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Performance and combustion characteristics of a diesel engine with titanium oxide coated piston using Pongamia methyl ester[†]

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Abstract

Owing to the increasing cost of petroleum products, fast depletion of fossil fuel, environmental consideration and stringent emission norms, it is necessary to search for alternative fuels for diesel engines. The alternative fuel can be produced from materials available within the country. Though the vegetable oils can be fuelled for diesel engines, their high viscosities and low volatilities have led to the investigation of its various derivatives such as monoesters, known as bio diesel. It is derived from triglycerides (vegetable oil and animal fates) by transesterification process. It is biodegradable and renewable in nature. Biodiesel can be used more efficiently in semi adiabatic engines (Semi LHR), in which the temperature of the combustion chamber is increased by thermal barrier coating on the piston crown. In this study, the piston crown was coated with ceramic material (TiO_2) of about 0.5 mm, by plasma spray method. In this present work, the experiments were carried out with of Pongamia oil methyl (PME) ester and diesel blends (B20 & B100) in a four stroke direct injection diesel engine with and without coated piston at different load conditions. The results revealed 100% bio diesel, an improvement in brake thermal efficiency (BTE) and the brake specific fuel consumption decreased by about 10 % at full load. The exhaust emissions like carbon monoxide (CO) and hydrocarbon (HC) were decreased and the nitrogen oxide (NO) emission increased by 15% with coated engine compared with the uncoated engine with diesel fuel. The peak pressure and heat release rate were increased for the coated engine compared with the standard engine.

Keywords: Titanium oxide; Combustion; Performance; Emissions; Pongamia methyl ester; Transesterification.

1. Introduction

Compression ignition engines are employed particularly in the field of heavy transportation and agriculture on account of their high thermal efficiency and durability. However, diesel engines are the major contributors of oxides of nitrogen and particulate emissions. Hence more stringent norms are imposed on exhaust emissions. Vegetable oils are considered as good alternative to diesel as their properties are closer to those of diesel and can be used to run a compression ignition engine without any modifications. They are renewable sources of energy, eco-friendly and largely available with low sulfur content, and are safe to store [1-3].

Attempts have been made in the last two decades to find the suitable methods for using vegetable oils in diesel engines. Suresh Kumar et al. [4] studied the performance and emissions of diesel engine with Pongamia pinnatta methyl ester at various blends and they reveal that 40% blends by volume provide better performance and improved exhaust emissions. Lakshminarayana Rao et al. [5] have studied the combustion analysis of diesel engine with various blends of rice bran oil methyl ester and their results showed that the ignition delay, rate of heat release are decreases also HC and CO emissions are decreased and NOx emissions are slightly increased with increase in blends.

Deepak Agarwal et al. [6] have investigated the effect of linseed oil, mahua oil, and rice bran oil and linseed methyl ester in a diesel. It has been reported that brake specific fuel consumptions were higher for vegetable oil compared to diesel fuel. It has been concluded that the 20% of linseed oil methyl ester blend was optimum that improved the thermal efficiency and reduced the smoke density. The researchers [7, 8] have studied the performance and combustion characteristics of diesel engine with rubber seed oil and its blends. They reported that the smoke, HC and CO emissions are higher and NO emissions are lower at peak load for 100% rubber seed oil methyl ester. Balusamy and Marappan [9] have studied the performance and combustion characteristics of s diesel engine with methyl ester of thevetia peruviana seed oil as fuel. They reported that the CO, HC emissions are less but NOx and smoke are slightly higher than that of diesel (Puhan et al. [10]).

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In a normal diesel engine, approximately thirty percent of the total energy is rejected to the coolant. The low heat rejection (LHR) engine concept is based on suppressing this heat rejection to the coolant and recovering the energy in the form of useful work. Some important advantages of the LHR concept are improved fuel economy, reduced hydrocarbon, smoke and carbon monoxide emissions [11-13]. In this concept, the combustion chamber is insulated by using high temperature materials on engine components, such as pistons, cylinder head, valves, cylinder liners and exhaust ports. By reducing lost energy and eliminating the need for a conventional cooling system, this engine system will dramatically improve overall performance of the engine [14-17]. Low cetane fuel can also be burnt in LHR engines and it is enabled by a higher combustion chamber temperature at the time of fuel injection.

