brake thermal efficiency.

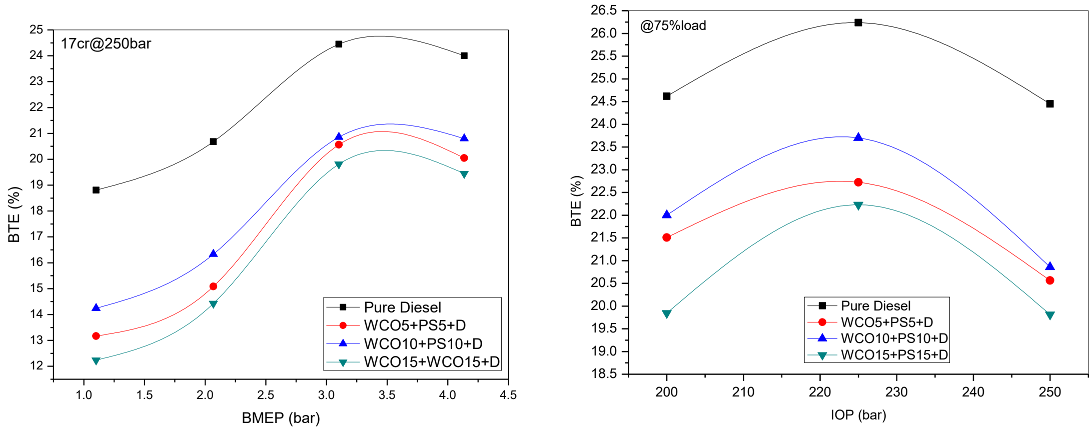


Figure 5. Variation brake thermal efficiency versus brake mean effective pressure at 250 bar and all injection opening pressures for dual biodiesel blended in diesel.

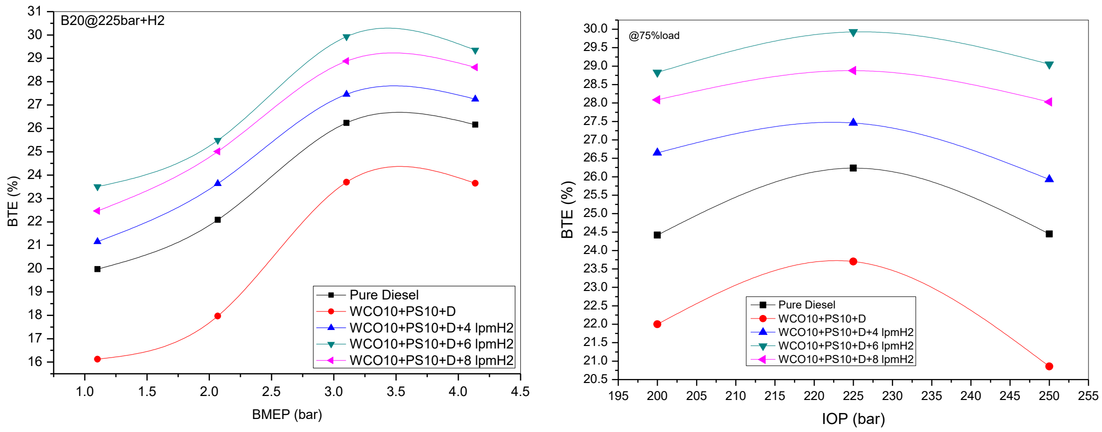


Figure 6 Variation brake thermal efficiency versus brake mean effective pressure at 225bar and injection opening pressure at 75% load for dual biodiesel blended in diesel along with hydrogen induction.

Brake Specific Energy Consumption

Brake specific fuel consumption is the ratio between mass flow rate of the tested fuel and effective power [11]. The brake specific fuel consumption of CI engine depends on the relationship among volumetric fuel injection system, density of fuel, lower heating value and viscosity [24]. Brake specific energy consumption is a more authentic parameter for comparing fuels with different calorific values and densities. This energy consumption can be obtained as the product of brake specific fuel consumption and calorific value of the fuel. The energy equivalents and energy shares are shown in Table 5 for B20 along with 4, 6 and 8 lpm rate of hydrogen induction.

