Performance and Emissions of Emulsified Biodiesel Operated Diesel Engine

H. Raheman, and Sweeti Kumari

***Abstract*—**Experiments were conducted to determine the required hydrophile lipophile balance (HLB) for carrying out emulsification of biodiesel blend JB10 emulsified with water by 10% and 15% volume basis. The performance and emissions of a 10.3 kW, single cylinder, 4-stroke, water cooled, direct injection (DI) diesel engine were studied at different engine loadings when operated with emulsified biodiesel fuel and compared with those when operated with diesel (HSD) and biodiesel blend (JB10). The results showed that JB10 and its emulsified fuel exhibited similar combustion stages as that of HSD and no undesirable combustion features such as unacceptable high rate of rise of cylinder gas pressure were observed. Ignition delay was longer with increasing percentage of water in the emulsified fuel at higher engine loads. Brake specific fuel consumption (BSFC) decreased while brake thermal efficiency (BTE) increased with increase in proportion of water in the emulsified fuel for all engine loadings. Emulsified fuel with 15% water had same BSFC as that of HSD and JB10 for all engine loadings. However, BTE of emulsified fuel decreased by 7-8% as compared to HSD and JB10. Reduction (30-50%) in emissions of CO, CO_2 and NO_x was observed for emulsified fuel as compared to JB10 and HSD. Hence, emulsified biodiesel JB10 with water can be recommended for long run use in diesel engine in place of biodiesel alone for lesser environmental pollution.

***Keywords*—**Combustion, Diesel engine, Emissions, Emulsified fuel and Jatropha biodiesel.

I. INTRODUCTION

FASTER depletion of fossil fuels and strict emission regulations drive the researchers to search for alternative fuels. for diesel engines. Efforts have been made to use straight vegetable oils as fuel in diesel engines. But higher viscosity of vegetable oil restricts its direct use in diesel engines. So the vegetable oils are converted in to biodiesel using transesterification process. Biodiesel is a promising substitute fuel which gives reasonably satisfactory performance, reduced emissions except oxides of nitrogen (NO_x) and does not require any engine modifications. However, the only drawback reported in using biodiesel in diesel engine is production of more NO_x due to availability of higher oxygen and temperature. This problem can be overcome by either retarding the injection timing which needs engine modification or by using exhaust gas recirculation (EGR) system in the engine, but volumetric efficiency will be reduced due to higher temperature and pressure of air. Hence, the other possibility of reducing NO_x emission from engine running with biodiesel could be by using its emulsion with water.

The decrease in emissions achieved by properly designed diesel-water emulsification is universal regardless of engine. The primary benefit of water-diesel emulsions in diesel engines is a notable reduction in NO_x emissions [1], [2]. The addition of water in the form of emulsion improved combustion efficiency. It was found that brake power, engine power and also the engine torque were improved with the emulsified fuels for both diesel and benzene till addition of 25% water. Adding water to diesel-benzene could reduce bad emissions of the vehicles [3], [4]. Nano-additive blend reduced peak pressure heat release rate and ignition delay as compared to neat diesel, it was also reported that there was reduction in NO_x and smoke emissions with emulsified fuel [2]. The emulsion method had higher potential of simultaneous reduction of NO and smoke emission at all loads than water injection method. However, CO and HC levels were higher with emulsion than water injection [5]. Emissions of NO_x and PM decreased up to 30% and 60%, respectively where as hydrocarbons and carbon monoxide increased with increasing water content in the emulsion. The combustion efficiency was improved when water was emulsified with diesel up to 15 % [6]. The combustion started earlier for biodiesel and its blends compared to diesel [7]. The peak cylinder pressure of biodiesel and its blends was found to be higher than that of diesel fuel at lower loads and almost identical at higher engine loads. The peak pressure rise rate and peak heat release rate for biodiesel were higher than those for diesel fuel at lower engine loads, but were lower at higher engine loads [8].

Water emulsified fuels are accorded more priority due to the simultaneous reduction of NO_x and smoke. No engine modification is required to use the emulsified fuel directly into the cylinder. But emulsification process is difficult due to immiscibility of water and fuel. Surfactant is added to overcome this difficulty and improve the stability for longer duration. The presence of surfactant is crucial for stability of water fuel emulsion. It reduces the interfacial tension between

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water and fuel and stabilizes the emulsion for longer hours. The added water acts as diluents, which lowers the combustion temperature and suppresses NO_x formation.

