Hindawi Publishing Corporation
Journal of Biomedicine and Biotechnology
Volume 2012, Article ID 235485, 8 pages
doi:10.1155/2012/235485

Research Article

Eucalyptus Biodiesel as an Alternative to Diesel Fuel: Preparation and Tests on DI Diesel Engine

Lyes Tarabet,[1] Khaled Loubar,[2] Mohand Said Lounici,[3] Samir Hanchi,[1] and Mohand Tazerout[2]

[1] *LSE, Ecole Militaire Polytechnique, P.O. Box 17 Bordj El Bahri, Algeria*
[2] *GEPEA, UMR 6144, DSEE, Ecole des Mines de Nantes, P.O. Box 44307 Nantes, France*
[3] *LDMV, Université de Boumerdes, P.O. Box 35000 Boumerdes, Algeria*

Correspondence should be addressed to Lyes Tarabet, ltarabet@gmail.com

Received 25 January 2012; Accepted 14 March 2012

Academic Editor: Kazim Husain

Nowadays, the increasing oil consumption throughout the world induces crucial economical, security, and environmental problems. As a result, intensive researches are undertaken to find appropriate substitution to fossil fuels. In view of the large amount of eucalyptus trees present in arid areas, we focus in this study on the investigation of using eucalyptus biodiesel as fuel in diesel engine. Eucalyptus oil is converted by transesterification into biodiesel. Eucalyptus biodiesel characterization shows that the physicochemical properties are comparable to those of diesel fuel. In the second phase, a single cylinder air-cooled, DI diesel engine was used to test neat eucalyptus biodiesel and its blends with diesel fuel in various ratios (75, 50, and 25 by v%) at several engine loads. The engine combustion parameters such as peak pressure, rate of pressure rise, and heat release rate are determined. Performances and exhaust emissions are also evaluated at all operating conditions. Results show that neat eucalyptus biodiesel and its blends present significant improvements of carbon monoxide, unburned hydrocarbon, and particulates emissions especially at high loads with equivalent performances to those of diesel fuel. However, the NOx emissions are slightly increased when the biodiesel content is increased in the blend.

1. Introduction

In the wake of present energy-environment crises, it has become crucial to find renewable and alternative clean energy sources. One of the principal routes to undertake the problem of increasing prices and pollution problems of petroleum fuels is by using biomass sources, particularly vegetable oils. Several chemical properties of oils, among them are the high viscosity and high molecular weight, cause poor fuel atomization and low volatility, leading to incomplete combustion and severe engine deposits, injector coking, and piston ring sticking [1–4]. To overcome these problems caused by the high viscosity of vegetable oils, several techniques have been used such as preheating the oil, blending or diluting the oil with other conventional fuel, oil microemulsification, transesterification, or thermal cracking/pyrolysis [5–7]. Previous researches showed that the most suitable technique to improve the properties of vegetable oils is the transesterification. It consists of a catalyzed chemical reaction implying vegetable oil and an alcohol which produces esters (biodiesel) and glycerol [8–12]. Methyl or ethyl esters of vegetable oils referred to as biodiesel have several advantages and can be used in any existing design of diesel engine without any hardware modification. Numerous biodiesels derived from different sources have been tried as alternative to diesel fuel for several years. A lot of researchers have reported that biodiesels are of comparable performance to diesel fuel. Moreover, significant reduction in emissions of carbon monoxide, hydrocarbon, and smoke observed. However, a slight increase in NOx emissions and specific fuel consumption were depicted [13–16].

The eucalyptus tree is nonedible specie capable of growing in nearly all climatic conditions. It grows up to nearly 200 meters. In Algeria, the eucalyptus trees occupy a surface of 430 km^2 with potential production of 144800 m^3

per annum. Eucalyptus oil can be extracted from eucalyptus leaves, abundantly available throughout the year. Currently, the eucalyptus oil uses are limited just for few traditional applications such as medicine or traditional pharmacopoeia. But there is not a comprehensive investigation on applying eucalyptus oil in diesel engines yet except an experimental investigation related to performance and emissions of diesel engine running with paradise biodiesel-eucalyptus oil blend [17]. Hence, a study was carried out to run a diesel engine with esterified eucalyptus oil which is produced from Algerian eucalyptus and its blend with diesel fuel at Département des Systèmes Energétiques et Environnement, Ecole des Mines de Nantes. The important physical and chemical properties of the obtained eucalyptus biodiesel are also determined. The engine tests are carried out on a Lister-Petter diesel engine fuelled with neat eucalyptus biodiesel, neat diesel fuel, and their blends (containing 75%, 50%, and 25% biodiesel by volume). Experiments are conducted at different power outputs (20%, 50%, 70%, and 90% load). The results of combustion parameters, engine performance, and exhaust emissions are determined and discussed.

