PERFORMANCE ANALYSIS OF A BIODIESEL FUELLED DIESEL ENGINE WITH THE EFFECT OF ALUMINA COATED PISTON

by

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Original scientific paper
DOI: 10.2298/TSCI160229134S

Biodiesel is one of the best alternative fuels to Diesel engine among other sources due to having potential to reduce emissions. Biodiesel is a renewable, biodegradable and environment friendly fuel in nature. The advantages of biodiesel are lower exhaust gas emissions and its biodegradability and renewability compared with petroleum-based diesel fuel. The energy of the biodiesel can be released more efficiently with the concept of semi adiabatic (thermal barrier coated piston) engine. The objective of this study is to investigate the performance and emission characteristics of a single cylinder direct injection Diesel engine using 25% biodiesel blend (rubber seed oil methyl ester) as fuel with thermal barrier coated piston. Initially the piston crown was coated with alumina (Al_2O_3) of thickness of 300 micron (0.3 mm) by plasma coating method. The results revealed that the brake thermal efficiency was increased by 4% and brake specific fuel consumption was decreased by 9% for B25 with coated piston compared to uncoated piston with diesel. The smoke, CO, and HC emissions were also decreased for B25 blend with coated piston compared with the uncoated piton engine. The combustion characteristics such as peak pressure, maximum rate of pressure rise, and heat release rate were increased and the ignition delay was decreased for B25 blend for the coated piston compared with diesel fuel.

Key words: *rubber seed oil methyl ester, Diesel engine, alumina coated piston, performance, emission, combustion, thermal barrier coating, biodiesel*

Introduction

Energy demand is increasing day by day due to modernization and industrialization of any country in world. Most of the developing countries like India import fossil fuels to fulfill their energy demand. In the current situation, fast depletion of fossil fuels, increasing cost of petroleum fuels and stringent emission norms imposed by the government have urged the researchers to search for an alternative fuel for compression ignition (CI) engines like biofuel and biomass. Vegetable oils and biomass fuels have been found to be potential fuel for Diesel engines. These fuels are easily available, biodegradable, environment friendly, and renewable in nature [1, 2]. The use of raw vegetable oils used as fuel for Diesel engines without modification causes some damage to parts of the engine and also, the performance is greatly affected

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[3, 4]. However, the long term operation of the engine problems of injector coking, dilution of engine oil, deposits in various parts of the engine due to its higher viscosity [5].

Purushothaman and Nagarajan [6] conducted the experiment in CI engine to study the performance, emission, and combustion characteristics of a Diesel engine using with orange oil and reported that that the brake thermal efficiency (BTE) was higher CO and HC emissions were lower and NO_x were higher compared to diesel fuel. Leenus *et al.* [7] tested the suitability of cotton seed oil as a fuel for Diesel engines with different methods. It is reported that preheating of cotton seed oil or its blend with diesel is a very effective way to lower its viscosity and improve its performance. Blending small quantities of orange oil and diethyl ether with cotton seed oil are also other effective methods to improve the performance of Diesel engines.

Esterification is one of the methods to convert the vegetable oil into its methyl ester to reduce the viscosity of the fuel and improves the cetane number and heating value. Several researchers have used biodiesel as an alternate fuel in the existing CI engines without any modifications [8-12]. Pugazhvadivu [13] studied the addition of ethanol with 5% and 10% with biodiesel diesel blends on a Diesel engine and found that the addition of ethanol to biodiesel diesel blends did not alter the engine performance significantly lowered NO_x and smoke emissions. Hanumantha *et al.* [14] investigated the use of Jatropha oil methyl ester and its blends with diesel fuel additive. They found that B25 have closer performance to diesel and B100 had lower BTE and the blends showed lower smoke, CO_2, and CO emissions compared to diesel fuel. Vedaraman *et al.* [15] studied the preparation of sal oil biodiesel and tested in Diesel engine. It is reported that the exhaust emissions such as CO, HC, and NO_x are reduced by 25, 45, and 12%, respectively, compared to diesel without significant affecting the thermal efficiency.