Due to shortage of fossil fuels, considerable research work was taken up to replace fossil fuel with biodiesel. Many of research reported that use of biodiesel blend JB10 in diesel engine resulted in giving similar performances and reduced emissions as compared to diesel except NO_x [11-14]. Hence, attempt should be made to reduce NO_x for biodiesel blend fuels. The reduction in NO_x formation with emulsified diesel has prompted us for trying emulsified biodiesel blend in diesel engine with the following objectives: To study the stability characteristics of the JB10 emulsified fuel with surfactant, to compare the fuel properties of JB10 and its emulsified fuel and to study the performance and emissions characteristics of a diesel engine when operated with JB10 and its emulsified fuel.

II. Methodology

A two step 'acid–base' process; acid-pretreatment followed by main base-transesterification reaction; using methanol as reagent and H_2SO_4 and KOH as catalysts for acid and base reactions, respectively, was followed to produce biodiesel from crude jatropha oil. After that JB10 (10% jatropha biodiesel and 90% HSD) was prepared by blending.

A. Selection of Surfactant

Nonionic surfactants Span 80 (HLB 4.3) and Tween 80 (HLB 15.0) surfactant were selected. In order to increase the stability of emulsion, combination of two surfactants were used. Span 80 (Sorbitan monoleate) and Tween 80 (Polysorbate 80 or Polyoxyethylene sorbitan monoleate) are non-ionic surface active agent. Both are regarded as non-toxic, non-irritating, non-corrosive in nature without any source for secondary pollutants formation in engines. It does not generate any toxic byproducts during combustion [3-4].

To stabilize the emulsion, two surfactants (emulsifiers) were blended; the resulting hydrophile lipophile balance (HLB) of the blend was easily calculated using Eqns. 1 and 2.

$$\%\,(A) = \frac{100\,(X - HLB_{(B)})}{HLB_{(A)} - HLB_{(B)}} \qquad (1)$$

$$\%(B) = 100 - \%(A) \qquad (2)$$

There exist two distinct emulsion types for oil and water; oil-in-water type and water-in-oil type. Water–in–oil type is suited best type of fuel for internal combustion engines rather than oil–in–water type. The reason behind the use of water–in–oil emulsion (WOE) as engine fuel is mainly due to the micro – explosion phenomenon of droplet of water, which caused large fragmentation of the oil and less change in viscosity with water content. While using emulsion as fuel, care must be taken so that there may be no side effects and it should be produced economically. The proportion of emulsifiers which were used to prepare W/O emulsions with HLB values of 4.3 to 6.0 (http://www.firp.ula.ve/archivos/historicos/76_Book_HLB_ICI.pdf).

To determine desired HLB, three samples were prepared for HLB 4.3, 5 and 6 by taking same amount of oil, water and surfactant with different proportion of SPAN 80 and TWEEN 80 such as HLB 4.3 (SPAN 80 100%), HLB 5 (SPAN 80 93% and TWEEN 80 7%) and HLB 6 (SPAN 80 83% and TWEEN 80 17%) and mixing them in a homogenizer at same speed for the same time at room temperature. The emulsion giving highest stability i.e. the one that separated last is the suitable HLB value selected.

B. Preparation of Emulsified Fuel

At first JB10 (10 percent Jatropha biodiesel and 90 percent HSD) was prepared. After that, homogenizer was used to prepare the emulsified fuel by mixing JB10, water (10%, 15% and 20% by volume) and surfactant (HLB 5) mixer (0.5%, 1% and 2% by volume) at various test speed of homogenizer (2000, 2500 and 3000 rpm) for 15 min duration at room temperature. Total twenty-seven samples were prepared for evaluation of stability characteristics using Eqn. 3. Each sample was replicated thrice to get a reasonable output.

Stability characteristics of the biodiesel emulsion fuel

$$\text{Separated water layer } (\%) = \frac{(H_2O)_{initial} - (H_2O)_{final}}{(H_2O)_{initial}} \times 100 \qquad (3)$$

Where,

$(H_2O)_{initial}$ = initial water content

$(H_2O)_{final}$ = final water content

C. Experimental Setup for Engine Testing with Emulsified Biodiesel blend

The experimental setup for engine testing comprised a constant speed, 10.3 kW, 4-stroke, single cylinder, water cooled, direct injection (DI) diesel engine and a hydraulic dynamometer (Fig. 1). Rotor shaft of the hydraulic dynamometer was coupled to the engine flywheel by a universal shaft and a gear box having 1:2 gear ratio. The dynamometer was equipped with a strain gauge based load cell and a digital readout for measuring engine torque. Load was applied by turning the loading wheel of the dynamometer keeping water pressure at 1.5 kg/cm^2. The technical specifications of the test engine and the hydraulic dynamometer are given in Table I.

