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FIRST LAW ANALYSIS OF DIESEL ENGINE PERFORMANCE USING DIESEL AND BIO-DIESEL FUEL

Tapan K. Gogoi[1+], N.K Sarma[1], A Ahmed Choudhury[1] and T. Talukdar[1]

[1]*Department of Mechanical Engineering, Tezpur University, Napaam, Tezpur, 784028, India*

[+] Corresponding author email:tapan_g@tezu.ernet.in

ABSTRACT

In this study, the performance of a single cylinder four stroke direct injection (DI) diesel engine is analyzed in the light of first law of thermodynamics. An energy balance study is carried out to quantify the various losses associated with diesel engine processes on the basis of experimental performance and emission data. The engine was fuelled with normal diesel and Jatropha Methyl Ester (JME) in order to obtain experimental results corresponding to steady state engine operations at full load. For both the fuel operations at full load, the energetic performance parameters of the engine were evaluated. The results showed lower brake thermal efficiency (BTE) and higher fuel consumption in respect of JME. From the energy analysis, it was seen that the fuel energy input was more with JME due to higher fuel consumption although the fuel calorific value was less for JME. The indicated power (IP) produced by the engine with JME operation was comparatively higher. The energy loss with the exhaust gases was marginally higher and the loss of energy due to cooling was slightly lower for the JME. However the unaccounted heat losses were significantly higher and this was the reason of lower BTE with JME. The viscosity of JME was higher (5.03 cSt) compared to diesel (2.2 cSt) and may be due to higher viscosity, the JME fuel did not atomize properly resulting in poor combustion. The combustion efficiency was found to be less with JME and higher losses of energy due to combustion inefficiency resulted in higher unaccounted losses and hence lower BTE with JME.

Keywords: Diesel engine, Biodiesel, Jatropha methyl ester, Energy analysis.

1. INTRODUCTION

The enormous growth of population and increasing number of vehicles employing internal combustion engines has drastically increased the demand for fossil fuels. This has ultimately created an alarming situation of imbalance between energy supply and demand. Fluctuating oil prices in the international market and regular price hike is a real big problem for developing countries like India which rely heavily on foreign oil imported in huge quantities every year. The use of biodiesel in diesel engine can play a vital role in helping the developing countries to reduce the dependence on foreign oil and make considerable savings in the annual oil import bill. Biodiesel is basically monoalkyl esters of long chain fatty acids derived from plants or animal matters. It is the name given to transesterified vegetable oil to describe its use as a diesel fuel. Biodiesel produced from different sources has been accepted as a clean alternative fuel worldwide. The advantages with biodiesel are that it is biodegradable, nontoxic, and essentially free of sulfur and aromatics, but contains about 10% built in oxygen, a factor which favours combustion. Its higher cetane number improves the ignition quality even when blended with petroleum diesel.

Biodiesel fuelled diesel engine results in substantial reduction of unburned hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM). In India biodiesel obtained from non edible plant species such as *Jatropha curcas (Ratanjot), Pongamia pinnata (karanj), Azadirachta indica (Neem), Madhuca indica* (*Mahua*), *Hevea brasiliensis* (*Rubber seeds)* sources has tremendous potential as possible renewable alternate diesel fuels. However the disadvantage with these biodiesel is that its viscosity is high and calorific values are significantly low. High viscosity leads to poorer atomization of the fuel spray, improper air fuel mixing and incomplete combustion. Lower fuel calorific value results in higher fuel consumption. Biodiesel is less suitable for low temperature application as its cloud and pour points are higher than those for petro diesel. At low temperature, fuel forms wax crystals, which can clog fuel lines and filters in a vehicle's fuel system.

Many researchers [1-12] have experimentally evaluated engine performance, fuel combustion and emission characteristics in conventional diesel engines fuelled with various bio-diesels and its diesel blends. Higher brake specific fuel consumption (BSFC) and reduced brake thermal efficiency (BTE) are most common observation with biodiesel blends.