The concept of a semi adiabatic engine is to reduce engine coolant heat losses, hence improve engine performance and also a most effective way of increasing useful work of the engine and to reduce the losses. So the energy of biodiesel can be released more efficiently. There have been many studies about coated engines and biodiesel usage in standard Diesel engines in the literature [16-18]. Providing ceramic coating on piston crown is an effective way of burning high viscous vegetable oils in Diesel engine by retaining the heat produced from combustion of the fuel in the combustion chamber. If the heat rejected to the coolant is reduced, thermal efficiency could be improved [19-21]. Also by the use of thermal barrier coated piston increases the peak pressure and heat release rate of the biodiesel fuel with increase in thermal efficiency and reduces the smoke, CO, and HC emissions [22, 23]. The influence of coating material, thickness, and technique on engine performance and emissions has been studied the coated engine evolution [24]. They reported that the engine performance in terms of power, fuel consumption, and thermal efficiency of low heat rejection (LHR) engine for all fuels except the volumetric efficiency with biodiesel. The coolant heat losses were decreased and the exhaust heat losses were increased and the engine emissions have improved (except NO_x) in LHR engine. The objective of the present work is to investigate the performance, emission and combustion characteristics of 25% rubber seed oil (RSO) methyl ester-diesel blend as fuel in a Diesel engine with and without coating on the piston crown. The measured values for the coated piston engine with biodiesel blend are compared with base engine with diesel and biodiesel blend.

Preparation of rubber seed oil methyl ester

The process of converting vegetable oil into biodiesel is known as transesterification process. In this process, one liter of raw RSO is heated in a reactor to remove its moisture. Potassium methoxide is prepared by dissolving 8-10 grams of potassium in a 250 ml of methanol. This methoxide is mixed with preheated oil and the reaction carried out and stirred under nominal speed at constant reaction temperature of 65 °C for two hours. After eight hours of settling period, ester separates as an upper layer and glycerol settles at bottom and separated by decantation. Then the ester was washed with warm distilled water to remove impurities. In this reaction of 790 ml of RSO methyl ester (RSME) was produced from one liter of RSO. The important properties of diesel, RSO, and its methyl ester are given in tab.1.

Table 1. Properties of diesel, RSO and its methyl ester

Properties	Diesel	RSO	RSME	Testing methods
Density [kgm^{-3}]	830	920	882	EN ISO 3675
Kinematic viscosity at 40 °C [cSt]	3.720	52	5.19	EN ISO 3104
Flash point [°C]	52	175	157	EN ISO 3679
Fire point [°C]	60	184	163	EN 23015
Calorific value [$MJkg^{-1}$]	43	36.55	38.83	DIN 51900
Cetane number	48	38	52	EN ISO 5165

Experimental set-up and procedure

Experiment was conducted in a 4-stroke single cylinder direct injection (DI) constant speed Diesel engine. The technical specifications of the test engine are listed in tab. 2. The engine is coupled with swinging field electrical dynamometer, which is used to apply the brake load to the engine. Two separate fuel tanks were used for diesel fuel and RSME blend. The fuel consumption was determined by measuring the time taken for a fixed volume of fuel from burette to flow into the engine. The exhaust gas emissions like HC, CO, and NO were measured by using AVL- 444 gas analyser and the smoke opacity was measured by AVL- 437 smoke meter.

An AVL make digital data acquisition system with piezoelectric pressure transducer and an optical crank angle encoder were used to record the cylinder pressure at every one degree crank angle. The pressure signal and the TDC position signal were acquired by an analog to digital converter and are processed with the help of computer. The cylinder pressure and heat release rate are calculated with the average of 50 cycles. The schematic of the experimental set-up is shown in fig.1. The emissions error and range are given in tab. 3.

Table 2. Specifications of the test engine

Make	Kirloskar
Type of cooling	Air
Bore diameter	87.5 mm
Stroke length	110 mm
Brake power	4.44 kW
Compression ratio	17.5:1
Speed	1500 rpm
Fuel injection	23° bTDC
Injection pressure	200 bar

Semi adiabatic engine

In a CI engine, out of the total heat energy supplied, only about one third of supplied energy is converted to useful work, one third is lost through exhaust gases and the

