International Journal of I.C. Engines and Gas Turbines
Vol. 3: Issue 1
www.journalspub.com

Performance Analysis of a Biodiesel Fueled Diesel Engine with the Effect of Titanium Oxide (TiO_2) Coated Piston

K. Kusuma[1], *E.L. Nagesh*[2]
[1]Department of Mechanical Engineering, JNTUH, Hyderabad, India
[2]St. Peter's Engineering College, Hyderabad, India

ABSTRACT
*Biodiesel is one of the best alternative fuel to diesel engine among other sources due to contain high potential to reduce emissions. Biodiesel is a renewable, biodegradable and environment friendly fuel in nature. The benefit of biodiesel are lower exhaust gas emissions and its biodegradability and renew ability are 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 (DI) diesel engine using 25% biodiesel blend (Jatropha Di-Ethyl Ether: JDEE) as fuel with thermal barrier coated piston. Initially the piston crown was coated with Titanium Oxide (TiO_2) of thickness of 300 micron (0.3mm) by plasma coating method. The results disclosed that the brake thermal efficiency (BTE) was increased by 4% and BSFC was decreased by 9% for B25 with coated piston comparatively uncoated piston for 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 like peak pressure, maximum rate of pressure rise and heat release rate were increased and the ignition delay were decreased for B25 blend for the coated piston in compare to diesel fue*l.

Keywords: biodiesel, combustion, diesel engine, emission, Jatropha di-ethyl ether

Corresponding Authors
E-mail: kusumakenpi@rediffmail.com, el.nagesh@gmail.com

INTRODUCTION

Energy demand is increasing day by day due to modernization and industrialization of any country in world wide. 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 alternate fuel for compression ignition 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 amiable 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 [3, 4]. However, the long-term process 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 compression ignition engine to study the performance, emission and combustion characteristics of a diesel engine using orange oil and described that the brake thermal efficiency was higher, carbon monoxide (CO) and hydrocarbon (HC) emissions were lower and oxides of nitrogen (NOx) were higher compared to diesel fuel. Martin 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 increase 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 important methods to convert the vegetable oil into 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 compression ignition (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 NOx and smoke emissions. Rao et al. [14] investigated the use of Jatropha oil methyl ester and its blends with diesel fuel additive.

They found that B25 has closer performance to diesel and B100 has lower brake thermal efficiency and the blends showed lower smoke, CO_2 and CO emissions compared to diesel fuel. Vedaraman et al. [15] studied the formulation of sal oil bio diesel and tested in diesel engine. It is reported that the exhaust emissions such as CO, HC and NOx 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 heat losses of coolant, hence its improve engine performance and also a most effective way of increasing useful work of the engine and to reduce 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 to burning high viscous vegetable oils in diesel engine by retaining heat produced from the combustion of fuel in combustion chamber. If the heat rejected to coolant is reduced, then thermal efficiency could be improved [19–21]. Also with the use of thermal barrier coated piston increases the peak pressure and heat released rate of the bio diesel 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 process [24]. They reported that the engine performance in terms of power, fuel consumption, and thermal efficiency of LHR engine for all fuels except the volumetric efficiency with biodiesel. The coolant heat losses were reduced and the exhaust heat losses were improved and the engine emissions have improved (except NOx) in LHR engine.

The motive of the immediate work is to investigate the performance, emission and combustion characteristics of 25% Rubber seed oil methyl ester-diesel blend as fuel in a diesel engine with and without coating on the piston crown. The measured value of the coated piston engine with diesel and biodiesel blend are compared with base engine with diesel and biodiesel blend.

PREPARATION OF JATROPHA DI-ETHYL ETHER: (JDEE)

The process of converting vegetable oil into biodiesel is known as transesterification process. In this process, 1 l of raw Jatropha Di-Ethyl Ether: (JDEE) is heated in a reactor to remove its moisture. Potassium methoxide is prepared by dissolving 8–10 g 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 2 hours.

After 8 hours of settling period, ether separates as an upper layer and glycerol settles at bottom and separated by decantation. Then the ether was washed with warm distilled water to remove impurities.

In this reaction of 790 ml of JDEE was produced from 1 l of Jatropha seed oil. The important properties of diesel, Jatropha seed oil and its ethyl ether are given in Table 1.

EXPERIMENTAL SETUP AND PROCEDURE

Experiment was conducted in a four strokes single cylinder direct injection constant speed diesel engine. The technical specifications of the test engine are listed in Table 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 Jatropha oil Diethyl ether 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 such as HC, CO and NO were measured by using AVL-444 gas analyzer and the smoke opacity was measured by AVL-437 smoke meter.