D. Measurement of Cylinder Gas Pressure

The cylinder gas pressure was measured by a Kistler Model-SN14 piezoelectric pressure transducer mounted on the cylinder head. Crankshaft position and the engine speed were obtained using a rotary Encoder (Model-E50S8) and it was connected to the crankshaft.

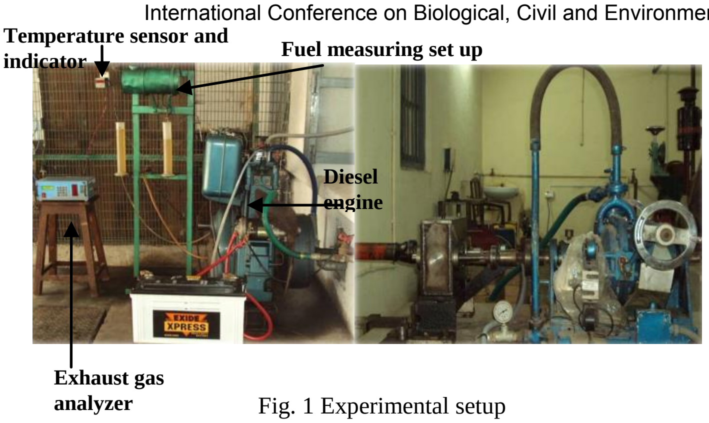

Fig. 1 Experimental setup

TABLE I
TECHNICAL SPECIFICATIONS OF ENGINE AND HYDRAULIC DYNAMOMETER

Particulars	Details	Particulars	Details
Engine		Hydraulic dynamometer	
Type	DM14	Type	Hydraulic
Number of cylinders	1	Water pressure at inlet (kg/cm^2)	1.5
Bore × stroke (mm)	114.3 × 116	Power (HP)	Max. 100
Cycle	4-stroke	Max. speed range (rpm)	5650-8000
Maximum power (kW)	10.3, naturally aspirated		
Rated speed (rpm)	1500		
Compression ratio	15.5 : 1		
Injection timing (° before TDC)	24		

E. Testing Procedure

The engine was first run on diesel (HSD) as reference fuel in order to determine the rated engine load in terms of torque. The rated load was found to be 52.0 N-m. It was taken as 100% engine load. Accordingly, intermediate engine loads corresponding to 20%, 40%, 60% and 80% of the torque obtained at rated power were calculated as 10.4, 20.8, 31.2 and 41.6 Nm, respectively. The test for each fuel was conducted for a total of six engine loads in the governor controlled range and the load was applied at 30 min interval. After letting the engine to run for 15 min to achieve stabilized condition, different readings were recorded at 5 min interval for a particular load. Test for each fuel was also replicated thrice and the values of each parameter obtained in each of these tests were averaged.

III. RESULTS AND DISCUSSION

A. Stability Characteristics of Emulsified Fuel

The separated layer of water in the emulsified fuel obtained from biodiesel blend (JB10) with different HLB values of surfactants and water is shown in Fig. 2. From this figure it can be seen that the emulsified fuel with HLB 5 produced separated water layer at longer time interval i.e. water mixed with JB10 was separated after 72 hours as compared to 24 hours and 48 hours for HLB 4.3 and 6, respectively. Hence, the surfactant percentage (Span 80, 93% and Tween 80, 7%) giving HLB 5 was selected for further study in optimizing the speed of homogenizer, amount of surfactant and water to be added in making emulsified fuel from JB10.

After 24 hours | After 48 hours | After 72 hours

Fig. 2 Test for deciding suitable HLB values by using different amount of surfactants

B. Stability Characteristics of JB10 Emulsified Fuel with Different Amount of Surfactants

Stability of all emulsified fuels prepared (JB10 with 10% water- JB10S10W, JB10 with 15% water – JB10S15W and JB10 with 20% water – JB10S20W) by varying the surfactant quantity keeping HLB as 5 and rpm of the homogenizer were evaluated in terms of separated water.