2. Biodiesel Preparation and Its Characterization

To remedy the problem of eucalyptus oil high viscosity (30 cSt at 40°C) [18], ethyl transesterification is tested in this study. Biodiesel was prepared using 97 mL (92 g) of eucalyptus oil and 42 mL (33 g) of ethanol with 1 g of sodium hydroxide (NaOH) as catalyst (1% of oil by weight). After dissolving NaOH catalyst in ethanol, the eucalyptus oil was added to the reaction tank to start the transesterification reaction. The mixture was agitated thoroughly for 1 hr at 45°C. The stirring process is characterized by the mixture color conversion from clear yellow to reddish yellow. Once the separation is operated, the glycerol is removed as a dark-brown-colored liquid from the bottom of the flask. Then, the eucalyptus biodiesel is washed to remove the remaining alcohol and catalyst in the biodiesel phase. The previous parameters affecting the transesterification yield such as the reaction time and the ratios oil : alcohol : catalyst have been fixed after adjustments, which give the optimal yield estimated at 95%.

The important chemical and physical properties of the biodiesel and its blends were then determined by standard methods and compared with diesel (Table 1). It can be seen that the main eucalyptus biodiesel properties are comparable to those of diesel fuel. These results show that eucalyptus oil holds good potential as biodiesel nonedible feedstock.

3. Engine Test Equipment and Procedure

A constant speed engine tests are carried out on a single cylinder DI air-cooled LISTER PETTER (TS1) diesel engine developing a power output of 4.5 kW at 1500 rpm. It has a bore of 95.3 mm, a stroke of 88.9 mm, a displacement volume of 630 cm^3, and a compression ratio of 18. The experimental setup is shown in Figure 1. An electrical dynamometer is

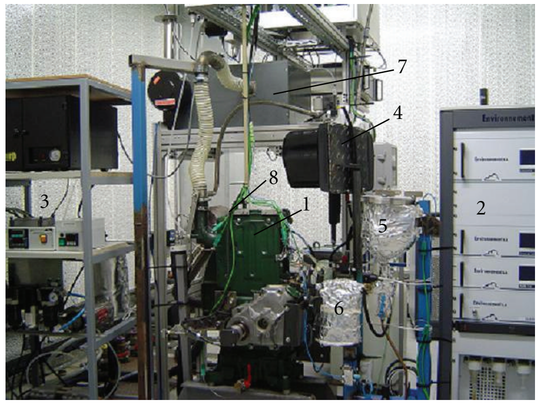


Figure 1: Photographic view of the experimental setup. (1) Diesel engine, (2) gas analyzer, (3) particulate analyzer, (4) diesel tank, (5) biodiesel tank, (6) orifice meter, (7) air tank, (8) wires of different sensors.

used for loading the engine. An orifice meter connected to a large tank is attached to the engine manifold to measure the air flow. The fuel flow rate is measured with a Coriolis mass flow meter. This meter uses the Coriolis effect to measure the amount of fuel moving through the element. Chromel-alumel thermocouple in conjunction with a slow speed digital data acquisition system is used for measuring the exhaust gas temperature. An exhaust analyzer (COSMA) is used for measuring hydrocarbons (HC) by a flame ionization detector, while carbon monoxide (CO) emissions are measured using an infrared device. Nitrogen oxide (NO) in the exhaust is measured by using a BECKMAN chemiluminescence NO/NOx analyzer. The particulate matter emissions containing carbon smoking emissions are measured by a balance type TEOM1105. The accuracies of the measurements and the uncertainties in the calculated results are shown in Table 2.

A high-speed digital data acquisition system in connection with two AVL piezoelectric transducers is used for measuring the cylinder pressure and fuel line pressure histories. An optical shaft position encoder is used to give signals at TDC. Engine in-cylinder pressure and crank angle signals are sampled for 100 consecutive cycles at the increments of 0.1 crank angle intervals. Before each experiment, the engine is regulated according to the manufacturer catalogue values. All data are collected after the engine has stabilised. During the entire investigations, the working parameters of the test engine are fixed as injection timing of 20°CA before TDC for, engine speed of 1500 rpm, and compression ratio of 18. Experiments are performed with neat eucalyptus biodiesel and its blends with diesel fuel (75% eucalyptus biodiesel, 50% and 25% proportions by volume) at various engine power outputs (0.9, 2.25, 3.15, and 4.05 kW).