Beg and Rehman [18] have tested linseed oil in a semi adiabatic single cylinder diesel engine under variable compression ratio. It has been reported that the brake thermal efficiency was found to be 16.34% and 18.64% for compression ratio of 10 and 20 respectively. It has been further reported that the esterified linseed oil, there was an increase in exhaust gas temperature, NOx emission and lower smoke emission. It has been concluded that esterified linseed oil showed lower ignition delay in insulated engine due to better combustion. Sreenivasa Reddy et al. [19] have used an insulated cylinder head in a 3.67 kW, 4 stroke, single cylinder direct injection diesel engine to study the performance of a semi adiabatic engine. It has been concluded that the ceramic-coated engine showed improvement in thermal efficiency, increase in friction, and increase in exhaust gas temperature and some loss in volumetric efficiency.

Ekrem Buyukkaya et al. [20] have studied the performance and emission characteristics of a thermal barrier coated turbocharged six cylinder diesel engine at various speeds and different with injection timings. It has been reported that the SFC was reduced about 1-8% and the NOx emissions were reduced by 11% for 18^{o} BTDC with LHR engine compared to the uncoated engine. It has also been reported that the particulate emissions decreased by about 40% for LHR engine, while the NOx emissions were increased by about 9% compared to those of the standard engine due to higher exhaust gas temperature for the LHR engine.

Banapurmath and Tewari [21] have studied the performance and emission characteristics of a thermal barrier coated (Zirconia) diesel engine at constant speed with honge oil and its methyl ester with optimized injection timing as 19^{o} CA BTDC for vegetable oil and its methyl ester with LHR engine at full load. It has been reported that the CO and HC emissions were reduced for LHR engine with Honge oil methyl ester compared with Honge oil. Heat release rate was better for HOME when compared with Hanbey Hazer [22] who studied the performance and emission characteristics of a ceramic coated ($MgO-ZrO_2$) diesel engine using canola methyl ester blends at different speeds at full load. It has been reported that the power of the engine is increased about 8.4% for diesel and 3.5% for biodiesel and the SFC decreases about 5% for diesel and 8% for alternative fuels. The CO and smoke emissions decreased about 24% and 8.2% respectively, while the NOx emissions were increased about 7.3% for alternative fuels.

Table 1. The properties of diesel and pongamia methyl ester.

S. No	Properties	Diesel	PME	Biodiesel specifications as per ASTM
1	Fuel standard	ASTMD975	-	ASTMD6751
2	Specific gravity 60^{o}C	0.8530	0.876	Not reported
3	Density (kg/m^3)	830	880	Not reported
4	Kinematic viscosity (cSt) @40^{o}C	3.8	5.6	1.9-6.0
5	Flash point (^{o}C)	60	217	130, min
6	Cloud point (^{o}C)	-15 to 5	-3 to 12	Not reported
7	Fire point (^{o}C)	63	223	Not reported
8	Cetane number	47	52	47, min
9	Heating value	42800	36120	Not reported
10	Carbon residue	0	0.02	0.05 Mass%, max
11	Acid number (mg KOH/g)	0.01	0.04	0.8, max
12	Oxygen	0	11	By weight

Therefore, in the present investigation, the piston crown was coated with 0.5 mm thickness of titanium oxide to achieve semi LHR engine which withstands higher temperature in the combustion chamber that promotes the combustion. The objective of the present study is to improve the performance, and combustion and emissions of a diesel engine with TiO_2 coated piston using 100% Pongamia oil methyl ester and its 20% blend at different load conditions. The measured values are analyzed and compared with the base engine with diesel.

2. Materials and methods

2.1 Preparation of biodiesel (PME)

Transesterification is a chemical process of transforming large, branched, triglyceride molecules of vegetable oils and fats into smaller, straight chain molecules, almost similar in size to the molecules of the species present in diesel fuel. The process takes place by the reaction of vegetable oil with alcohol (methanol) in the presence of a catalyst. Pongamia oil contains high free fatty acids (FFA) upto 20%. It requires a two step process to be converted into biodiesel. The first step is acid-catalyzed esterification by using 0.5% H_2SO_4, alcohol 6:1 molar ratio with respect to the high FFA Pongamia oil to produce methyl ester by lowering the acid value and the next step is alkali-catalyzed transesterification [12].