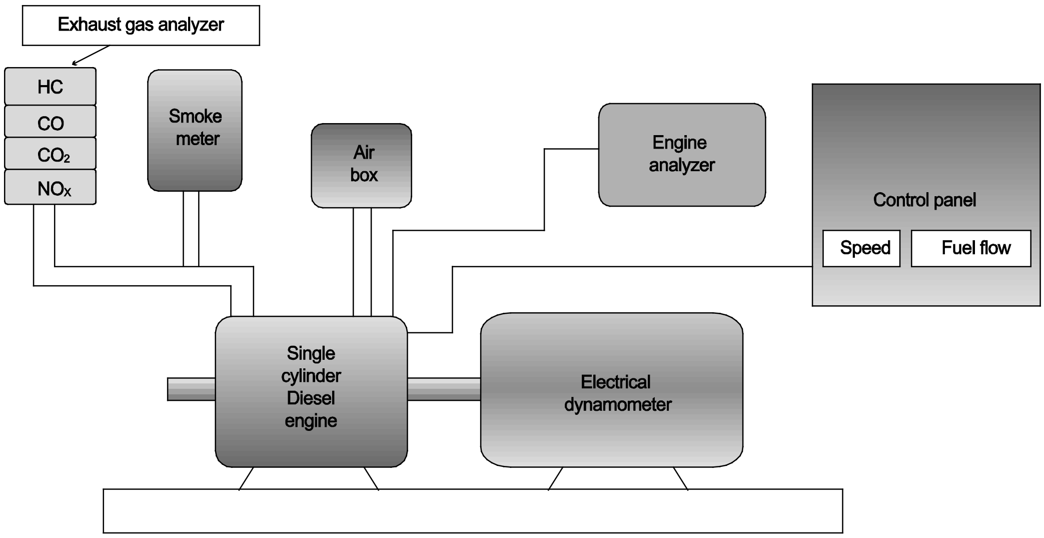

Figure 1. Schematic of experimental set-up

Table 3. Emission accuracy and error range

Sl. no.	Instruments	Measuring range	Accuracy	Percentage of accuracy
1	AVL DiGAS 444 five gas analyzer			
	Carbon monoxide	0-10 vol.%	±0.02 vol.%	±0.2
	Carbon dioxide	0-20 vol.%	±0.02 vol.%	±0.15
	Hydrocarbon	0-20000 ppm	±15 ppm	±0.2
	Oxygen	0-22 vol.%	±0.02 vol.%	±0.3
	Nitric oxide	0-5000 ppm	±50 ppm	±0.2
2	AVL 437 Smoke meter	0-100%	±1	±1

rest carried away by the cooling water. Reducing the heat transfer to the coolant increases the exhaust energy. One method of obtaining the previous condition is to thermally insulate the combustion chamber (only piston crown) converting it into a semi adiabatic engine. This method insulates the piston crown, using high temperature materials, which allows *hot* operation near to adiabatic conditions. Further, the efficient combustion process in semi-adiabatic engine will allow multi fuel capability. The present investigations aim to achieve the best performance from combustion of biodiesel fuel. Semi-adiabatic engine is made with 300 microns of Al_2O_3 bond coat is used, which creates a higher combustion chamber temperature that may lead to the improvement in the combustion characteristics of biodiesel, BTE of the engine and reduction in the exhaust emissions.

Results and discussion

In this study, methyl ester was made of raw rubber seed oil and it was used as alternative to diesel fuel. First the test was conducted with diesel and B25 fuels to obtain a base line data in an uncoated engine. Then the experiment was repeated in a coated engine with B25 blend. The performance of the engine was evaluated in terms of BTE, brake power (BP), specific fuel consumption, and the emission values such as HC, CO, NO, and smoke were measured. The measured and calculated parameters were analyzed and compared with diesel.

Cylinder peak pressure

The cylinder peak pressure variation with crank angle for diesel and 25% biodiesel blend for uncoated and coated piston engine at full load is shown in fig. 2. The peak pressure is an important parameter to decide the efficiency of the fuel. The cylinder pressure also depends also on the burned fuel fraction during the premixed burning phase *i. e.* initial stage of combustion and the ability of the fuel to mix well with air and burn.