The variation of brake specific energy consumption (BSEC) with brake mean effective pressure (BMEP) for different fuels is presented in Figure 7. The reason for the higher BSEC of biodiesels in Figure 7 can be attributed to the combined effects of the three variables i.e., relative fuel density, viscosity and heating value of the blends [25]. Biodiesel fuel was administered in the engine on a volumetric basis per stroke, thus, larger quantities of biodiesel were nourished into the engine. Hence, to produce the same power, excess biodiesel fuel was needed due to its less calorific value compared to diesel fuel [26, 27]. BSEC reduced with the increase in injection pressure for all fuels tested. This was due to the better atomisation at higher injection pressure which exhibited more surface area of fuel droplets to the high temperature air salient to complete fuel combustion [28]. Further increase in IOP, i.e., 250 bar, decreased the ignition delay, which in turn decreased homogeneous mixing possibility and led to incomplete combustion, hence, more BSEC. A similar trend was observed by previous researchers [11]. The hydrogen-assisted combustion dual biodiesel blends showed a decrease in BSEC with increasing flow of hydrogen, which can be attributed to the uniform mixing of hydrogen with air and diffusivity and led to the near complete combustion of the fuel. For this reason, the fuel consumption was decreased.

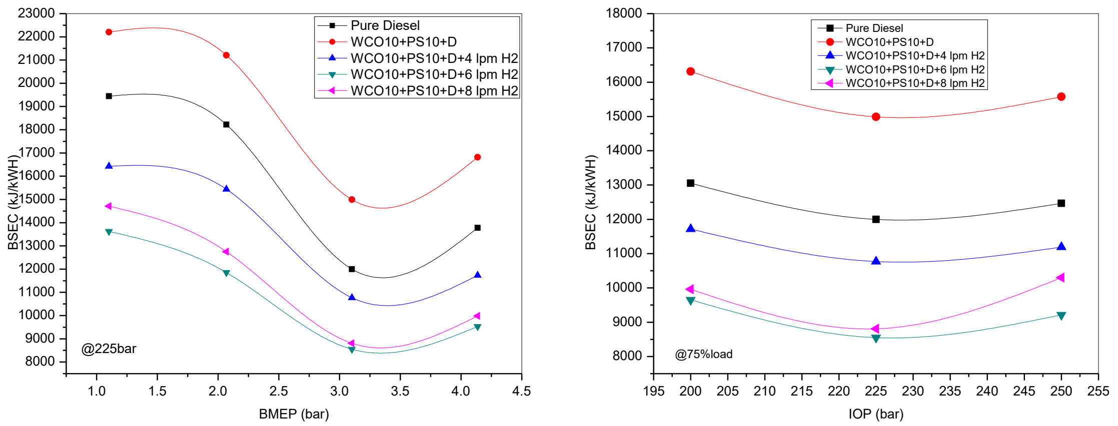


Figure 7 Variation brake specific energy consumption versus brake mean effective pressure at 225bar and for injection prresure at 75%load for dual biodiesel blended in diesel along with hydrogen induction at three different rates.

Emission Analysis

The emission constituents considered were carbon monoxide (CO), oxides of nitrogen (NO_x) and unburned hydrocarbon (HC). The effect of IOP on the emission constituents for Diesel+WCOBD+PSBD blends and diesel for different test pressures are shown in Figure 8 and 9. Features like higher cetane number than diesel and less sulphur and more oxygen, are environmentally friendly and can reduce HC and CO in the exhaust gas. For these reasons, different studies have been conducted on biodiesel blended with diesel and the results show that emission concentration varies and depends on biodiesel source and engine condition [14, 20, 29]. Hydrogen possesses many superior combustion and emission characteristics than other liquid or gas fuels. For instance, due to the omission of the carbon atom, hydrogen combustion does not produce any harmful emissions such as HC, CO, sulphur oxides, or organic acids [30].

Carbon Monoxide Emission

Figure 8 shows the effect of IOP on CO for biodiesel and biodiesel blends of diesel. The CO emission reduced with increased IOP. This may be due to the fuel being atomised into very fine droplets and more surface areas were accessible for combustion, which resulted in the formation of a good quality fuel mixture that caused a complete combustion [28]. Whereas for pressure of 250bar, the performance drop led to an incomplete combustion which resulted in the increase of CO emission at all loads. Consistent and tangible reduction in CO emission were found at 75% load with 225 bar pressure for dual biodiesel blended with diesel 0.08% and the reduction percentages in the CO emission were 7.5%, 26.257% and 12.5% with 4 lpm, 6 lpm and 8 lpm of H_2 induction to emulsified fuel. The primary reason for the reduced CO emission was due to the decrease in the amount of total carbon in the inducted fuel.