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Most of the combustion analyses [3,4,9,11,13] performed on biodiesel reveal lower ignition delay, early heat release although biodiesel has slightly higher viscosity and lower volatility. Some of the above investigations [6,10,12,13] have reported reduction in HC, CO and PM emissions as well. Government of India through its National Biofuel Policy has been actively working on promotion of plant derived fuel for partial substitution of diesel. Among the many non edible plant sources of biodiesel, *Jatropha curcus* and *Karanj* are the two major feed stocks that have been considered as most suitable. *Jatropha* grows fast and is a drought tolerant plant that can be cultivated in degraded, barren, forest land and draft-prone areas. It has enormous potential for biodiesel production and has been recommended by National Biodiesel Board of India as a source of alternative fuel for blending with commercial diesel [4]. The oil content is 35-40% in the seeds and 50-60% in the kernel. Many researchers have used raw *Jatropha* oil and its methyl ester (biodiesel) as fuel in unmodified diesel engine. However most of the works [1,2,4, 5,9,10,11,14] have concentrated on performance, emission and combustion characteristics and no work specifically on energy analysis of diesel engine system with JME is available. Usually conventional diesel engine performs well with lower percentage blends. Engine performance deteriorates with increase in concentration of biodiesel in the fuel blend. It's quite important to analyze the behavior of pure 100% biodiesel on engine performance to find out the possible changes and modification that will be required to overcome the difficulties with the use of pure biodiesel. The present study therefore analyzes the performance of a single cylinder four stroke diesel engine using conventional diesel and 100% biodiesel (JME) fuel while at the same time an energy balance study quantifies the various losses associated with the engine processes for different fuel operations at full load. Fuel properties of the tested fuels are listed in Table 1.

Table 1: Properties of diesel and JME

Fuel	Density at 15deg. C (kg/m^3)	Calorific value (kJ/kg)	Viscosity at 40 deg. C (cSt)
Diesel	0.8395	41848	2.20
JME	0.8885	36800	5.03

2. TEST SET UP AND PROCEDURE

The test set up (Fig. 1) is a single-cylinder, four-stroke, naturally aspirated, Kirloskar DI diesel engine with a rated power of 3.5 kW at 1500 rpm. The engine was provided with necessary instruments for measurement of air flow rate, fuel flow rate, pressure, temperature, load and speed. The fuel flow and the air flow rates were measured by flow transducers. Cylinder pressure was measured by the piezo electric sensor mounted in the cylinder head.

Thermocouples were used to measure different temperatures, such as exhaust temperature, coolant temperature, and inlet air temperature. The engine was coupled with an eddy current dynamometer for controlling the engine torque through computer. The engine speed was measured by a rotary crank angle encoder. Two rotameters were provided for engine cooling water and calorimeter water flow measurement. A Lab view based engine performance analysis software package was provided for on line performance evaluation. An INDUS five gas analyzer was used to measure the concentration of gaseous emissions. For each fuel operation at full load, three test run were performed under identical conditions to check for the repeatability of the results which was found to be within acceptable limit and the average results have been reported in this paper.

Fig. 1: Test engine set up

3. ENERGY ANALYSIS

Experiments with engines very often involve an energy balance on the engine. For simplifying the first law calculations of the test engine, it was assumed that the engine operates at steady-state, the combustion air and the exhaust gases each forms ideal gas mixtures. Further, the potential and kinetic energy effects of the incoming air and fuel and outgoing exhaust gas streams were ignored. Total seven species (CO, CO_2, O_2, NO, HC, H_2O, and N_2) were taken into consideration. It was assumed that the reference environment has a temperature (T_0) of 298.15 K and a pressure (P_0) of 1 atm. The detailed methodology of calculation of various terms associated with energy balance study is described in this section.

Fuel Energy Input (kW) = $\dot{m}_f$ × Calorific Value (1)

Where $\dot{m}_f$ is the fuel flow rate of the engine in kg/sec.

$$\text{Brake power (BP) (kW)} = \frac{2\pi NT}{60000} \qquad (2)$$

Where N is the engine rpm, T is the engine torque measured by the dynamometer.