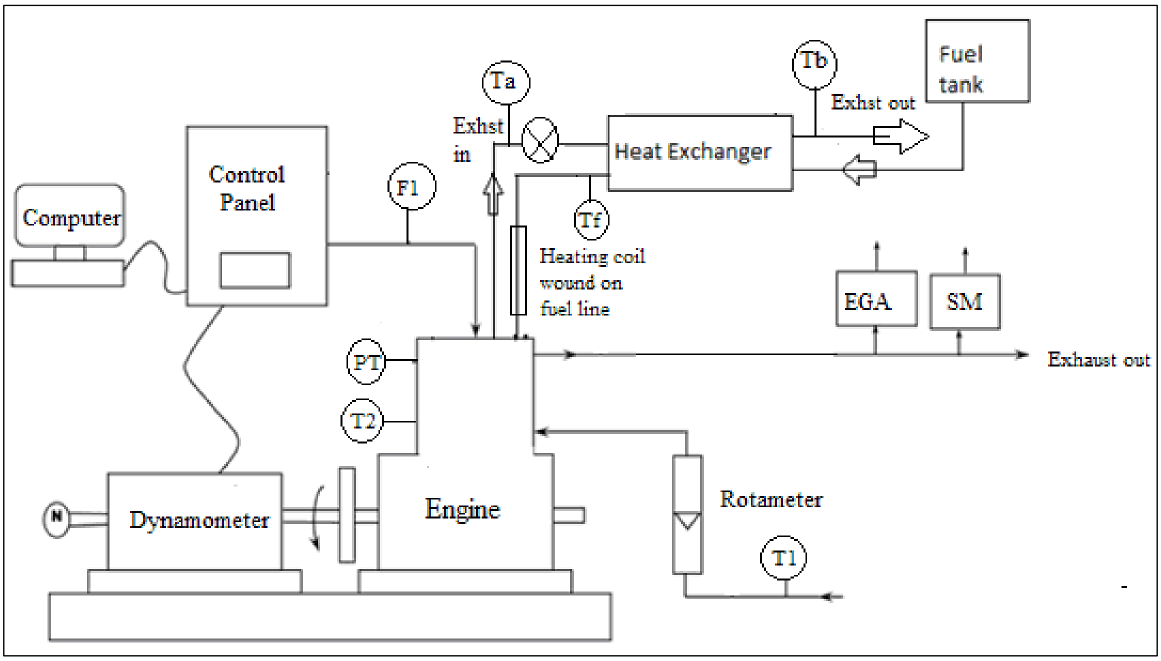

***Fig. 1.** Schematic of experimental set-up.*

An AVL make digital data acquisition system with piezo electric 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 is processed with the help of computer. The cylinder pressure and heat release rate are calculated with the average of 50cycles.

The schematic of the experimental set up is shown in Figure 1. The emissions error and range are given in Table 3.

Table 1. *Properties of diesel, rubber seed oil and its methyl ester.*

Properties	Diesel	JSO	JDEE	Testing methods
Density (kg/m^3)	830	914	884.2	EN ISO 3675
Kinematic viscosity at 40°C (cSt)	3.720	31.2	4.4	EN ISO 3104
Flash point (°C)	52	125	165	EN ISO 3679
Fire point (°C)	60	148	172	EN ISO 23015
Calorific value (MJ/kg)	43	39.6	41.3	DIN 51900
Cetane number	48	47	58.5	EN ISO 5165

Semi-Adiabatic Engine

In a compression ignition 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 rest carried away by the cooling water. Releasing the heat transfer to the coolant increases exhaust energy. One method of obtaining the above condition is to thermally insulate the combustion chamber (only piston crown) converting it into a semi adiabatic engine. This method isolates the piston crown, using high temperature materials, which allow "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 TiO_2 bond coat is used, which creates a higher combustion chamber temperature that may lead to the improvement in the combustion characteristics of biodiesel, brake thermal efficiency of the engine and reduction in the exhaust emissions.

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 rev/m
Fuel injection	23° before TDC
Injection pressure	200 bar

RESULTS AND DISCUSSION

In this study, ethyl ether was made of raw Jatropha 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 brake thermal efficiency, brake power, specific fuel consumption and the emission values like HC, CO, NO and smoke were measured. The measured and considered parameters were analyzed and compared with diesel.

Table 3. *Emission accuracy and error range.*

SI. no	Instruments	Measuring range	Accuracy	Percentage of accuracy
1	AVL DiGAS 444 five gas analyser			
	Carbon monoxide(CO)	0–10% Vol	±0.02% Vol	±0.2
	Carbon dioxide(CO_2)	0–20% Vol	±0.02%Vol	±0.15
	Hydrocarbon (HC)	0–20000 ppm	±15 ppm	±0.2
	Oxygen(O_2)	0–22%Vol	±0.1502%Vol	±0.3
	Nitric Oxide(NO)	0–5000 ppm	±50 ppm	±0.2
2	AVL437 Smoke meter	0–100%	±1	±1

Cylinder Peak Pressure

The cylinder peak pressure fluctuation with crank angle for diesel and 25% bio diesel blend for uncoated and coated piston engine at full load is shown in Figure (2). The peak pressure is an essential parameter to decide the efficiency of the fuel. And also the cylinder pressure depends 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. Maximum peak pressure and maximum pressure rise rate corresponding to large amount of fuel burned in remixed stage. The cylinder peak pressure for B25 with the titanium oxide coated piston is increased by 3.2 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 and 67.2 bar with the base engine, whereas for the Titanium Oxide coated piston it is 74.2 bar at maximum load. The lower peak pressure was acquired 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.