High peak pressure and maximum rate of pressure rise correspond to large amount of fuel burned in premixed stage. The cylinder peak pressure for B25 with the alumina coated piston is increased by 3.2 bar and 5 bar, respectively, compared with base engine using B25 biodiesel blend at full load. The peak pressure obtained for diesel and B25 is 69 bar and 67.2 bar with the base engine, whereas for the alumina coated piston it is 72.2 bar at maximum load. The lower peak pressure was obtained for B25 with the uncoated engine due to low calorific value of the fuel. The increase in peak pressure for B25 with coated piston may be due to the reduction in total heat release when compared with uncoated engines.

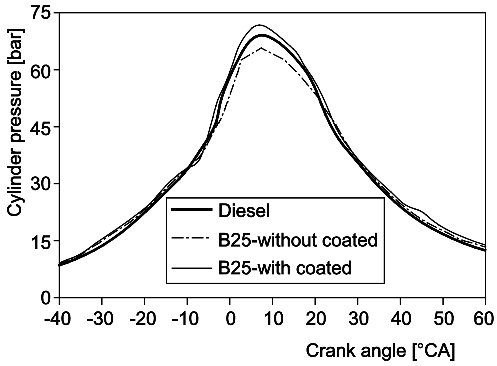

Figure 2. Variation of cylinder peak pressure with crank angle at full load

Heat release rate

The heat release rate with crank angle for full load for diesel and B25 biodiesel blend with uncoated and coated piston engine is shown in fig. 3. It is observed that B25 with uncoated engine has lower heat release and it is higher for coated engine at full load. It is noticed that the premixed combustion phase was increased and diffusion combustion phase was decreased for coated engine for biodiesel blend due to shorter ignition delay. The heat release rate obtained for 25% biodiesel blend is 73.5 kJ/kgm^3 with coated piston engine at full load. The heat release rate for diesel and B25 biodiesel blend the base engine is 67 kJ/kgm^3 and 63.2 kJ/kgm^3 at full load. This is due to the higher operating temperature associated with the coated engine, resulting in better performance. The lower calorific value of biodiesel shows less heat release than coated engine.

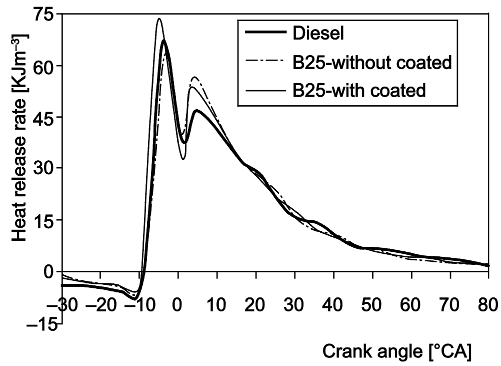

Figure 3. Variation of heat release rate with crank angle at full load

Maximum rate of pressure rise

The variation of maximum rate of pressure rise with BP for both the engine operations is shown in fig. 4. The rate of pressure rise depends on the combustion rate in the