The legend EBX represents a blend including X% biodiesel, that is, EB100 represents neat eucalyptus biodiesel. Readings of engine speed, fuel flow, air flow, and so forth are recorded in order to determine engine performance parameters.

Table 1: Properties of tested fuels.

Property	EB100	EB75	EB50	EB25	Diesel
Average molecular weight	310	275	245	213	170
Carbon content (wt.%)	77.0	—	—	—	86
Hydrogen content (wt.%)	12.18	—	—	—	14
Oxygen content (wt.%)	10.32	—	—	—	0
Nitrogen content (wt.%)	0	—	—	—	0
Gross heating value (MJ/kg)	40	40.76	42.53	43.80	45.76
Specific gravity at 15°C	896	891	884	876	852
Viscosity at 40°C (cSt)	2.99	2.62	2.36	1.91	1.57
Flash point (°C)	105	84	76	71	67
Cetane number	53	52.25	51.5	50.75	49

Table 2: The accuracies of the measurements and the uncertainties in the calculated results.

Measurements	Accuracy
Load	±0.1 N.m
Speed	±3/min
Temperatures	±1.6°C
Cylinder pressure	±2 bars
Crank angle	±0.05°V
Fuel volumetric rate	±0.5%
Air flow rate	±1.0%
HC	±10 ppm
CO	±50 ppm
NO	±100 ppm
Particulates	±10 ng/s
Calculated results	Uncertainty range (%)
Power	0.4–1.9
BSFC	0.6–2.0
BTE	0.7–2.0

Exhaust gas analyzers are calibrated carefully before making measurements, based on the manufacturer's recommended procedure. Standard span gases and zero gas are used for the calibration of HC, CO, and NO.

4. Results and Discussion

4.1. Combustion Parameters and Heat Release. The determination of combustion characteristics is based on the cylinder pressure variation with respect to crank angle. Figure 2 shows cylinder pressure profiles at different power outputs for diesel fuel, eucalyptus biodiesel, and their corresponding blends. It can be seen that EB100 results in higher peak pressure as compared to diesel fuel for all tested loads. For 0.9 kW engine power output representing 20% load, one can observe the shift of the different curves and the increasing of the maximum cylinder pressure. The peak pressures are found equal to 70.98 bar, 70.99 bar, 72.43 bar, 72.64 bar, and 72.74 bar, respectively, for neat diesel fuel, EB25, EB50, EB75, and EB100. Also, Figure 2 (power output of 0.9 kW) shows that peak pressure increases with the increase of the amount of biodiesel in the blend. This is due to the enhanced combustion rate as a result of rapid combustion of biodiesel at the premixed combustion period. For the other load, the same trend is observed. Diesel fuel represents the lowest peak pressure occurs so far after TDC.

The rate of pressure rise (ROPR) at various power outputs for diesel, eucalyptus biodiesel, and their blends is shown in Figure 3. As compared to diesel fuel, the ROPR of neat biodiesel, and its blends presents a higher peak, and it occurs earlier due to the high cetane number and oxygen concentration. High cetane number makes autoignition easily and gives short ignition delay [19]. At 0.9 kW, the ROPR peak position in terms of °CA is found as 4.3, 4.7, 4.9, 4.5, and 4.2 before TDC, respectively, with neat diesel, EB100, EB75, EB50, and EB25. When engine power output is increased, the ROPR peaks of all tested fuels occur so far BTDC due to the ignition delay decreasing [19].

Figure 4 shows the heat release rate for the tested fuels at various power outputs. Because of the vaporization of the fuel accumulated during ignition delay, at the beginning a negative heat release is observed, and after combustion is initiated, this becomes positive. When raising the biodiesel content in the blend, premixed combustion starts earlier at all power outputs due to the improvement in the blend cetane number. After the ignition delay, premixed fuel air mixture burns rapidly, followed by diffusion combustion, where the burn rate is controlled by fuel-air mixture. It can also be observed that the combustion at low-power output (0.9 kW) is more pronounced for the premixed phase and for high-power output (4.05 kW); however, it is more pronounced at the diffusion phase. The engine load increasing leads to accumulate more fuel in the combustion chamber and to reduce the ignition delay making the quantity of fuel nonmixed with air in the ignition delay period increasing as well and continue to burn in the late combustion.