This transesterification process involves making the triglycerides of Pongamia oil react with methyl alcohol in the presence of a catalyst to produce glycerol and fatty acid ester.

Table 2. Test engine specifications.

Make	Kirloskar, single cylinder
Engine	Four stroke, diesel engine
Type	Vertical, watercooled engine
Bore (mm)	80
Stroke (mm)	110
Power (kW)	3.7
Compression ratio	16.5:1
Speed	1500 rpm
Fuel injection	23° before TDC

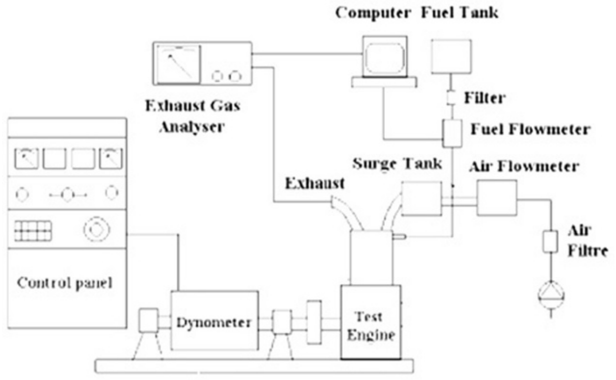

Fig. 1. Schematic of test engine setup.

Table 3. The uncertainities of measured and calculated parameters.

Parameters	Maximum errors
BTE	1.01
BSFC	1.01
EGT	1.28
CO	0.2
HC	0.15
NO	1.01
Smoke	0.1

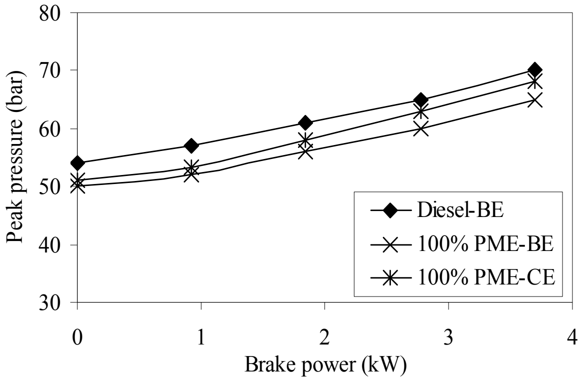

Fig. 2. Variation of peak pressure with BP.

Specified amount (1000 ml) of Pongamia oil (200 ml) of methyl alcohol and (10 g) of sodium hydroxide were taken in a round bottom flask. The contents were stirred till ester formation began. The mixture was heated to 70°C and held at that temperature with constant speed stirring for 1 hr, and then it was allowed to cool overnight without stirring. Two layers were formed. The bottom layer consisted of glycerol and top layer was the ester. The properties of diesel, Pongamia oil and its methyl ester are given in Table 1.

2.2 Experimental setup and procedure

The engine tests were conducted on a four-stroke-single cylinder direct-injection water-cooled diesel engine as shown in Fig. 1. The test engine specifications are given in Table 2. The test engine is coupled with electrical dynamometer to provide the brake load. The engine is operated with and without coated piston at a rated speed of 1500 rev/min using 100% Pongamia oil methyl ester and diesel fuel with varying load conditions, from no load to full load in steps of 25%. The engine was coupled with dynamometer. Two separate fuel tanks were used for the diesel fuel and Pongamia oil methyl ester. The volumetric fuel flow rate and the volumetric air flow rate were measured using a 50 cm^3 burette/stop watch and a U-tube manometer, respectively. The fuel consumption was determined by measuring the time taken for a fixed volume of fuel to flow into the engine. The exhaust emissions were measured by the AVL 444 five gas analyzer and the smoke density was measured by Bosch smoke meter. The combustion parameters were measured with the help of pressure sensor, TDC encoder and data acquisition chord with the help of computer. The uncertainties of the measured parameters are shown in Table 3.

3. Results and discussion

In the present investigation, tests were carried out on a single cylinder diesel engine with and without coated piston using 100% bio diesel and diesel at varying load conditions. The performance, combustion and emissions parameters values of both the piston operations were measured and analyzed for cylinder pressure, heat release rate, ignition delay, brake thermal efficiency, brake specific fuel consumptions, exhaust gas temperature, carbon monoxide, nitrogen oxide and smoke emissions and compared with the without coated piston engine.