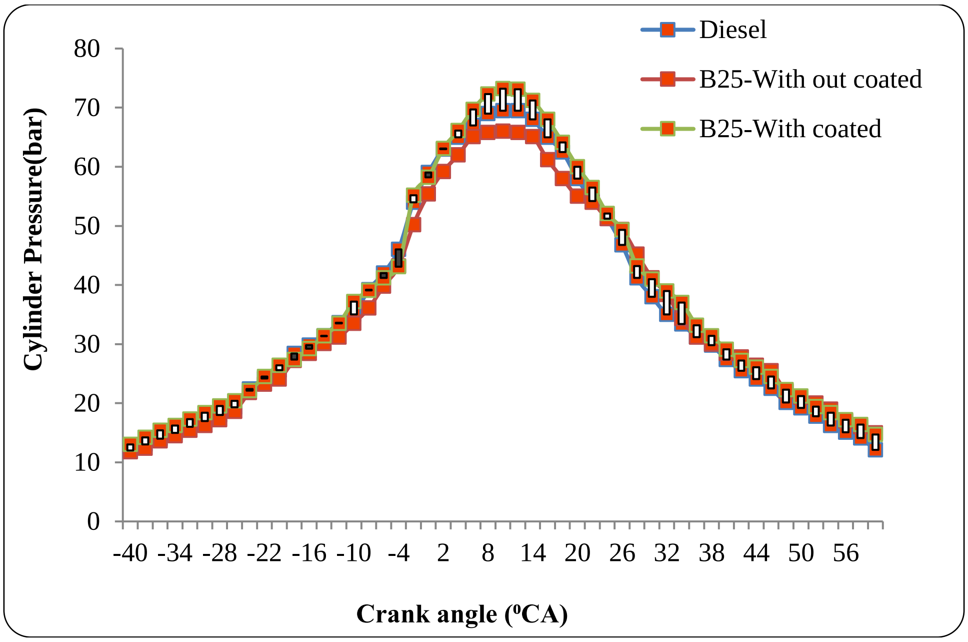

Fig. 2. *Variation of cylinder peak pressure with CA at full load.*

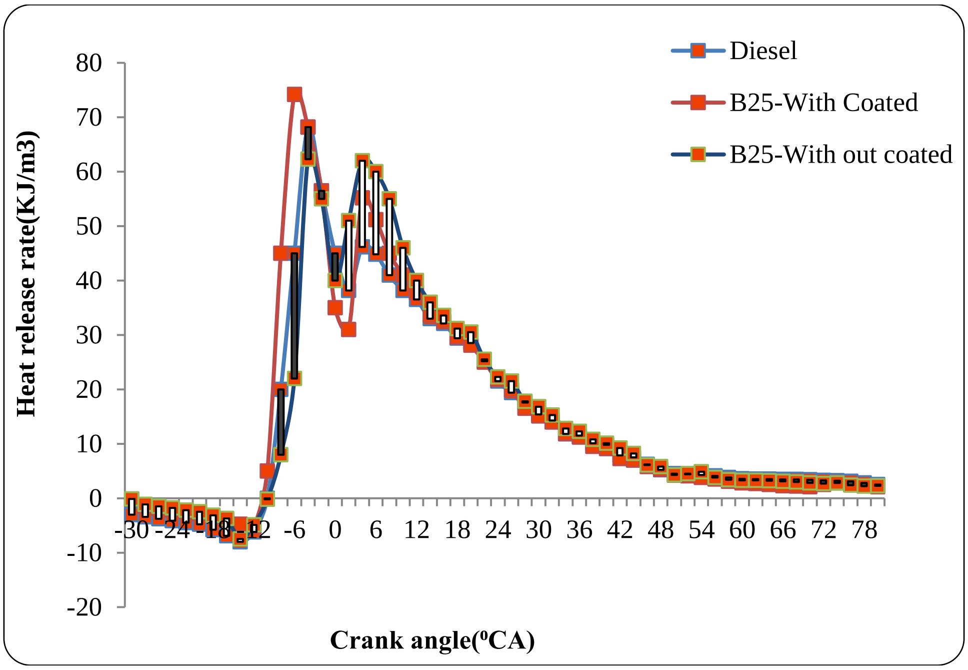

Fig. 3. *Variation of heat release rate with CA at full load.*

Heat Release Rate

The heat releasing rate with crank angle with full load for diesel and B25 biodiesel blend with uncoated and coated piston engine shown in Figure 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/kg m^3 with coated piston engine at full load. The heat discharge rate for diesel and B25 biodiesel blend for base engine is 67 and 63.2 kJ/kg m^3 with full load. This is due to the higher operating temperature associated with the coated engine, resulting in better performance. Lower calorific value of biodiesel shows less heat release than coated engine.