Frictional power (kW), $FP = IP - BP$ (3)

Heat lost to coolant (kW),

$$\dot{Q}_w = \dot{m}_{w.engine} C_{pw} (T_2 - T_1) \quad (4)$$

Where $\dot{m}_{w,engine}$ is the mass flow rate of engine cooling water. The volume flow rate of cooling water is measured by adjusting the flow rate of rotameter (engine) and this is multiplied with the density of water to obtain $\dot{m}_{w,engine}$. T_1 and T_2 are the engine water inlet and outlet temperatures respectively. C_{pw} is the specific heat of water evaluated at the mean of the temperatures T_1 and T_2. The density of water is also evaluated halfway between T_1 and T_2.

The exhaust energy was calculated from the enthalpies of products following the procedure outlined in [15]. The remainder of the energy that was not measured which can be found from energy conservation is termed as unaccounted miscellaneous losses. Based on the emission results obtained at full load and considering equilibrium of these species in the combustion products, the following molar based reaction equation was considered.

$$C_xH_yO_z + \lambda(O_2 + 3.76N_2) \rightarrow aCO + bCO_2 + cH_2O + dO_2 + eC_xH_yO_z + fNO + gN_2 \quad (5)$$

The values of these coefficients per mole of fuel were calculated and the exhaust energy in kW was calculated using equation (6). The molecular formula of NRL diesel is approximated as $C_{12}H_{23}$ [16], the chemical formula of pure biodiesel is derived from the fatty acid composition of Jatropha Curcus oil as $C_{18.197}H_{40.86}O_{2.064}$. Table 2 shows the typical emission results for diesel and JME at full load. The values of the coefficients for the two fuels at full load are shown in Table 3.

Table 2: Emission results

Fuel	CO (%)	CO_2 (%)	O_2 (%)	NO (ppm)	HC (ppm)
Diesel	0.19225	12.5499	11.5000	15.0414	0.0197
JME	0.27663	18.4128	16.9474	22.4184	0.0239

Table 3: Molar coefficient

Fuel	a	b	c	d	e	f	g
Diesel	0.19225	12.5499	11.5000	15.0414	0.0197	0.11381	109.415
JME	0.27663	18.4128	16.9474	22.4184	0.0239	0.13256	157.441

$$\dot{Q}_{ex} = \dot{n}_f \sum_{i=1}^{n} a_i \Delta\bar{h}_i \quad (6)$$

In the above equation, $\Delta\bar{h}_i$ is enthalpy change of the i th product corresponding to the states of exhaust gas temperature and the reference temperature. This is expressed as $\Delta h = h(T) - h(T_0)$ and a_i is the molar amount of the i th component (i.e., the coefficient of the component i in the reaction equation). n is the number of products considered in the exhaust gases.

4. RESULTS AND DISCUSSION

4.1 Performance analysis

4.1.1 Brake thermal efficiency and brake specific fuel consumption

The BTEs for diesel and JME at full load are shown in Fig. 2. BTEs for the two fuel operations were closer to each other, being marginally lower for JME. The BTE values were 24.836% and 23.647% for diesel and JME respectively. BSFC for the tested fuels at full load is shown in Fig. 3. BSFC of the engine operated with JME was higher due to higher fuel consumption rate. Fuel consumption rate was more for the biodiesel due to higher injection line pressure and reduced fuel loss on account of its higher viscosity and density. Moreover, calorific value of JME was less and therefore when it was attempted to load the engine in order to produce a given BP (3.5 kW at full load) it resulted in increased fuel consumption in respect of JME. The BSFC value for JME was 0.414 kg/kWh against 0.346 kg/kWh corresponding to that of normal diesel.