4.2. Performance Parameters. The Brake-specific fuel consumption (BSFC) is the ratio between mass flow of the tested fuel and effective power. Figure 5 represents the BSFC variation with power output at engine speed of 1500 r/min for diesel, biodiesel, and their blends. In general, the BSFC is found to increase with raising the biodiesel quantity in

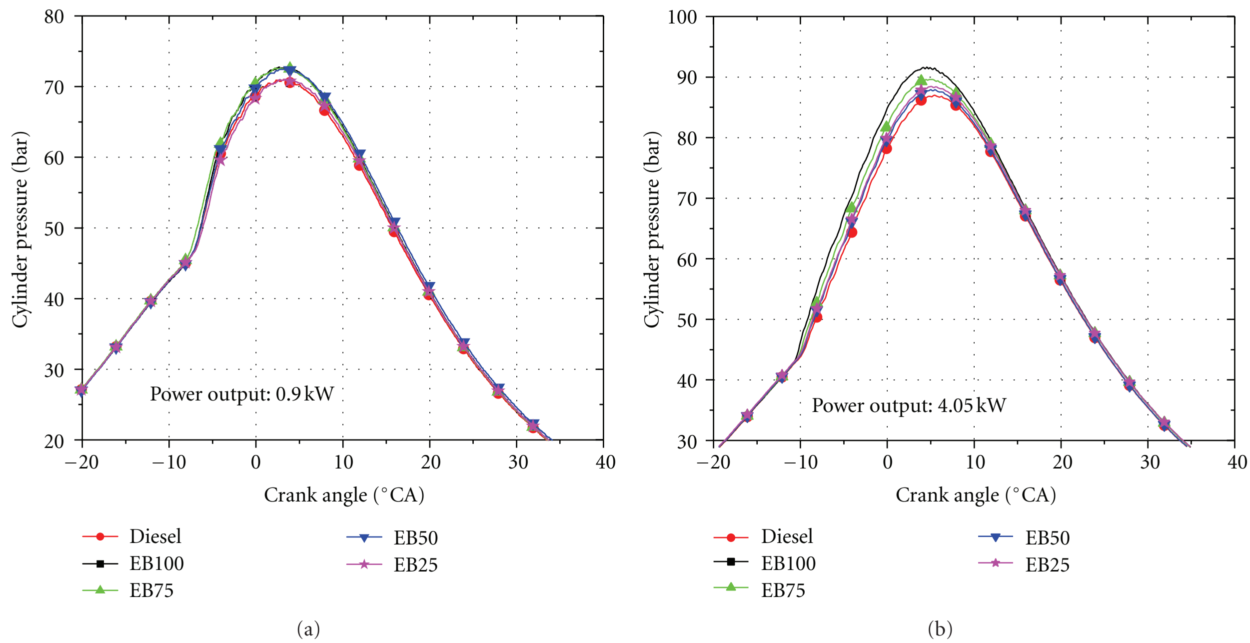


Figure 2: Cylinder pressure for different power outputs.