Maximum Rate of Pressure Rise

The fluctuation of maximum rate of pressure rise with brake power for both the engine operations is shown in Figure 4. The rate of pressure rise depends on the combustion rate in the 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 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 decrease in ignition delay period and increase in rate of pressure rise.

Ignition Delay

The ignition delay variation with brake power for both the piston engine operations is illustrated in Figure 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 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.

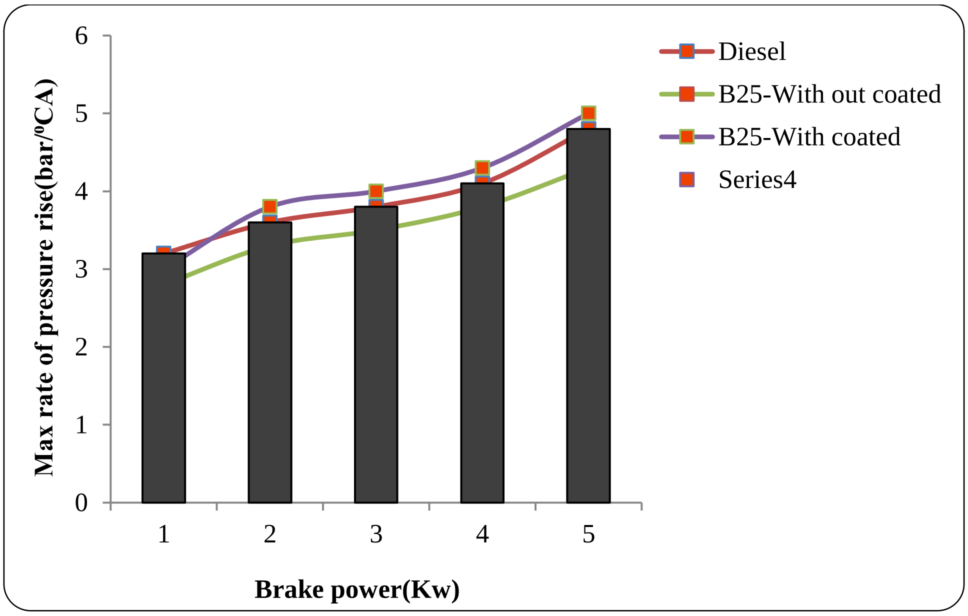

Fig. 4. *Variation of maximum rate of pressure rise with BP.*

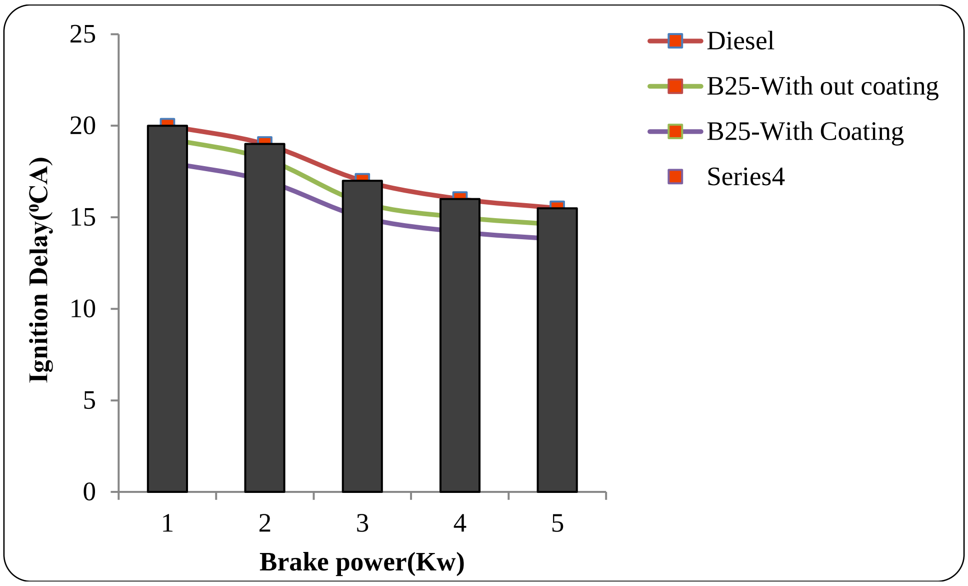

Fig. 5. *Variation of ignition delay with BP.*

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 return produce larger dispersion and shorter ignition delay. A decrease in ignition delay means a smaller amount of fuel accumulation prior to ignition.

Brake Thermal Efficiency (BTE)

The fluctuation of brake thermal efficiency with brake power for the uncoated and coated engine for diesel and biodiesel mixture is shown in Figure 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 apply 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 the BTE of the engine. It is analyzed that the brake thermal efficiency increases with increase in brake power at all loads.