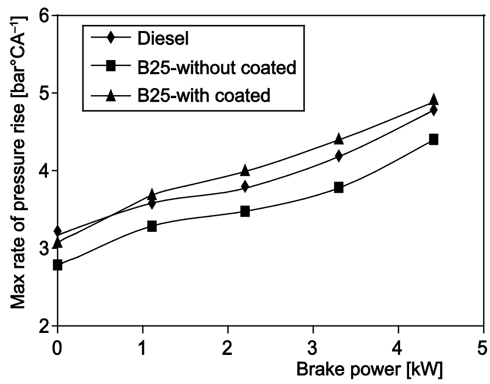

Figure 4. Variation of maximum rate of pressure rise with BP

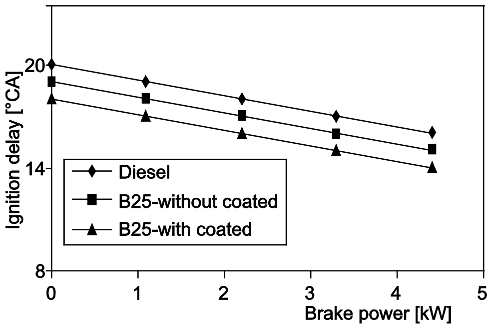

Figure 5. Variation of ignition delay with BP

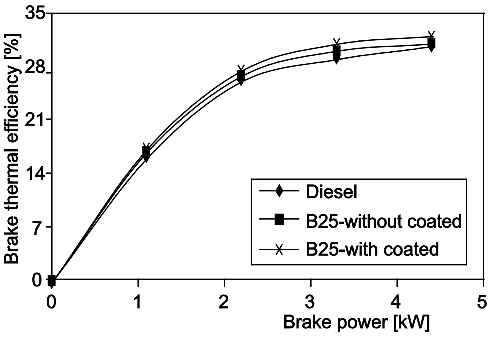

Figure 6. Variation of BTE with BP

initial stages and it is influenced by the amount of fuel taking part in the premixed combustion phase. It is observed that the maximum rate of pressure rise for B25 with coated piston engine increased by 0.5 bar/°CA at full load compared to B25 with uncoated engine at maximum load. The maximum rate of pressure rise for diesel and B25 with base engine is 4.8 bar/°CA and 4.5 bar/°CA, respectively, at full load. This may be due to more retainment of heat in the combustion chamber by the coated piston resulting in decreases the ignition delay period and increases the rate of pressure rise.

Ignition delay

The ignition delay variation with BP for both the piston engine operations is illustrated in fig. 5. Ignition delay is calculated as the period from the start of injection to the start of combustion in terms of the crank angle and it depends on the cetane number of the fuel. The ignition delay for diesel and B25 with the base engine is 16 °CA and 15 °CA, respectively, whereas for coated engine with B25 is 14 °CA at full load. The biodiesel blend has shorter ignition delay due to higher cetane number of biodiesel than diesel fuel. It is observed that the ignition delay of biodiesel blend is significantly lower than that of diesel. As the temperature of air in the cylinder is fairly high at the time of injection, the biodiesel undergoes chemical reactions and polymerization. In spite of the higher viscosities of biodiesel, lighter compounds (volatile matter) are produced through cracking of higher fatty acids of esters. These lighter compounds in turn produce larger dispersion and thus shorter ignition delay. A decrease in ignition delay means a smaller amount of fuel accumulation prior to ignition.

Brake thermal efficiency

The variation of BTE with BP for the uncoated and coated engine for diesel and biodiesel blend is shown in fig. 6. The BTE of the engine without coating was observed to be decreased than diesel and in order to enhance the efficiency, additional heat has to be supplied for the burning of biodiesel blend. The coating prevents the heat losses from the engine due to its low thermal conductivity, which aptly acts as an insulator and reduces the heat transfer between the combustion chamber and surroundings.

As the heat gets accumulated in the combustion chamber, in-cylinder temperature could have been increased, which increases the combustion efficiency and hence BTE of the engine. It is observed that BTE increases with increase in BP at all loads. The BTE obtained for B25 with coated piston engine is increased by 2.9% compared to B25 with base engine. The BTE for B25 with and without coated engine is 30.84% and 31.74%, respectively, and for diesel it is 30.48% at full load. The increase in BTE for the coated piston engine with biodiesel blend may be due the higher combustion temperature and reduction in heat loss from the combustion chamber by the coated piston, resulting in complete combustion of biodiesel blend and thus increased BTE.

Brake specific fuel consumption

The variation of brake specific fuel consumption (BSFC) with BP for the all the tests fuels is shown in fig. 7. It is noticed that BSFC was higher for B25 blend with uncoated engine than diesel, due to its higher viscosity and lower calorific value. The combustion of B25 is improved as the heat trapped in combustion chamber help enhance the burning of fuel with the coated engine. Therefore, BSFC for B25 was decreased with coating than without coating, at all loading conditions. It is observed that the BSFC is decreased by 8.5% for the B25 blend with coated piston compared with base engine at maximum power output. The BSFC obtained for B25 with coated piston is 0.28 kg/kWh, whereas for the diesel and B25 blend are 0.3 kg/kWh and 0.29 kg/kWh, respectively, with the base engine at full load. This is due to the reduction of heat loss from the combustion chamber by the coated piston, resulting in increases the combustion chamber peak temperature and thus decreased in BSFC at full load.