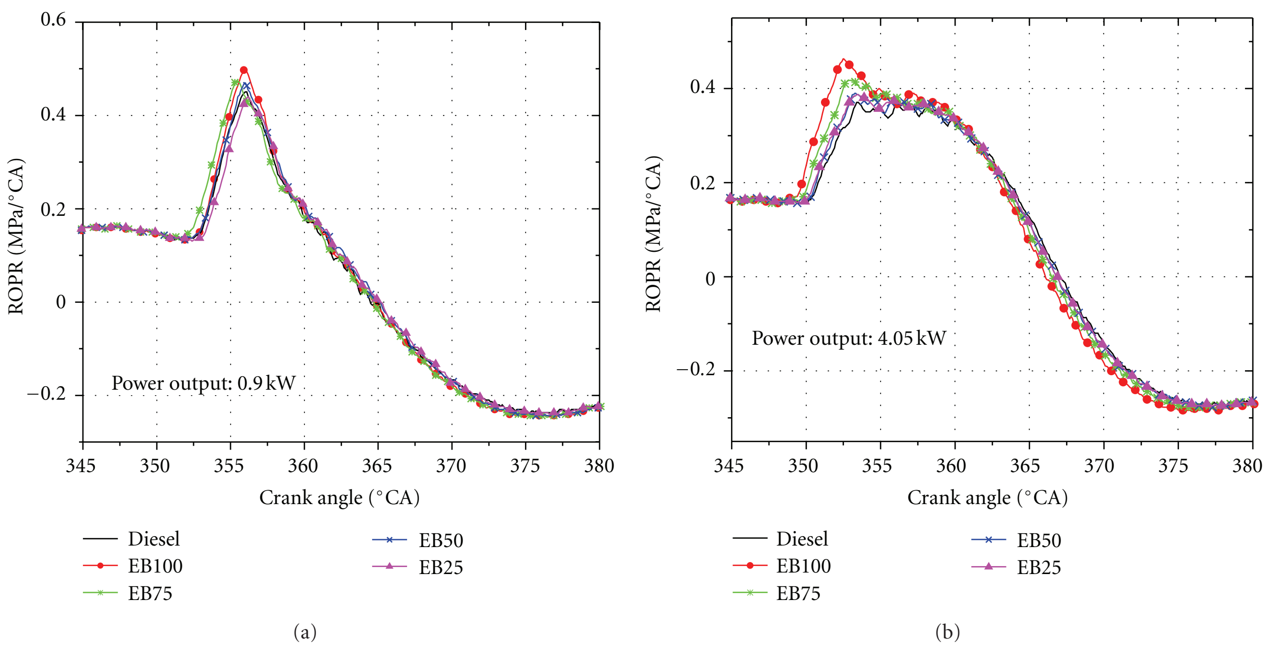
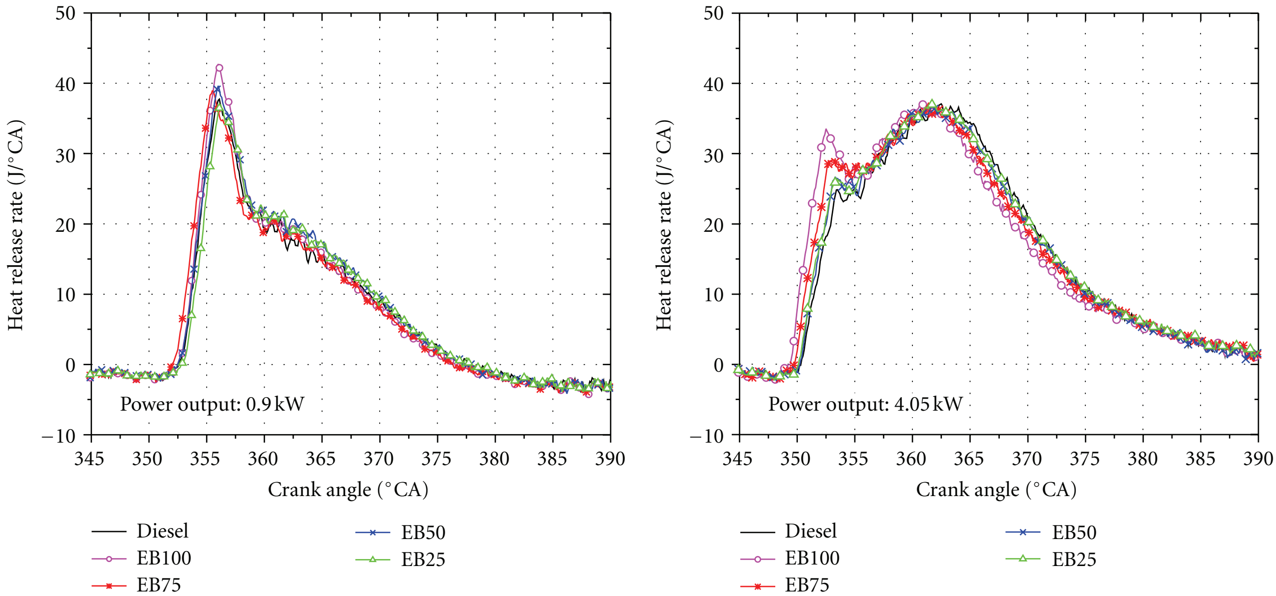


Figure 3: The rate of pressure rise (ROPR) at various power outputs.

the blends under all ranges of engine loads. The BSFC of a diesel engine depends on the relationship among volumetric fuel injection system, fuel specific gravity, viscosity, and heating value. When increasing biodiesel proportion in blends, calorific value decreases and leads to increase the flow rate of the blends for maintaining the same operating conditions in terms of power output for all fuels. As expected, when the power output increases, the BSFC decreases sharply for all fuels. As an example, for a power output of 2.25 kW, the BSFC of the pure diesel is found 23%, 18%, 3.5%, and 0.6% respectively, lower than neat biodiesel, EB75, EB50, and EB25. At high-power output (3.15 or 4.05 kW), EB25 and EB50 are found to be the blends that give lower BSFC.