It can be seen from Fig. 3, that there is no separation of water layer up to 48 hours for all the emulsified fuels and after that there are some variations in separated layer of water. From this figure it can be seen that homogenizer running at 2000 and 3000 rpm produced emulsified oil with higher separated layer of water as compared to 2500 rpm. This might be due to improper mixing at 2000 rpm and reduction in binding ability of surfactant at 3000 rpm. Hence, 2500 rpm of the homogenizer was selected. Further, among the water quantity added (i.e. 10%, 15% and 20%), 10% gave better result with 0.5% and 2% surfactant, whereas 15% water produced lesser separated layer of water for 1% surfactant. While comparing the separated layer of water at 2500 rpm of the homogenizer for different percentage of surfactants, no much variation was observed. Hence, taking cost into account, a minimum surfactant of 0.5% was selected for making emulsified fuel with JB10 and 10% or 15% water named as JB10S10W or JB10S15W, respectively.

C. Fuel Properties

The various fuel properties namely density, kinematic viscosity, calorific value, acid value, flash point and water content of HSD, crude Jatropha oil (CJO), Jatropha biodiesel (JB) and its emulsified fuel were determined following the standards and these are summarized in Table II along with latest Indian biodiesel standards (IS 15607). It can be seen from Table II that fuel properties of JB10 and its emulsified fuel are quite comparable with those of HSD and are well within the latest Indian standards for biodiesel.

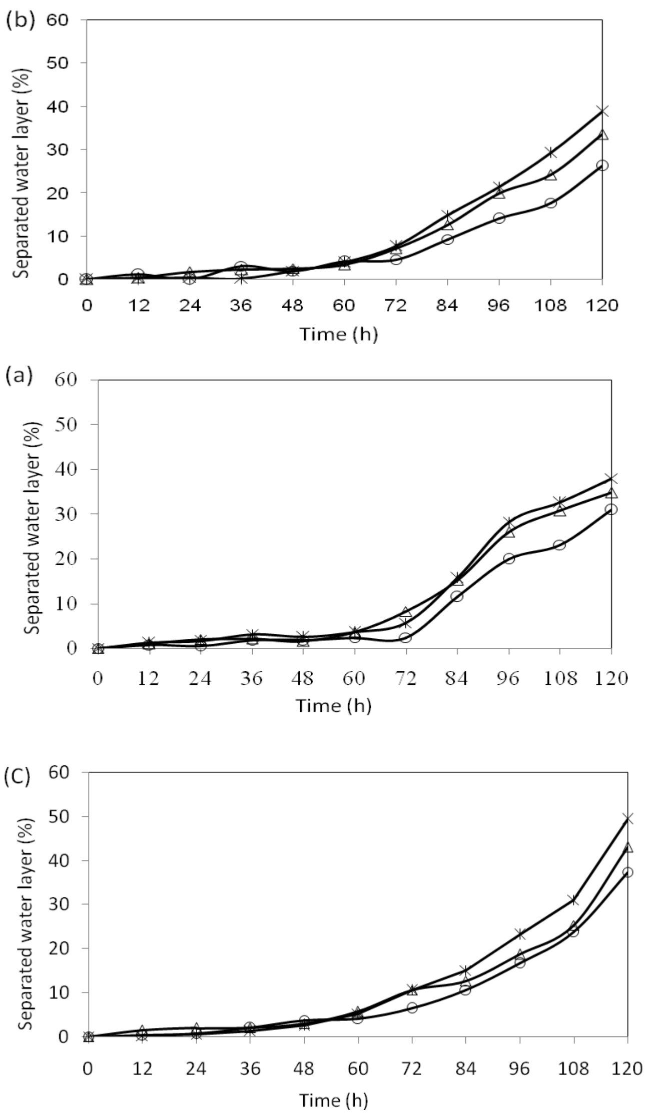

Fig. 3 Effect of mixing speed on the stability behavior of W/JB10 emulsion with 0.5% surfactant: (a) 10% W/JB10 emulsion, (b) 15% W/JB10 emulsion, and (c) 20% W/JB10 emulsion, 2500 rpm, 2500 rpm, and 3000

1. Density

The density of CJO was reduced by about 3.34% on its conversion to biodiesel. The density of fuel blend JB10, JB10S10W, JB10S15W and JB10S20W were found to be 0.96, 3.50, 4.22 and 5.54% higher than that of HSD, respectively. The density of emulsified fuel was observed to increase with increase in concentration of water in it. This was due to higher density of water as compared to JB10. Also, higher densities of CJO and JB as compared to HSD might be attributed to the higher molecular weights of triglyceride molecules present in them.