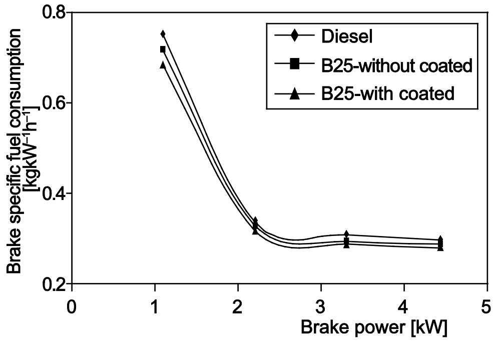

Figure 7. Variation of BSFC with BP

Carbon monoxide emissions

The variation of CO emission with BP for B25 with and coated piston engine is illustrated in fig. 8. It is observed that the CO emission is lower for biodiesel due to the function of temperature and availability of oxygen in biodiesel. However, for the coated engine the heat a loss to the coolant and exhaust has been higher, which in turn aids in the evaporation and oxidation of biodiesel by utilizing the temperature rise in the combustion chamber effectively. The CO emission decreased by 42% for B25 fuel with coated engine compared to without coated engine at full load. The CO emission for the coated piston engine with B25 is 0.1% vol., whereas for the diesel and B25 with the base engine is 0.17 and 0.14% vol., respectively, at full load. The reason for decrease in CO emission for the coated engine with B25 due to more complete combustion of bio diesel blend in insulated environment of the combustion chamber by the coated piston and more oxygen molecules present in the biodiesel.

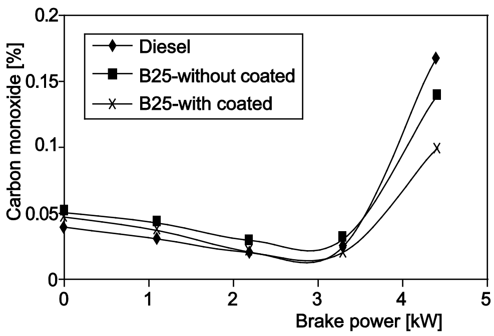

Figure 8. Variation of CO with BP

Hydrocarbon emissions

The variation of the HC emissions with BP is shown in fig. 9. The reasons for HC emission from a Diesel engine due to wall quenching, fuel that vaporizes from the nozzle sac volume during the later part of combustion. It is observed that the HC emission for biodiesel without coating is higher than diesel on account of its higher viscosity, which affecting the combustion process, resulting in a less complete combustion. However, with the coated engine, B25 relatively undergoes better combustion than in uncoated engine, by retaining the heat inside the combustion chamber, resulting in better burning of the fuel and this has resulted in the decrease of HC emission at all loads. Comparatively the HC emissions decreased by 50% for B25 blend with coated engine compared to without coated engine with B25 blend at full load. The HC emission for B25 with coated engine it is 32 ppm, whereas it is 65 ppm with the base engine at maximum power output. The HC emission for diesel with the base engine is 52 ppm at maximum power output. This decrease in HC emissions is due to high temperature in the combustion chamber by the coated piston operation of the engine, resulting in complete combustion of biodiesel.