The relationship between brake thermal efficiency (BTE) and equivalence ratio is presented in Figure 6 as regards the engine speed of 1500 rpm. The BTE of a diesel engine is inversely proportional to its BSFC and the heating value of the fuel. Since the BSFC values of the biodiesel and its



(a) (b)

FIGURE 4: Heat release rate at various power outputs.

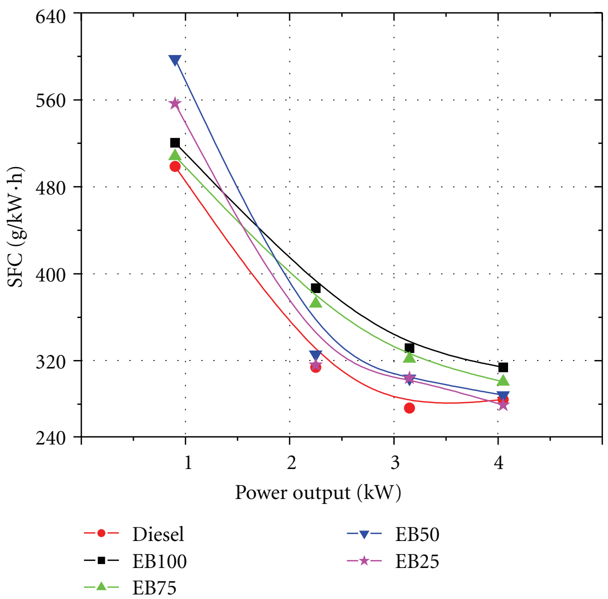


FIGURE 5: BSFC variation with power output.

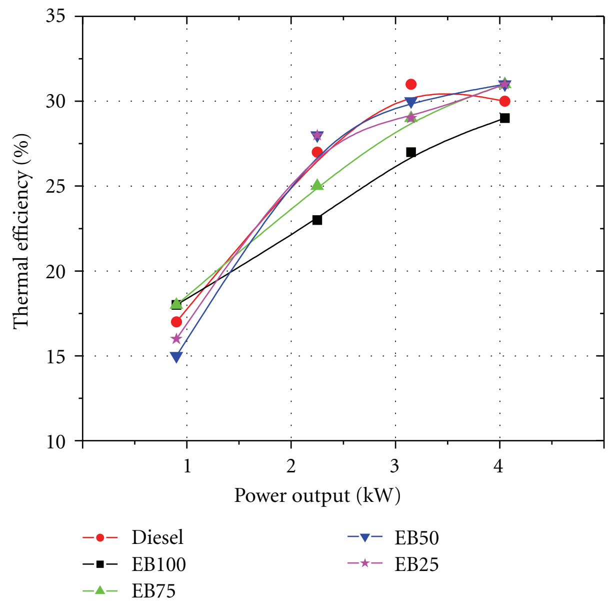


FIGURE 6: BTE variation with power output.

blends are higher than those with diesel fuel, the higher BTE with the diesel fuel is an expected result, which is seen in almost all examined power outputs. However, when the power output raised to 4.05 kW, the BTE value of the diesel fuel is decreased, and those of the other fuels are increased. The increase in such power output, especially under the higher load operating conditions, requires a larger amount of fuel. The amount of air entering the chamber is not sufficient for the larger amount of diesel fuel injected. As a result of this, the combustion process deteriorates beyond these operating conditions. But when the biodiesel or its blend is injected, there is no pronounced effect due to the presence of oxygen in the fuel molecule. The maximum BTE of EB75, EB50, and EB25 blends is around 32% obtained at power output of 4.05 kW against the 30% for diesel.

4.3. Emissions Parameters. Unburned hydrocarbon (HC) is an important parameter for determining the emission behaviour of the engine. The variation of unburned hydrocarbon (HC) with load for the tested fuels is given in