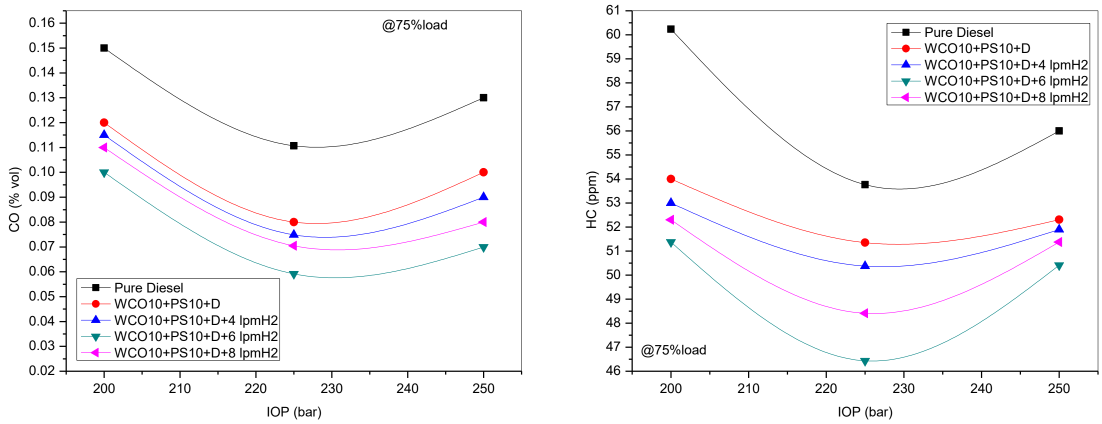


Figure 8. Variation of carbon monoxide and unburned hydrocarbon versus injection opening pressure at 75% load for dual biodiesel blended in diesel along with hydrogen induction at three different rates.

Unburned Hydrocarbon

The unburned hydrocarbon of tested engine with different injection pressures for the pilot fuel, base line fuel and fuel with hydrogen induction is shown in Figure 8. HC emission reduced with increased IOP of engine for base line fuel, biodiesel blended diesel mixture and biodiesel blended diesel mixture with hydrogen. HC emission increased for all test fuels with load, and there was a reduction in HC emission for biodiesel compared to diesel due to the presence of oxygen in its molecular structure that led to an efficient combustion [29, 31]. The decreasing trend of UHC was observed with increasing %age of H_2 substitution when compared with pure diesel because of its high flammability limit and calorific value [32]. At 225 bar, proper atomisation and mixing with maximum %age of burnt carbon content were achieved and UHC formation was greatly minimised.

Oxides of Nitrogen (NO_x) Emission

Comparison of NO_x emission for different injection pressures of the test fuels is illustrated in Figure 9. The NO_x emission level increased with increasing injection pressure because of a faster combustion and greater cylinder gas temperature due to peak pressure which occurred at the earlier crank angle [19, 33]. At pressure of 225bar, the NO_x emissions were 802.1 ppm, 890 ppm, 952.16 ppm, 1020.12 ppm and 1103.52 ppm for base line fuel, dual biodiesel blends of diesel, emulsified fuel with 4lpm, 6lpm, and 8lpm of H_2 induction, respectively. But this could be potentially established by the use of EGR technique and emulsified biodiesel as presented by Korakianitis et al. [34]. Nevertheless, a contrary trend was also observed by other researchers who claimed that the NO_x emissions were smaller for dual fuel combustion, particularly at medium and high engine loads, and they attributed it to the combined effects of hydrogen incantation and late pilot fuel injection, that contributed to low temperature combustion [35, 36]. Experimental and simulated analysis of inline cylinder pressure for B20+6lpm H_2. Pressure and temperature contours for bio-diesel 10WCOBD+10PSBD+80D+6lpm H_2. From Figure 10, it can be seen that the experimented and simulated peak pressures for 10WCOBD+10PSBD+80D+6lpm H_2 were 68.95bar and 70.87bar, respectively, with a variation of approximately 2.78%.