The brake thermal efficiency obtained for B25 with coated piston engine is increased by 2.9% compared to B25 with base engine. BTE for B25 with and without coated engine is 30.84% and 31.74% respectively and for diesel it is 30.48% at the 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 brake thermal efficiency.

Brake Specific Fuel Consumption (BSFC)

The variation of brake specific fuel consumption with brake power for the all the tests fuels is shown in Figure 7. It is noticed that the 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, the 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 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.

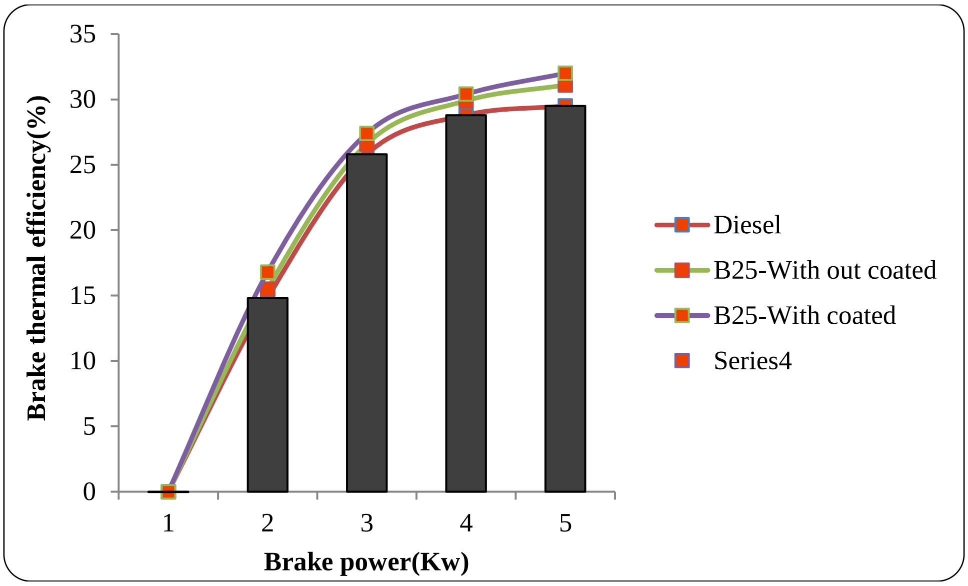

Fig. 6. *Variation of brake thermal efficiency with BP.*

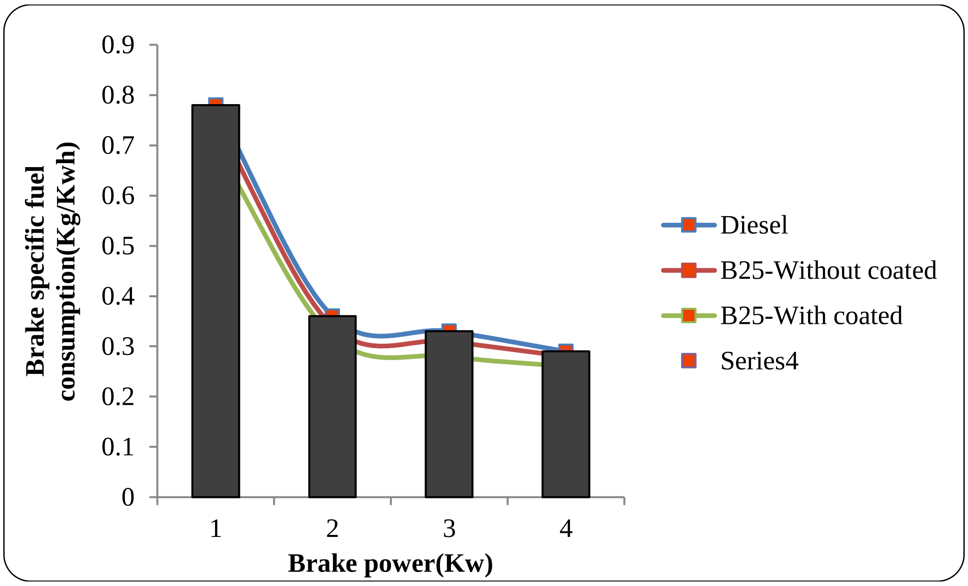

Fig. 7. *Variation of Brake specific fuel consumption with BP.*

Carbon Monoxide Emissions (CO)

The variation of carbon monoxide emission with brake power for B25 with and coated piston engine is illustrated in Figure 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 by42% 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%Vol and 0.14% 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.