3.1 Combustion analysis

Fig. 2 shows the variation of peak pressure with brake power for diesel and 100% Pongamia methyl ester at full load. The peak pressure depends on the amount of fuel taking part in the uncontrolled combustion phase, which is governed by the delay period and the spray envelope of the injected fuel. It can be observed from the figure that the peak pressure for the thermal barrier coated engine with 100% PME is increased by 3 bar with the 100% PME and lowered by 2 bar with diesel fuel compared with the base engine at full load. This may be

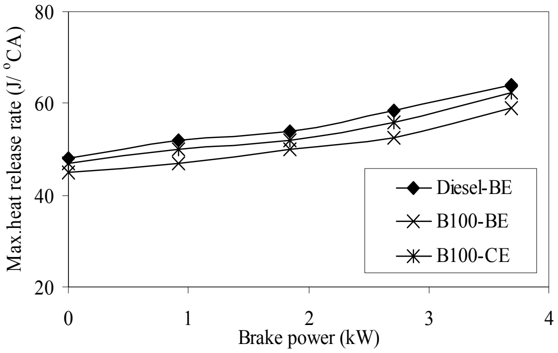

Fig. 3. Variation of maximum heat release rate with BP.

due to the better combustion of biodiesel at higher temperature of the combustion chamber by the thermal barrier coated piston, resulting in better combustion of biodiesel, and hence increases in peak pressure. The maximum cylinder peak pressure for the base engine with diesel and 100% PME are 70 bar and 65 bar respectively at full load, whereas for the coated engine with 100% PME is 67 bar at full load.

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Fig. 3 shows the variation of the maximum heat release rate with crank angle for both the engine operations. The premixed combustion phase is increased for the 100% PME with thermal barrier coated engine, due to the shortening of ignition delay by lower heat loss as compared to the base engine with diesel. The HRR is increased by 2.5 J/°CA for 100% PME with coated engine at full load compared to the base engine.

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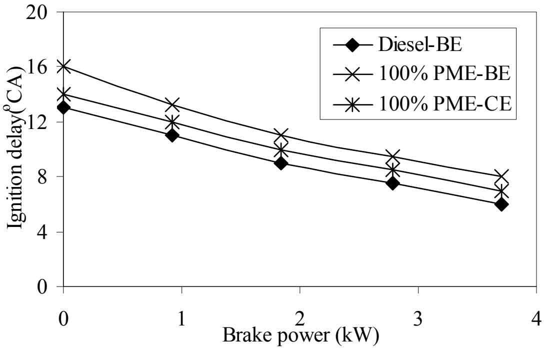

Fig. 4. Variation of ignition delay with BP.

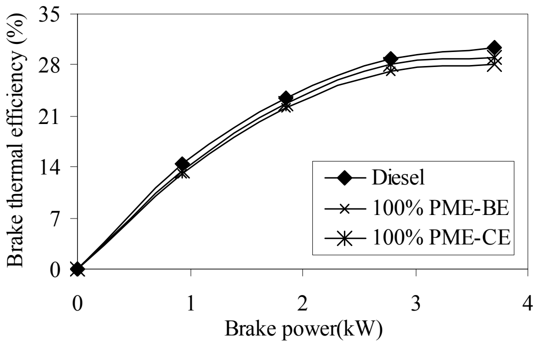

Fig. 5. Variation of Brake thermal efficiency with BP.

Fig. 4 depicts the variation of ignition delay with brake power for diesel and biodiesel at full load. Ignition delay is calculated as the period from the start of injection to the start of combustion in terms of the crank angle. The ignition delay is decreased for CE may be due to faster combustion of the biodiesel fuel compared with the base engine. The delay period for the base engine with diesel 100% PME are 6°CA and 8°CA respectively at full load, whereas for the CE with 100% PME is 5°CA at full load. This may be due to the higher combustion temperature of the coated piston, resulting in a shorter delay period.