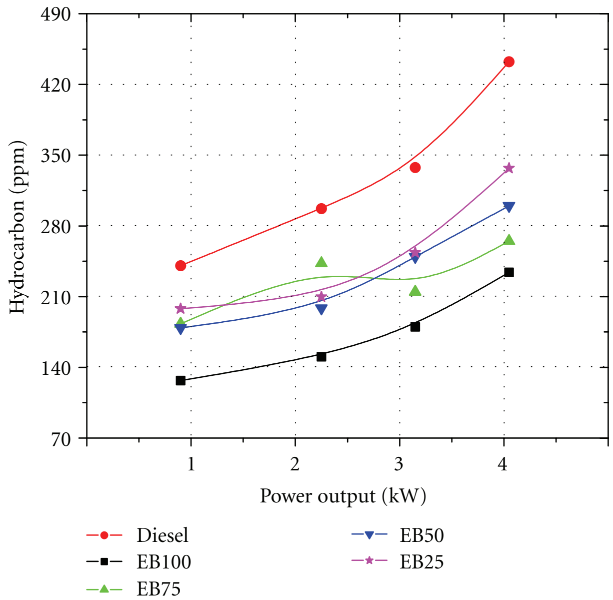


Figure 7: Unburned hydrocarbon emissions at various power output.

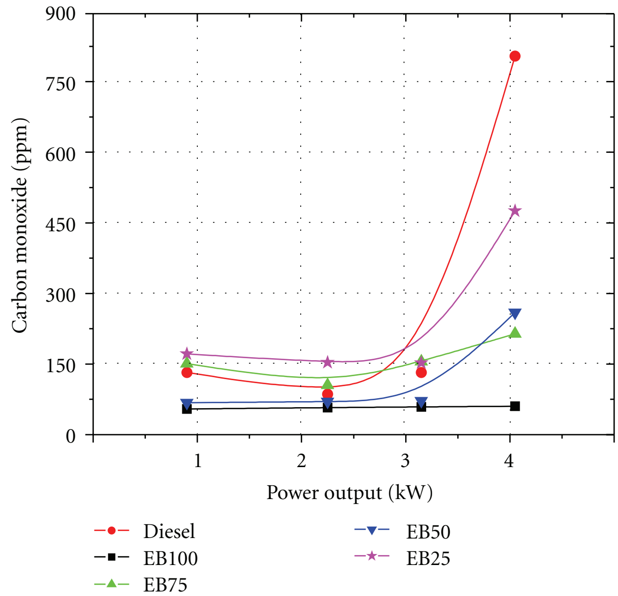


Figure 8: Carbon monoxide emissions at various power output.

Figure 7. It is shown that increasing biodiesel in the blends reduces significantly HC emissions comparatively to neat diesel. This is due to the increase in oxygen content in the blend which improves the combustion quality in the combustion chamber. It can be noticed that at high power levels (e.g., 4.05 kW), the reduction in HC emissions can reach 52% in comparison with neat diesel fuel.

The plot of Figure 8 shows the variation of carbon monoxide (CO) emissions for neat diesel fuel, neat biodiesel, and their blends at various load conditions (20%, 50%, 70%, and 90%). It is shown that increasing biodiesel in the blends at low and middle engine loads has only a slight effect on the CO emissions due to the dominant premixed lean combustion with excess air. At high engine loads (4.05 kW of power output), the CO emission of diesel fuel is 750 ppm but those of biodiesel and its blends are less than 450 ppm. The CO emissions of biodiesel and its blends at such load are evidently lower than those of diesel fuel. This is due to the fact that biodiesel which contains more number of oxygen atoms leads to more complete combustion.

Figure 9 points out the variation of nitrogen oxides (NOx) emission with power output for the different fuels tested. There are mainly three factors, oxygen concentration, combustion temperature, and time, affecting the Nox emissions. At partial loads (20%, 50%, and 70%), NOx emissions of neat biodiesel and its blends are higher than those of diesel fuel. Higher values of combustion temperature and presence of oxygen with biodiesel result in an increase in NOx generation. At high loads (90%), neat biodiesel emits less NOx than other tested fuels. The maximum NOx emission is observed at 3.15 kW power output for all tested fuels. However, biodiesel's lower sulfur content allows the use of NOx control technologies that cannot be otherwise used with conventional diesel. Hence, biodiesel's fuel NOx