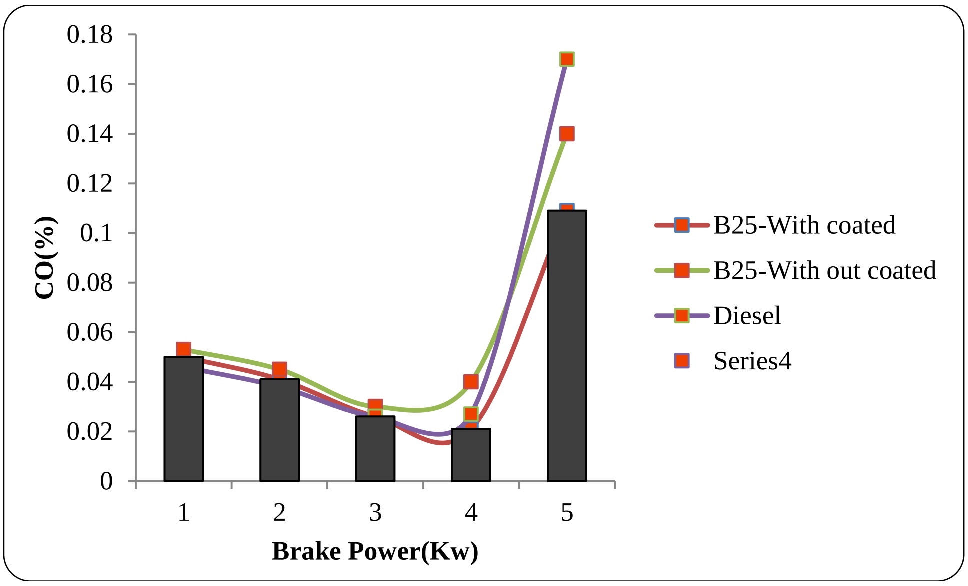

Fig. 8. *Variation of carbon monoxide with BP.*

Hydro Carbon Emissions (HC)

The variation of hydrocarbon emission with brake power is shown in Figure 9. The reason for HC emission from a diesel engine is due to wall quenching, fuel that vaporize 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 with coating for diesel on account of its higher viscosity, which affecting the combustion process, resulting in a less complete combustion.

Even so, with the coated engine, B25 relatively undergoes improved combustion than uncoated engine, by retaining the heat inside the combustion chamber, results improved burning of the fuel and this has been caused by 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 is 32 ppm, where it is 65 ppm with the base engine at maximum power output. The HC emission for diesel with the base engine is 52ppm at peak power output. This decrease in hydrocarbon emissions is due to high temperature in the combustion chamber by the coated piston operation of the engine, results incomplete combustion of biodiesel.

Nitrogen Oxide Emissions (NO)

The variation of nitrogen oxide emission with brake power is shown in Figure 10. The formation of NOx emission due to the peak flame temperature and excess oxygen within the combustion chamber. Many research studies reported that an increase in NOx emission for biodiesel due to the excess oxygen present in it, high combustion temperature. The NOx 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 NOx 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 bio diesel, resulting increase in the combustion chamber temperature. The increase in cylinder temperature and the presence of excess oxygen within the fuel has promoted the formation of NOx and therefore, the NOx emission for B25 with coating is higher than that of without coating. The NOx emission obtained for the uncoated engine with diesel and B25 are 1480 ppm and 1510 ppm respectively and for the coated piston with B25 is 1690 ppm at full load.