3.2 Performance analysis

The variation of brake thermal efficiency with brake power for diesel and biodiesel at full load is shown in Fig. 5. It is observed that the brake thermal efficiency for CE engine is higher than that of the base engine for both the fuels. The BTE for the base engine for diesel and 100% PME are 30.25% and 28.5% respectively at full load. For the coated engine with 100% PME is 29.13% at full load. The increase in BTE may be due to better vaporization biodiesel fuel at higher combustion temperature, resulting in complete combustion.

Fig. 6 shows the variation of brake specific fuel consump-

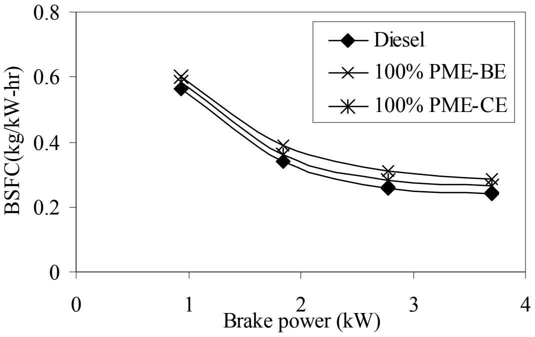

Fig. 6. Variation of BSFC with BP.

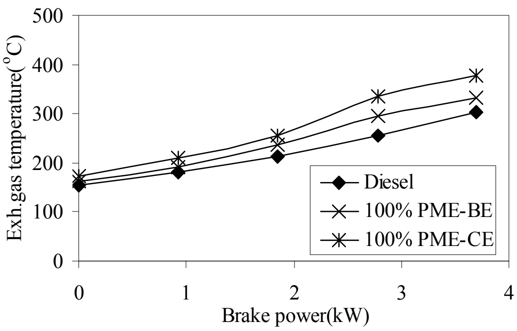

Fig. 7. Variation of exhaust gas temperature with BP.

tions with both the fuels. The average BSFC decrease in the CE is determined to be 8% for 100% PME compared with the base engine. The BSFC is decreased for 100% PME for the CE operations. The positive effect of increased cylinder temperature due to heat insulation the BSFC decreases for both the fuels in CE operations. The BSFC values for base engine with diesel and 100% PME are 0.240 kg/kWh and 0.275 kg/kWh respectively at full load. For the coated engine 100% PME is 0.253 kg/kWh at full load.

3.3 Emissions analysis

Fig. 7 shows the variation of exhaust gas temperature for both the fuels. The exhaust gas temperature is increased for CE, compared with the base engine. The exhaust gas temperature increased about 14% for 100% PME at full load. The increase in exhaust gas temperature for both the fuels used in the CE, compared with the base engine. This may be explained by the decrease in heat loss going into the cooling system and outside due to coating, and transfer of this heat to the exhaust gas. The exhaust gas temperature values for base engine with diesel and 100% PME are 302°C and 332°C respectively at full load. For the coated engine with 100% PME is 378°C at full load.

Fig. 8 shows the variation of carbon monoxide emission for both the fuels. Carbon monoxide (CO) emission is formed due to incomplete combustion of fuels, which is produced most readily from petroleum fuels, which contain no oxygen in their molecular structure. The CO emissions decreases in the CE were determined to be 20% for B100 compared with that of the base engine operations. It is observed the CO emissions for the test fuels used in base engine and CE is significantly decreased. The decrease in CO emission in the CE may be due to the in cylinder heat transfer reduction, increase in combustion duration and more oxygen content present in the biodiesel. The CO values for base engine with diesel and 100% PME are 0.08 %Vol and 0.05 %Vol respectively at full load. For the coated engine with 100% PME, it is 0.04 %Vol at full load.

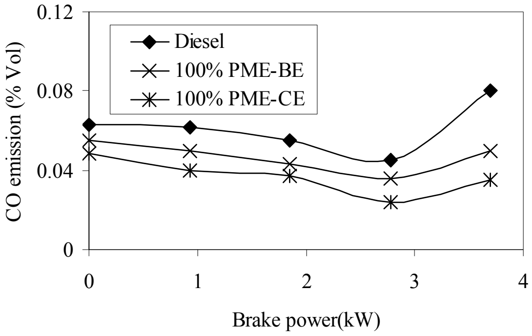

Fig. 8. Variation of CO emissions with BP.