TABLE II
FUEL PROPERTIES OF JATROPHA BIODIESEL, ITS EMULSIFIED FUEL WITH WATER AND HSD

Fuel type	Density, kg/m^3	Kinematic Viscosity, cSt	Calorific value, MJ/kg	Acid value, mg KOH/g	Flash point, °C	Water content, ppm
CJO	899	33.10	36.53	33.46	252	2140
JB	869	4.51	36.86	0.450	166	470
HSD	829	2.87	42.5	-	56	215
JB10	837	2.91	40.85	0.222	62	235
JB10S10W	858	3.93	38.72	0.294	68	353
JB10S15W	864	4.87	36.89	0.356	72	491
JB10S20W	875	6.82	33.76	0.378	90	558
Indian IS 15607-05	860-900	2.5-6.0	-	0.5 max	120 min	500 max

2. Kinematic Viscosity

The kinematic viscosity of JB1O, JB10S10W, JB10S15W and JB10S20W at 40 °C was found to be 1.01, 1.37, 1.69 and 2.38 times more than that of HSD, respectively. The kinematic viscosity increased with increase in concentration of water in the JB10 emulsified fuels and was found well within the limits prescribed by the Indian standards for biodiesel, except JB10S20W.

3. Calorific Value

The calorific values of CJO and JB were found to be around 36.53 and 36.86 MJ/kg, respectively, which were lower than that of HSD by 14.05% and 13.27%. This was due to the difference in their chemical composition from that of HSD or the difference in the percentage of carbon and hydrogen content or the presence of oxygen molecule in the molecular structure of CJO and JB. With increase in water content of emulsified fuel, calorific value decreased, because water present in the fuel was converted to steam by using some of the heat evolved by the combustion of fuel and the steam found during combustion was not condensed then this amount of heat was lost resulting in lower calorific value.

4. Flash Point

The flash points of CJO and JB were found to be 252 °C and 166 °C, respectively, and were quite high compared to 56 °C for the HSD. The flash points of JB10 and its emulsified fuel were also higher than that of HSD and found to be increased with increase in water concentration in the emulsified fuel. Generally, a material with a flash point about 90 °C or higher is considered as non-hazardous from storage and fire-hazard point of view.

D. Engine Performance

The performance of a 10.3 kW single cylinder 4-stroke water cooled DI diesel engine was studied with HSD, JB10 and its emulsified fuel (JB10S10W and JB10S15W) by varying the engine load. Cylinder gas pressure, heat release rate, fuel consumption, engine speed were measured and discussed in the following sections:

1. Cylinder Gas Pressure (CGP)

The combustion characteristics of different fuels were determined by studying the variation in CGP with respect to crank angle (CA) at different engine loadings (Fig. 4a and Fig. 4b for 20% and full engine load, respectively).

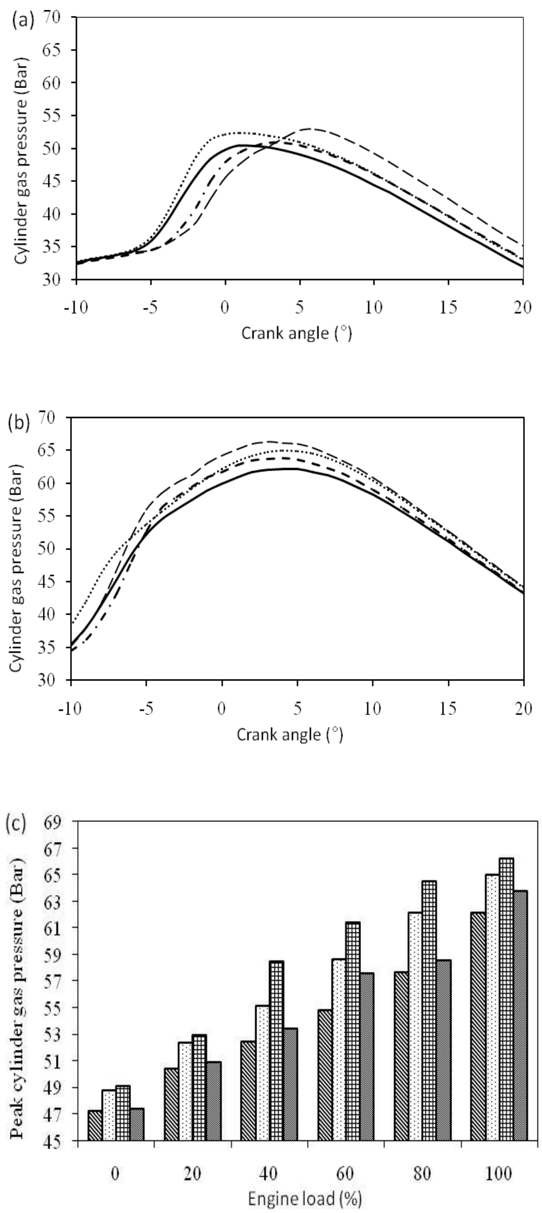

Fig. 4 Variations of cylinder gas pressure and peak cylinder gas pressure with respect to crank angle for JB10, its emulsified fuel and HSD: (a) At 20% engine load, (b) At full engine load, and (c) Peak cylinder gas pressure, ——— HSD, ... JB10, - - - - JB10S10W and — · — JB10S15W, HSD, JB10, JB10S10W, and JB1OS15W.