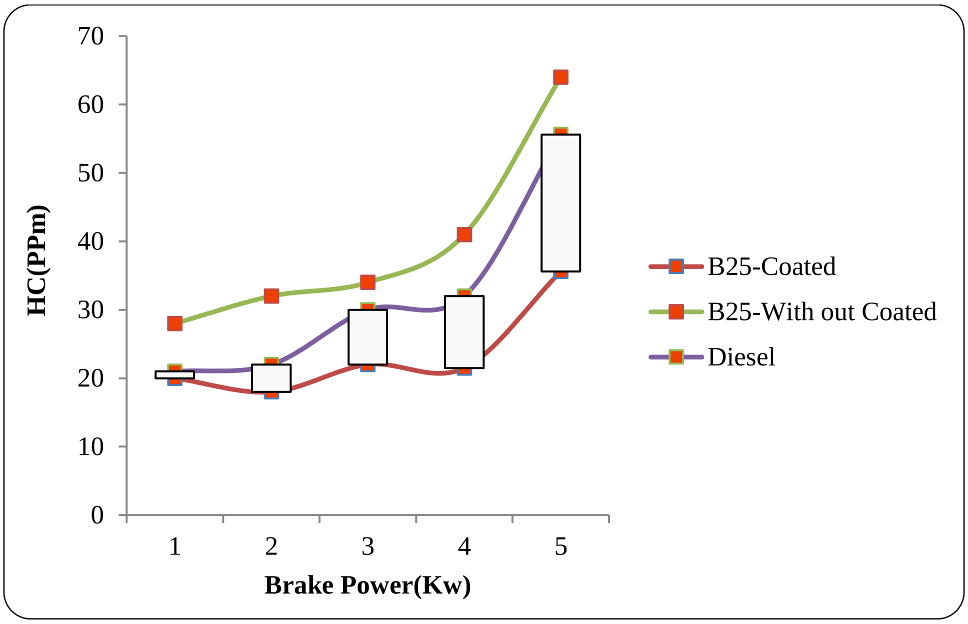

Fig. 9. *Variation of hydrocarbon emissions with BP.*

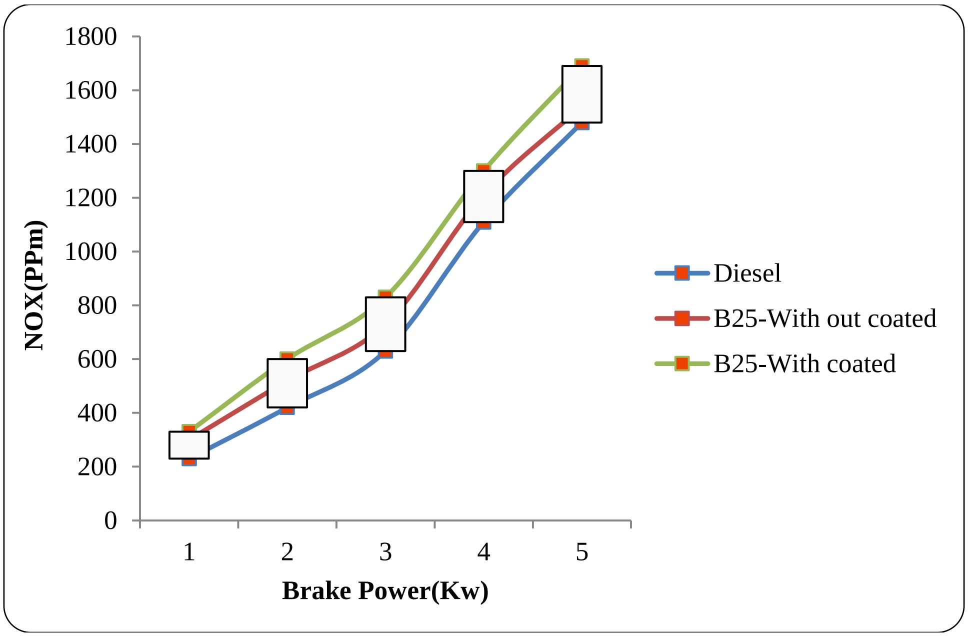

Fig. 10. *Variation of nitrogen oxide emissions with BP.*

Smoke Opacity

The fluctuation of smoke opacity with brake power for diesel and bio diesel blend is shown in Figure 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 blend 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 is 4.4% with base engine at full load.

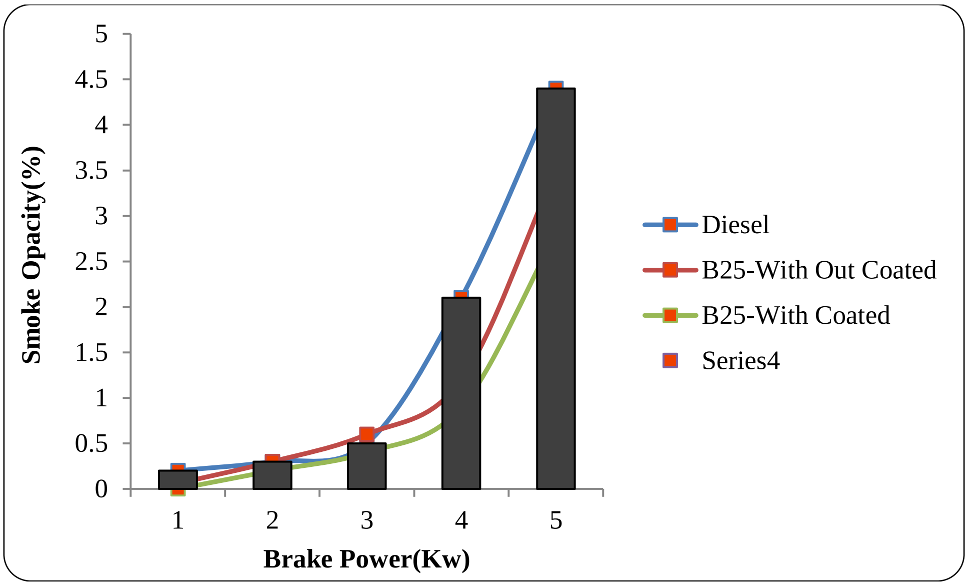

Fig. 11. *Variation of smoke opacity with BP.*

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.

CONCLUSION

The experimental test has been conducted on a single cylinder direct injection 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 brake thermal efficiency of B25 increased by 2.9% compared to B25 with base engine at full load. The BSFC 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 NOx 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/kg m^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 Jatropha seed oil biodiesel blend improved the combustion and performance characteristics and drastically reduced the exhaust emissions with slightly increased in NO emissions.