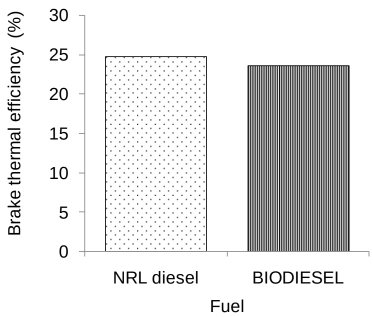

Fig. 2. BTE at full load

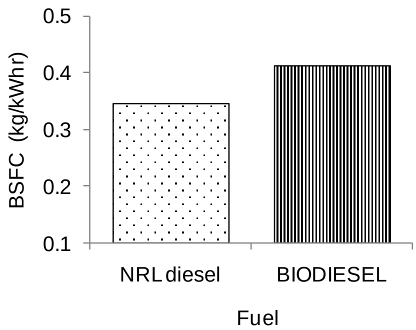

Fig. 3. BSFC at full load

4.1.2 Indicated power

IP is the power actually produced in the engine obtained from the pressure volume plot (indicator diagram). IP for the tested fuels at full load is shown in Fig. 4. IP for diesel and JME fuel operations were 6.399 kW and 6.696 kW respectively. It was observed that the compression work was lower for JME and there was a slight increase in the combustion and expansion work with JME. Hence the net work done during the cycle was more and this ultimately resulted in higher IP.

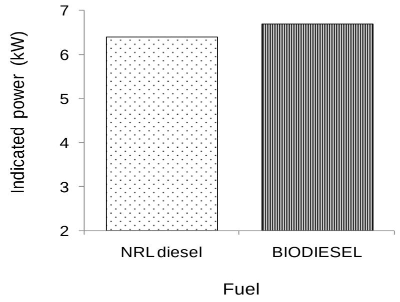

Fig. 4. IP at full load

4.1.3 Indicated thermal efficiency and indicated specific fuel consumption

Indicated thermal efficiency (ITE) is the ratio of IP to the input fuel energy and is another parameter that measures the performance of an engine. Fig. 5 shows the ITE and it was more or less same for both the fuels. ITE values were 45.406% and 45.237% for diesel and JME at full load respectively. As can be seen from Fig. 6, ISFC was comparatively higher for JME which was again due to higher fuel consumption in case of JME although the IP for JME was slightly higher.

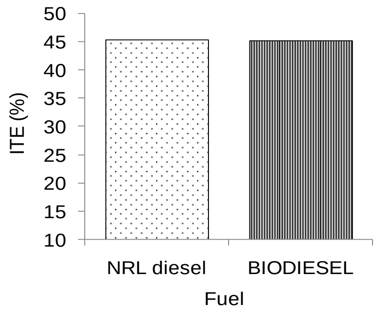

Fig. 5. ITE at full load

4.2 Energy analysis

4.2.1 Fuel energy

The energy input with the tested fuels is shown in Fig. 7. JME provides slightly higher energy input than diesel fuel for the same BP output. This was due to higher fuel consumption with JME, although its calorific value was less. Since the fuel energy input was more and the BP output being the same for both the fuels at full load, it resulted in slightly lower BTE in case of JME.

4.2.2 Energy losses in engine cooling

Fig. 8 shows the energy loss in cooling the engine. Cold water was circulated through the engine jacket for the purpose. The heat carried away by coolant generally consists of heat transferred to the combustion chamber walls from the gases in the cylinder, heat transferred to the exhaust valve in the exhaust process, and a substantial fraction of the friction work [17] . Heat loss to coolant for engine operation with diesel and JME were 3.719 kW and 3.648 kW respectively, slightly being less for JME.

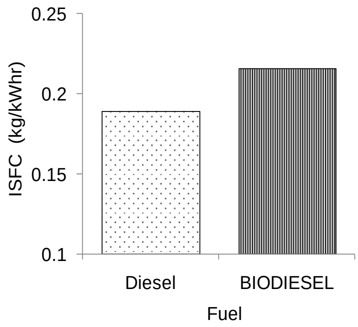

Fig. 6. ISFC at full load

4.2.3 Energy losses with exhaust gases

A major part of the fuel input energy is carried away by the hot exhaust gases. The energy loss accompanying the exhaust gases is shown in Fig. 9. Exhaust loss with JME was not significantly different from that of diesel. It was 3.605 kW with JME while the same for diesel was 3.556 kW.

4.2.4 Unaccounted losses

The unaccounted losses include heat transfer from the engine's external surface including losses resulting from incomplete fuel combustion. This is shown in Fig. 10. The unaccounted losses were more for JME, more than double when compared to diesel. Higher unaccounted losses in case of JME could be ether due to high rate of convective and radiation heat transfer or due to inefficient combustion of JME in the combustion chamber. The combustion efficiency of JME was less and it was 69.92% compared to 79.51% of diesel.