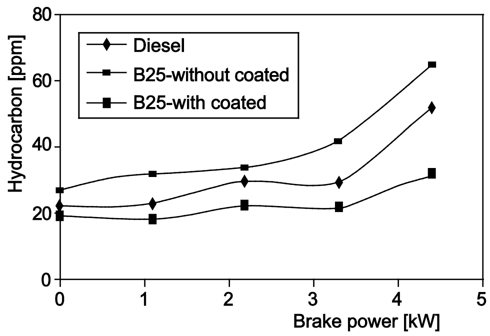

Figure 9. Variation of HC with BP

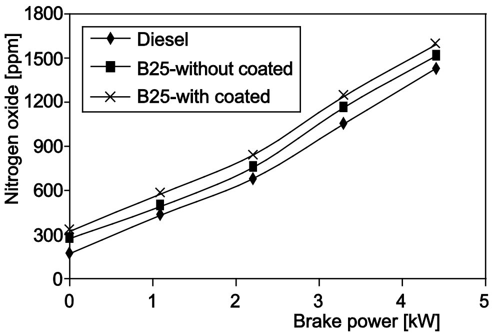

Figure 10. Variation of NO emissions with BP

Nitrogen oxide emissions

The variation of NO emission with BP is shown in fig. 10. The formation of NO_x emission due to the peak flame temperature and excess oxygen within the combustion chamber. Many research studies reported that an increase in NO_x emission for biodiesel due to the excess oxygen present in it, high combustion temperature. The NO_x emission is increased by 11% for B25 blend with coated piston and it is slightly increased compared with diesel and B25 at maximum load. The increase in NO_x emission with coated piston prevent the heat transfer by insulation on the piston crown, most of the heat is utilized in the fuel evaporation and combustion of biodiesel, resulting in increase the combustion chamber temperature. The increase in in-cylinder temperature and the presence of excess oxygen within the fuel has promoted the formation of NO_x and therefore, the NO_x emission for B25 with coating is higher than that of CNSLME without coating. The NO_x emission obtained for the uncoated engine with diesel and B25 are 1440 ppm and 1521 ppm, respectively, and for the coated piston with B25 is 1598 ppm at full load.

Smoke opacity

The variation of smoke opacity with BP for diesel and bio diesel blend is shown in fig. 11. Smoke produces in automotive engine as result of incomplete combustion of fuels. Smoke density is also an important parameter for determining the emission behavior of the engine. The smoke opacity increases with increase in engine loads due to more input fuel requirement with increase in loads. Biodiesel blends have favorable effect on smoke emissions due to more complete combustion with the presence of extra oxygen molecule in the fuel. As the cylinder wall and gas temperature increase due to coating, the smoke density decreases by a large amount with the coated engine. The maximum smoke opacity obtained for B25 is 3.2% with coated piton, whereas for base engine it is 3.95% at maximum power output. The smoke opacity of diesel it is 4.4% with base engine at full load.

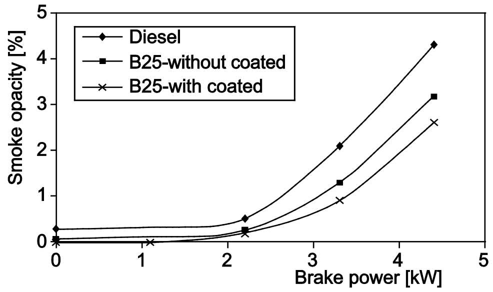

Figure 11. Variation of smoke opacity with BP

It is seen that the smoke opacity decreased by 28% for B25 blend with coated engine compared to diesel with base engine at full load. The reduction in smoke opacity is due to more oxygen molecules present in the biodiesel and higher combustion temperature by the coated engine, resulting in more complete combustion of the biodiesel blend.

Conclusions

The experimental test have been conducted on a single cylinder DI Diesel engine with diesel and B25 blend with base engine and partially stabilized coated piston Diesel engine at different load conditions. The following conclusions were drawn from the experimental results.

The BTE of B25 increased by 2.9% compared to B25 with base engine at full load. The BSFC decreased by decreased by 9% for the B25 blend compared to diesel with base engine at full load. The CO and HC emissions decreased by 42% and 50% for B25 blend, respectively, with alumina coated engine as compared to base engine with diesel at full load. The NO_x emissions increased by 11% for B25 blend with coated engine as compared to diesel with base engine full load. The peak pressure, maximum rate of pressure rise, and heat release rate were increased and ignition delay period was decreased for B25 with coated engine and compared with base engine with B25 at full load. The cylinder peak pressure, heat release rate, and maximum rate of pressure rise for B25 with coated piston operation are increased by 5 bar, 10 kJ/kgm^3 and 0.5 bar/°CA, respectively, and ignition delay was decreased by 1 °CA compared with the base engine. On the whole, it is concluded that the coated engine (semi adiabatic mode) operations with RSO biodiesel blend improved the combustion and performance characteristics and drastically reduced the exhaust emissions with slightly increased in NO emissions.

Nomenclature

Al_2O_3 – alumina
B25 – 25% biodiesel + 75% diesel blend
BP – brake power
BSFC – brake specific fuel consumption
BTE – brake thermal efficiency
CA – crank angle, [°]
CI – compression ignition
DI – direct injection
LHR – low heat rejection
RSME – rubber seed oil methyl ester

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Paper submitted: February 29, 2016
Paper revised: May 22, 2016
Paper accepted: May 23, 2016