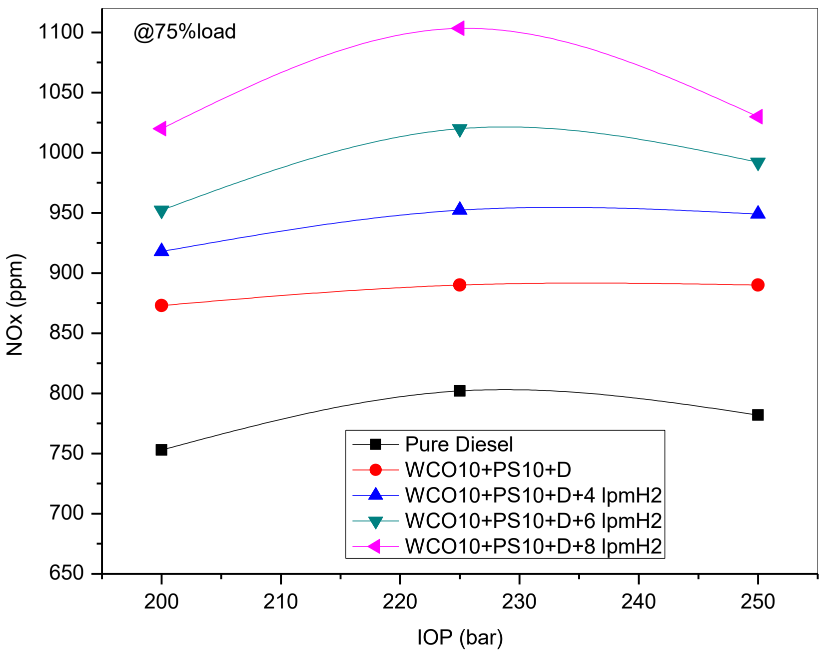


Figure 9. Variation of oxides of nitrogen versus injection opening pressure at 75% load for dual biodiesel blended in diesel along with hydrogen induction at three different rates.

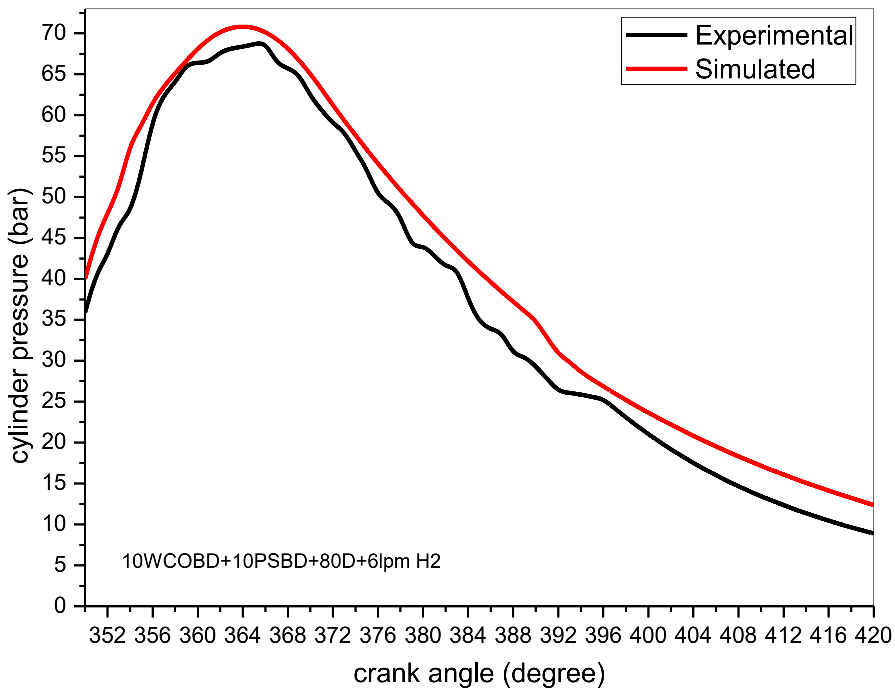
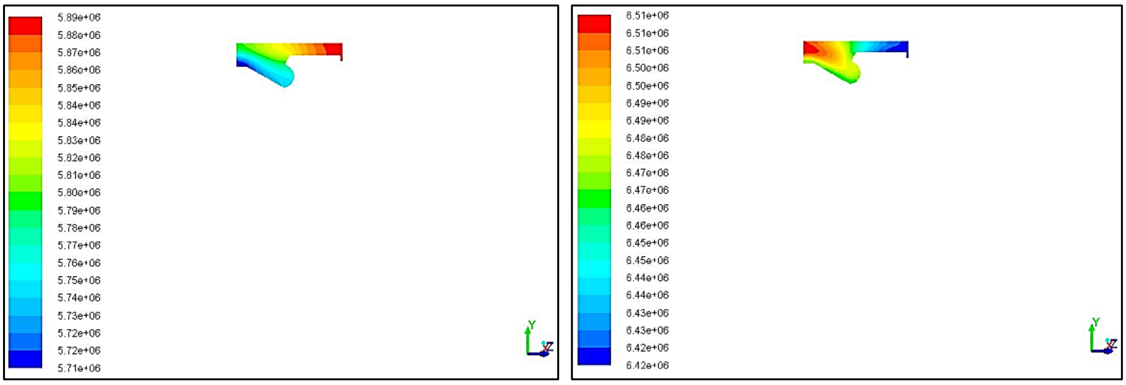
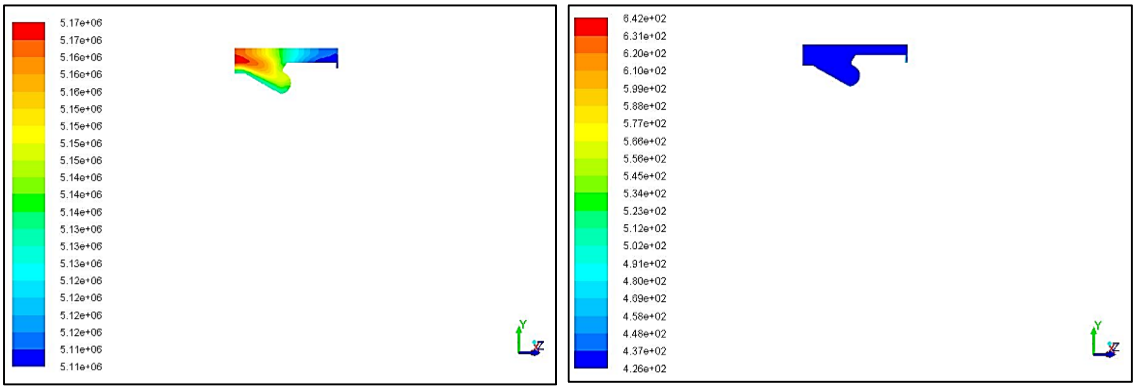