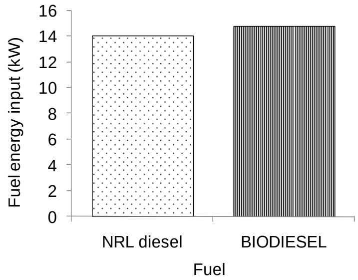

Fig. 7. Fuel energy input at full load

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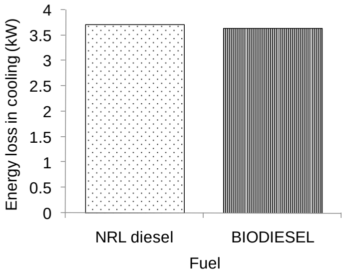


Fig. 8. Cooling loss at full load

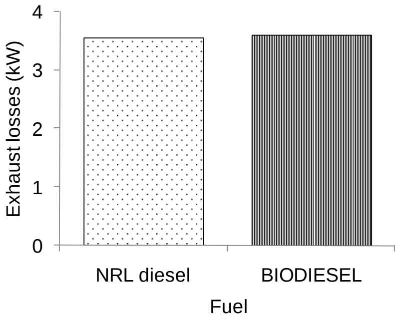


Fig. 9. Exhaust losses at full load

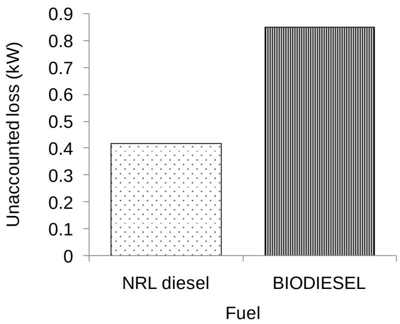
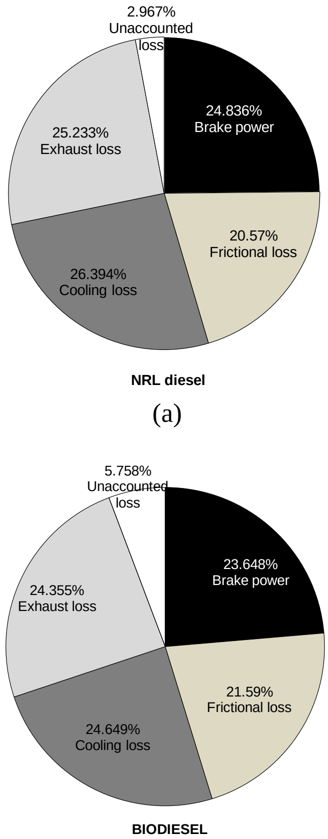


Fig. 10. Unaccounted losses at full load

4.2.5 Energy distributions at full load

Fuel energy input for diesel and JME being different, these losses can be shown as percentage of its fuel input energy. Fig. 11 shows the distributions of the fuel energy for the tested fuels. As can be seen, the cooling and exhaust losses as percentage of fuel energy were less, whereas the frictional and particularly the unaccounted losses were more for JME.



(b)

Fig. 11. Fuel energy distributions for (a) NRL diesel and (b) biodiesel

5. CONCLUSIONS

Based on the observations and the analyses it can be concluded the fuel energy input as well as the unaccounted losses were more in case of JME. This could probably be the reason of slightly lower efficiency with JME. Fuel consumption was more with JME due to its lower calorific value and also higher viscosity of JME may have affected the atomization and the subsequent combustion process leading to higher unaccounted losses. Therefore, it is summarized there is scope of improvement in engine performance when it is operated with pure biodiesel (JME).

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AUTHOR BIOGRAPHY

Dr. Tapan Kumar Gogoi is currently an Associate Professor of Mechanical Engineering at Tezpur University, Assam, India. He has more than 18 year of teaching experience including 5 years experience in research in the field IC engine, alternate fuel technology. Engine performance, combustion and emission analyses with alternate fuels, numerical simulation of engine processes, energy and exergy analyses of advanced hybrid thermal power systems, computational heat transfer and fluid flow, study of fuel spray and its atomization characteristics, spray combustion modeling including modeling of fuel injection system, droplet heating and evaporation are some of his current areas of research.