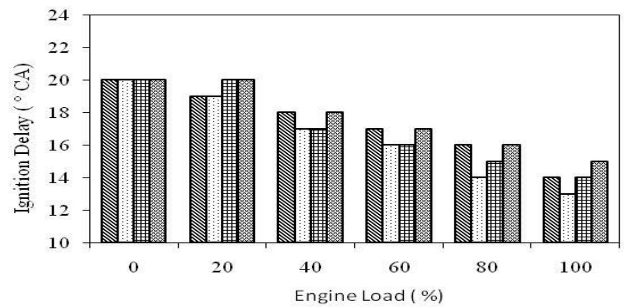

Fig. 5 Variations of ignition delay with engine load for JB10, its emulsified fuel and HSD, HSD, JB10, JB10S10W, and JB1OS15W

3. Ignition Delay (ID)

ID was calculated in terms of degree of crank angles between the start of fuel injection and the start of combustion and its variation with engine load for different fuels are presented in Fig. 5. It can be seen from this figure that the delay period for all the fuels tested decreased with increase in engine load. IDs for HSD, JB10, JB10S10W and JB10S15W were calculated to be 19°, 19°, 20° and 20° crank angle (CA), respectively at 20% load condition, as compared to 14°, 13°, 14° and 15° CA at full engine load. The elevated temperature existing in the combustion chamber at higher engine loads enhanced the fuel vaporization process and reduced the chemical delay and the overall ignition delay period. As the engine load decreased, the residual gas temperature and wall temperature decreased, which resulted in lower charge temperature at the time of fuel injection and hence lengthening the ignition delay period.It can also be seen from Fig. 6 that JB10 showed shorter ignition delay as compared to HSD due to higher cetane number of biodiesel. The emulsified fuels showed increased ignition delay as compared to JB10 due to the increase in percentage of water in the emulsion and vaporization of water created higher ignition delay period.

4. Brake Specific Fuel Consumption (BSFC)

The fuel consumption characteristic of an engine is an important parameter that reflects how economical the engine performance is. The variations in the brake specific fuel consumption (BSFC) with engine load for JB10, its emulsified fuel and HSD are shown in Fig. 6. It can be seen from this figure that the BSFC reduced with increase in engine load for all the fuels tested. This was due to the higher percentage increase in brake power with increase in engine load as compared to the increase in fuel consumption due to relatively less heat losses at higher engine loads.

BSFC for HSD was found to be lowest except at higher load, where as the emulsion containing 10% water content was having highest BSFC values among the fuel tested. When the percentage of water in the emulsion increased, BSFC

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decreased. The reduction in BSFC with higher water percentage in emulsified fuel might be attributed to the formation of finer spray due to rapid evaporation of water, longer ignition delay resulting in more fuel burning in premixed combustion and suppression of thermal dissociation due to lower cylinder average temperature. The evaporation and additional mass of water caused the cylinder average temperature to lower with increasing water amount in the emulsified fuel.

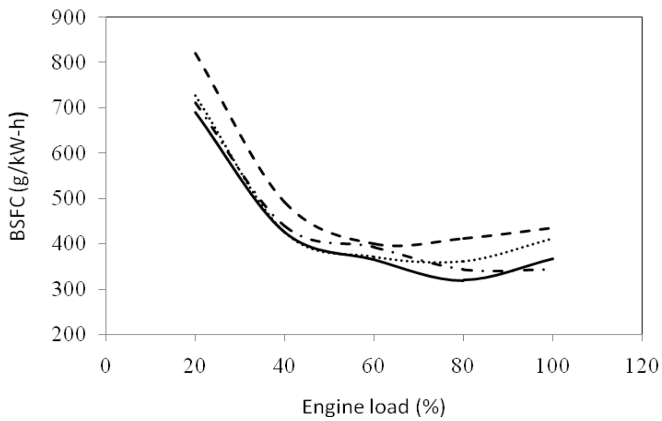

Fig. 6 Variations of BSFC for JB10, its emulsified fuel and HSD at different engine loads, ——— HSD, ... JB10, - - - - JB10S10W, and — · — JB10S15W