Figure 10. Comparison of simulated and experimental values of peak in-cylinder pressures against crank angles for 10WCOBD+10PSBD+80D+6lpm H_2.



(a) (b)

Figure 11. Pressure contour at crank angle (a) 352 degree and (b) 364 degree for 10WCOBD+10PSBD+80D+6lpm H_2.



(a) (b)

Figure 12. Pressure and temperature contours at crank angle (a) 372 degree and (b) 364 degree, respectively for 10WCOBD+10PSBD+80D+6lpm H_2.

CONCLUSIONS

Based on the experimental investigation to study the performance, emission and combustion characteristics of a single cylinder diesel engine using treble biodiesel blended with conventional diesel, which included hydrogen as the third biofuel to assist the combustion, the following conclusions were drawn:

- Emulsifying WCOBD and PSBD in conventional diesel to 10WCOBD10PSBD80D proportion; thermal efficiency decreased by 12.06%.
- BSEC was increased by 24.94% i.e., 11997.22kj/kwh for diesel and 14990.49kj/kwh for emulsified fuel
- BSEC for optimal blend i.e., B20+6lpm H_2 was 8550.89kJ/kwh, which was less than diesel.
- CO emission decreased by 27.27% i.e., for diesel CO was 0.11% and emulsified fuel was 0.08%. HC emission for diesel was 53.768ppm and biodiesel blend was 51.354% (decreased by 4.48%). No_x showed an increasing trend, 802.14ppm for diesel and 890ppm for biodiesel blend, which was 10.95 % more.
- As emulsified fuel was assisted by hydrogen induced combustion, the performance was increased with respect to the base line test fuel i.e., diesel, BTE being 26.2354% and 29.9314%, respectively, for an increase of 14.08%. BSEC decreased by 28.72%.

- CO emission decreased i.e., 0.05915% and 011071% for hydrogen assisted and pure diesel, respectively. HC emission decreased by 13.63%. No_x increased by 37.53% i.e., 1103.52ppm and 802.144 ppm, respectively.
- Best injection opening pressure was 225bar, where all parameters were optimised.
- Data acquisition was done after normalising the engine and 75% loading condition for all test fuel was optimum.
- Hydrogen induction was done at three different rates and 4lpm was the ideal rate, where the operating condition was optimum.
- Induction of hydrogen inline of biodiesel had outlaid the performance of diesel as a stand-alone fuel. Difficulty in storage and transportation only.

Maximum utilisation of WCO is recommended to convert it to biodiesel, with a neat disposal to ovoid spill that can damage the environment. Hydrogen induction enhances engine performance.

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NOMENCLATURES

WCOBD	Waste cooking oil biodiesel
PSBD	Palm stearin biodiesel
B10(5WCOBD5PSBD90D)	5%WCOBD+5%PSBD+90%Diesel
B20(10WCOBD10PSBD80D)	10%WCOBD+10%PSBD+80%Diesel
B30(15WCOBD15PSBD70D)	15%WCOBD+15%PSBD+70%Diesel
lpm	Liters per minute
CO	Carbon monoxide
HC	Hydro carbon
CO_2	Carbon dioxide
NOx	Oxides of nitrogen
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
BSEC	Brake specific energy consumption
IOP	Injection opening pressure
CR	Compression ratio
WCO	Waste cooking oil
PS	Palm stearin