NOMENCLATURE

BTE – Brake thermal efficiency
BSFC – Brake specific fuel consumption
EGT – Exhaust gas temperature
CO – Carbon monoxide
CO_2 – Carbon dioxide
HC – Hydrocarbon
NO – Nitrogen oxide emission
LHR – Low heat rejection
TiO_2 – Titanium Oxide
DI – Direct Injection
JSDEE – Jatropha seed oil Di-ethyl ether
B25 – 25% Biodiesel + 75% diesel blend
CI – Compression Ignition

REFERENCES

[1] A.S. Ramadhas, et al. Characterization and effect of using rubber seed oil as fuel in compression ignition engines, *Renew Energy*. 2005; 30: 795–803p.
[2] N. Reddy, J. Ramesh. Parametric studies for improving the performance of a Jatropha oil-fuelled compression ignition engine, *Renew Energy*. 2006; 31: 1994–2016p.
[3] O.M.L. Nwafor, G. Rice. Performance of rapeseed oil blends in diesel engines, *Applied Energy*. 1996; 54: 345–54p.
[4] M. Canakci. Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel, *Bioresource Technol*. 2007; 98: 1167–75p.
[5] P.K. Sahoo, et al. Biodiesel development from high acid Polanga seed oil and performance evaluation in a CI engine, *Fuel*. 2007; 86: 448–54p.
[6] K. Purushothaman, G. Nagarajan. Performance, emission and combustion characteristics of a compression ignition engine operating on neat orange oil, *Renew Energy*. 2009; 34: 242–5p.
[7] L.J. Martin, et al. A comparative analysis of different methods to improve the performance of cotton seed oil fuelled diesel engine, *Fuel*. 2012; 102: 372–8p.
[8] H. Raheman, S.V. Ghadge. Performance of compression ignition engine with Mahua (Madhuca indica) biodiesel, *Fuel*. 2006; 86: 2568–73p.
[9] G. Lakshmi Narayana Rao, et al. Combustion and emission characteristics of diesel engines fueled with rice bran oil methyl ester and its diesel blends, *Therm Sci*. 2008; 12: 139–50p.
[10] K.R. Suresh Kumar, R. Velraj, R. Ganesan. Performance and exhaust emission characteristics of a CI engine fueled with Pongamia pinnata methyl ester and its blends with diesel, *Renew Energy*. 2008; 33: 2294–302p.
[11] K. Rajan, S. Kumar, K.R. Performance and emission characteristics of diesel engine with internal jet piston using biodiesel, *Int J Environ Stud*. 2010; 67(4): 556–67p.
[12] J. Hemanandh, K.V. Narayanan. Experimental studies of emissions in a CI engine blended with refined sunflower oil, *Indian J Sci Technol*. 2013; 6(7): 4954–9p.
[13] M. Pugazhvadivu. Studies on the effect of ethanol addition to biodiesel; performance and emissions of a diesel

engine, *Indian J Sci Technol*. 2009; 2(11): 23–6p.
[14] Y.V. Hanumantha Rao, et al. Experimental investigations on Jatropha biodiesel and additive in diesel engine, *Indian J Sci Technol*. 2009; 2(4): 25–31p.
[15] N. Vedaraman, et al. Methyl ester of Sal oil (Shorea robusta) as a substitute to diesel fuel – a study on its preparation, performance and emissions in direct injection diesel engine, *Ind Crops Prod*. 2012; 36: 282–8p.
[16] H. Kawamura, S. Sekiyama. Combustion and combustion chamber for a low heat rejection engine, *SAE Int*. 1996, 960506, doi. 10.4271/960506.
[17] H. Hazar. Effects of biodiesel on a low heat loss diesel engine, *Renew Energy*. 2009; 34: 1533–7p.
[18] H. Hanbay. Cotton methyl ester usage in a diesel engine equipped with insulated combustion chamber, *Appl Energy*. 2009; 87: 134–40p.
[19] R. Kamo, et al. Coatings for improving engine performance, *SAE Trans*. 1997, 970204, doi: 10.4271/970204.
[20] G. Boehm, J. Harrer. Nickel coated pistons for improved durability in knock control engines, *SAE Trans*. 1990; 900453: 1031–103p.
[21] K. Rajan, M. Prabhahar. Performance and combustion characteristics of a diesel engine with titanium oxide coated Piston using Pongamia methyl ester, *J Mech Sci Technol*. 2013; 27(5): 1519–26p.
[22] N.R. Banapurmath, P.G. Tewari. Performance of a low heat rejection engine fuelled with low volatile Honge oil and its methyl ester (HOME), *Proc Inst Mech Eng Part A J Power Energy*. 2008; 222(3): 323–30p.
[23] J.B. Heywood. *Internal Combustion Engine Fundamentals*. New York, USA: Mc Graw Hill Publishers; 1998.
[24] M. Abedin, et al. Combustion, performance, and emission characteristics of low heat rejection engine operating on various biodiesels and vegetable oils, *Energy Convers Manage*. 2014; 85: 173–89p.