5. Brake Thermal Efficiency (BTE)

Brake thermal efficiency of a diesel engine is the efficiency with which the chemical energy of a fuel is converted into useful work. The BTEs of a diesel engine when operated with JB10, its emulsified fuel and HSD at different engine loadings are compared in Fig. 7. It can be seen from this figure that BTE increased with an increase in percent load for all the fuel tested. BTE improves due to the reduction in friction loss and increase in brake power with increase in percent load. It was also observed that the brake thermal efficiency of biodiesel was less than that of diesel due to its lower calorific value. Emulsified fuels JB10S10W and JB10S15W exhibited lowest and highest BTE at all engine loads, respectively. This was because of the micro explosion phenomenon due to volatility difference between water and fuels which enhanced air fuel mixing during higher engine torque and hence the improvement in combustion efficiency. This might be the possible reason for higher brake thermal efficiency even though the calorific value of the emulsified fuel was less than that of biodiesel.

E. Exhaust Emissions

CI engines generate undesirable emissions during the combustion process. Constituents of emissions for diesel engine such as carbon monoxide, carbon dioxide and oxides of nitrogen when operated with different fuels were recorded with the help of an exhaust gas analyzer and are discussed below:

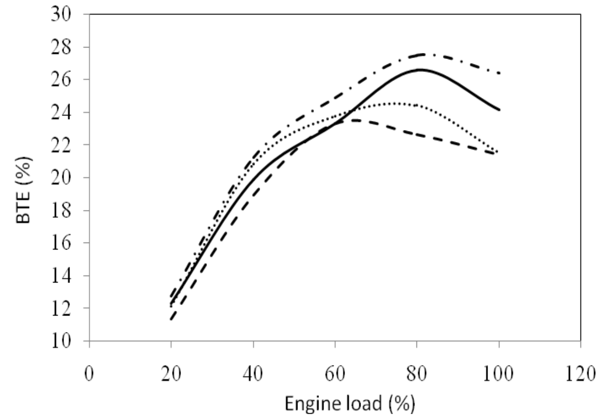

Fig. 7 Variations of BTE for JB10, its emulsified fuel and HSD at different engine loads, ——— HSD, ... JB10, - - - - JB10S10W, and — · — JB10S15W

1. Carbon Monoxide (CO)

CO is considered as undesirable emission as well as it represents lost chemical energy that was not fully utilized in the engine. The variations of CO with engine load for different fuels tested are shown in Fig. 8.

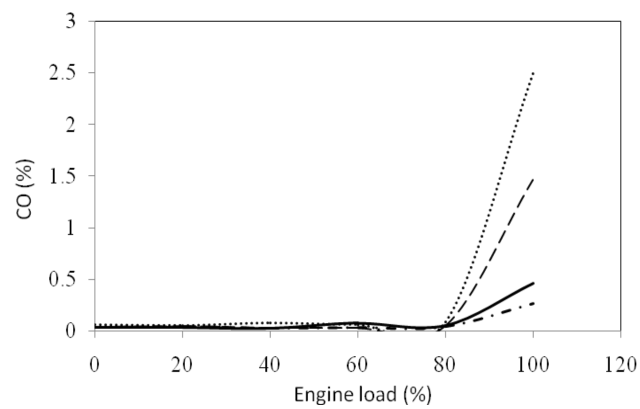

Fig. 9 Variations of CO for JB10, its emulsified fuel and HSD at different engine loads, ——— HSD, ... JB10, - - - - JB10S10W, and — · — JB10S15W

It can be seen from this figure that CO initially remain almost constant indicating not much greater differences except at higher load, it increased for all the fuel tested. At higher load, CO emission increased due to incomplete combustion of the excess fuel injected into the combustion chamber owing to low air-fuel ratio. The CO emission in general was found to be decreased significantly with increase in water content in the fuel blends at higher engine load tested.

2. Carbon Dioxide (CO_2)

The variations of CO_2 with engine load for JB10, its emulsified fuel and HSD have been presented in Fig. 9. It can be seen from this figure that the CO_2 emission in general increased with increase in engine load. As the amount of fuel injected into the combustion chamber increased with increase in engine load, quantity of fuel going through complete combustion also increased which resulted in an increase in cylinder temperature. At elevated temperature, performance of the engine improved with relatively better burning of the fuel resulting in higher CO_2 emission. It can also be seen from this figure that the emission of CO_2 had similar trend at all loads and no significant difference was observed between all the fuels tested. This might be due to higher losses and same combustion behavior of all the fuels tested at different engine loads.