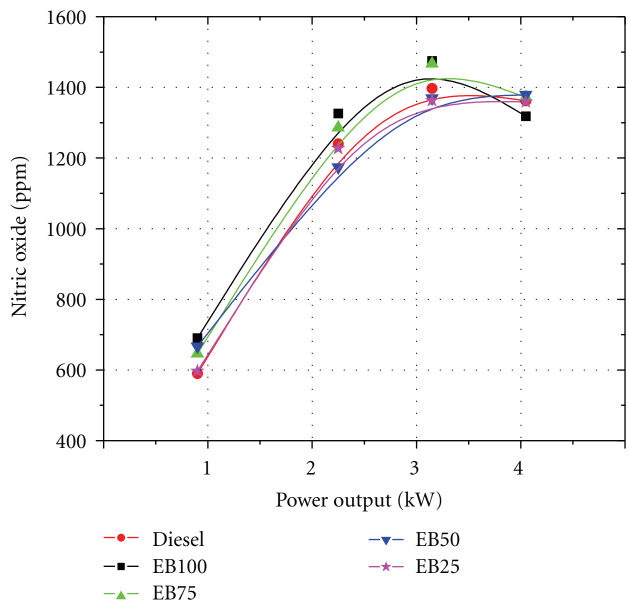


Figure 9: NOx emissions at various power output.

emissions can be effectively managed and eliminated by engine optimization (adjustment of injection timing and introducing to exhaust gas recirculation).

The variation of particulate emission for the tested fuels as a function of power output is presented in Figure 10. It can be noticed that the particulate emissions of biodiesel and its blends are slightly lower than that of diesel fuel at 0.9 and 2.25 kW of power output. But when the power output is increased more, the particulate emissions are significantly reduced for biodiesel and its blends as compared with diesel fuel. This is due to the oxygen content in the biodiesel that contributes to complete fuel oxidation. Another reason

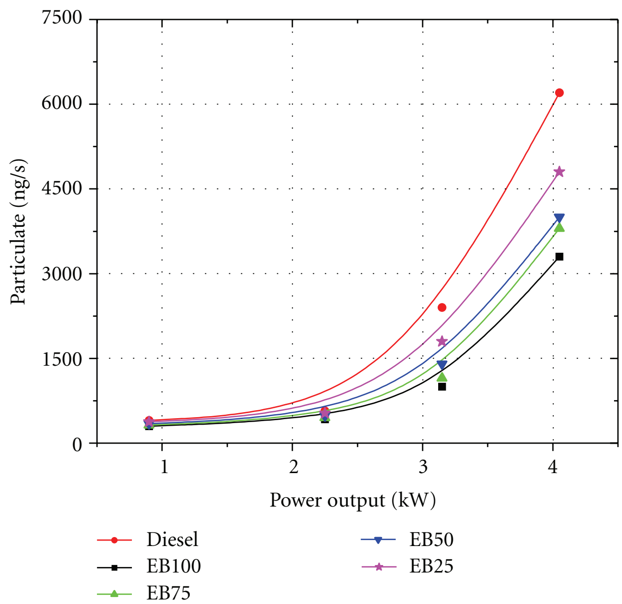


Figure 10: Particulates emissions at various power output.

of particulate emission reduction when using biodiesel is lower carbon content and absence of aromatics compounds as compared with diesel fuel. Also, it can be noticed from the figure that the particulate emissions are increased with increase in power output. This is essentially due to the decreased air-fuel ratio at higher loads because higher quantities of fuel are injected into the combustion chamber, and as result, part of the fuel goes unburnt into the exhaust.

5. Conclusion

The aim of this study is to investigate the suitability of eucalyptus biodiesel as an alternative to diesel fuel. Some properties of eucalyptus oil show that it is not possible to fuel diesel engines with this crude oil due to problems generated by its high viscosity and low volatility.

In order to decrease the oil viscosity, transesterification technique is carried out under optimum reaction condition. Analysis of basic properties of eucalyptus biodiesel shows that transesterification process is successfully employed to make the viscosity and other characteristics comparable to those of diesel fuel. On the basis of the exhaustive engine tests, the following conclusions can be drawn:

(i) analysis of combustion shows that biodiesel and all its blends exhibit similar pressure-time history as diesel fuel. No undesirable combustion features such as unacceptable high cylinder pressure rises are observed. The combustion starts earlier as the concentration of biodiesel in the blend is increased due to decreasing of ignition delay. The combustion duration increases with increase in the proportion of biodiesel in the blend due to rise of the fuel quantity injected in the cylinder;

(ii) the BSFC increases and BTE decreases with addition of biodiesel content in the blend. A reverse behaviour is observed with increase in engine load;

(iii) CO, HC, and particulates in the exhaust emissions decrease, whereas NOx increase with increases in percentage of biodiesel in the blend. However, the level of emissions increases with increase in engine load for all fuels tested.

A general conclusion is that the eucalyptus biodiesel can be used in the form of blends to compromise on the NO emissions and thermal efficiency.

Acknowledgment

The authors are very grateful to the technicians of the Energetic Department of Ecole des Mines de Nantes for their help on the experiment.

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