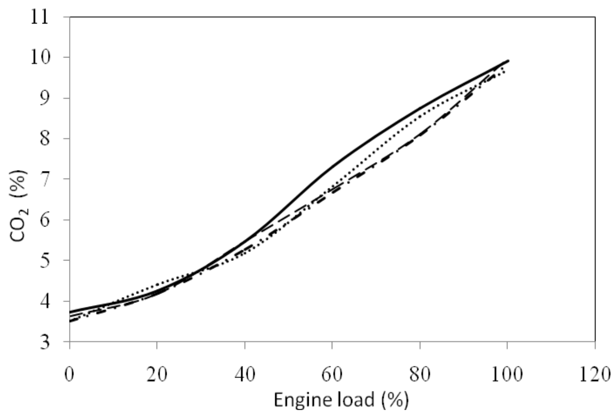

Fig. 9 Variations of CO_2 for JB10, its emulsified fuel and HSD at different engine loads ——— HSD, ... JB10, - - - - JB10S10W, and — · — JB10S15W.

3. Oxides of Nitrogen (NO_x)

At lower temperatures, nitrogen exists as a stable diatomic molecule but at higher temperature it becomes reactive. Hence, high temperature and availability of oxygen are the two main factors which facilitate the production of NO_x. It can be seen from Fig. 10 that the NO_x concentration in emission increased with increase in engine load. As the engine load increased, average gas temperature in the combustion chamber also increased as a result of increased heat energy liberation from the fuel. This led to higher NO_x emissions at higher loads up to 80%. Beyond this engine due to lesser availability of oxygen NO_x formation reduced for all the fuels tested.

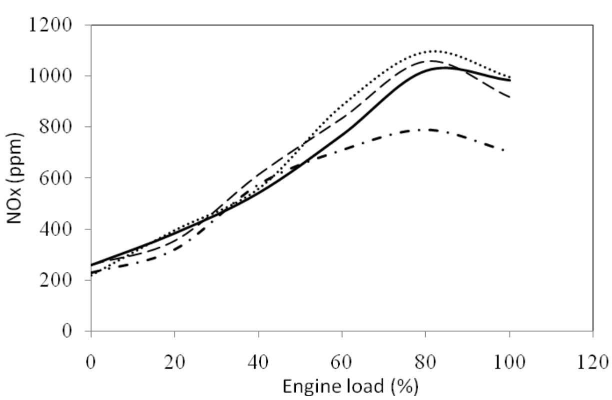

Fig. 10 Variations of NO_x for JB10, its emulsified fuel and HSD at different engine loads ——— HSD, ... JB10, - - - - JB10S10W, and — · — JB10S15W

The NO_x emission was found to be higher for JB10 than HSD, but NO_x emissions of emulsified fuels were found to be lesser than JB10. This was because the lower adiabatic flame temperature, due to the presence of water in the emulsified fuel, reduces the formation of NO_x. Another reason might be due to the finely dispersed water droplets of the emulsion causing a phenomenon known as heat sink. When heat sink occurs it results in the water contents of the inner phase partially absorbing the calorific value of the emulsions, thereby decreasing the burning gas temperature inside the combustion chamber and thus restraining the generation of NO_x.

IV. CONCLUSION

Based on the result of this study, the following specific conclusions were drawn:

(i) Among the hydrophile lipophile balance 4.3, 5 and 6 tested, HLB 5 was found to have better stability characteristics with JB10 emulsified fuel.
(ii) For lesser separation of water layer 0.5% surfactant SPAN 80 and TWEEN 80 was selected for making emulsified fuel at 2500 rpm from JB10 with 10% and 15% water by volume.
(iii) The fuel properties of JB, JB10 and its emulsified fuel were found to be slightly different from those of HSD but were well within the limits specified by the BIS standards for biodiesel, except JB10S20W.
(iv) Combustion analysis indicated that JB10 and its emulsified fuel exhibited similar pressure-crank angle trend as HSD and no undesirable combustion features such as unacceptable high CGP rise was observed.
(v) Ignition delay was longer with increasing percentage of water in the emulsified fuel at all engine loads.
(vi) BSFC and BTE of emulsified fuel with 15% water content was lower and higher respectively as compared to JB10 and emulsified fuel with 10% water content.
(vii) The exhaust gas emissions such as CO, CO_2 and NO_x from the diesel engine when operated with emulsified fuel were found to be lower than those of JB10 and HSD.

Hence, emulsified JB10 with water could be recommended to replace HSD for lesser emission.

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