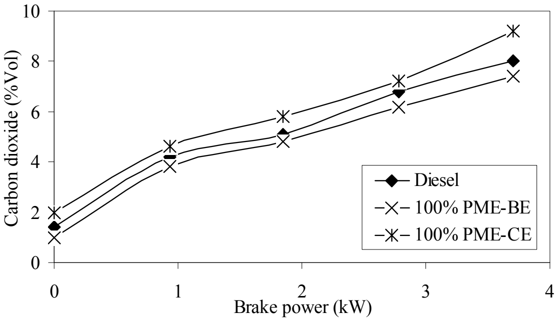

Fig. 9. Variation of CO_2 emissions with BP.

Fig. 9 shows the variation of carbon dioxide emission for both the fuels. It is observed that the carbon dioxide (CO_2) emission is increased with increase in load due to complete combustion of both the fuels. The CO_2 emissions increases for the CE for 100% PME compared with that of the base engine operations. It is observed the CO_2 emissions for the test fuels used in base engine and CE is significantly decreased. The increase in CO_2 emission in the CE may be due to the higher combustion temperature and there by reduction in cylinder heat transfer and more oxygen content present in the bio diesel. The CO_2 values for base engine with diesel and 100% PME are 8 %Vol and 7.4 %Vol, respectively, at full load. For the coated engine with 100% PME, it is 9.2 %Vol at full load.

The variation of hydrocarbon (HC) emission for both the fuels is depicted in Fig. 10. The emission of hydrocarbon from the coated engines is more likely to be reduced because of the decreased quenching distance and the increased lean flammability limit. It is observed the HC emissions for biodiesel used in CE decreased by 25% at full load compared with the base

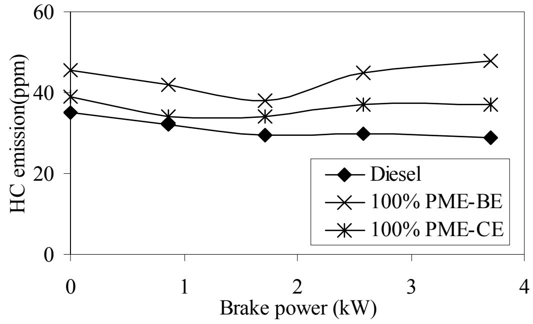

Fig. 10. Variation of HC emissions with BP.

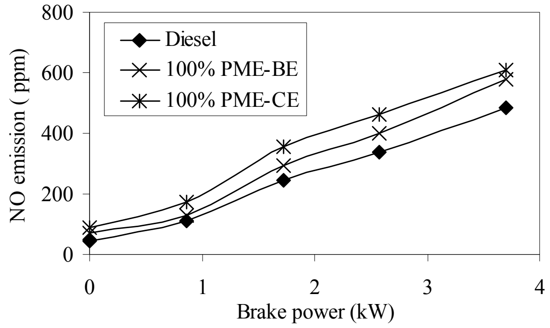

Fig. 11. Variation of NO emissions with BP.

engine. This may be due to higher temperatures of both in the gases and at the combustion chamber walls of the coated engine assist in permitting the oxidation reactions to proceed close to complete combustion. The HC values for base engine with diesel and 100% PME are 29 ppm and 48 ppm respectively at full load. For the coated engine with 100% PME, it is 3.6 ppm at full load.

The variations of nitrogen oxide emissions at different engine load for all the test fuels are shown in Fig. 11. The nitrogen oxide emission formed by chain reactions involving nitrogen and oxygen in the air. These reactions are highly temperature dependent. Since diesel engines always operate with excess air, NOx emissions are mainly a function of temperature and residence time. It is observed that the bio diesel used in both the engines cause more NO emissions. The increase in NO emission for CE may be due to higher combustion temperature and longer combustion duration. The average NO emissions increase in the CE was determined to be 12% for 100% PME at full load. The NO values for base engine with diesel and B100 are 486 ppm and 578 ppm, respectively at full load. For the coated engine with 100% PME are 562 ppm, and 667 ppm respectively at full load.

The variations of smoke density for both the engine operations for the test fuels are shown in Fig. 12. It might be expected that coated engines (CE) would produce less smoke than base engine for reasons such as high temperature gas and high temperature combustion chamber wall. The smoke densities decrease in CE was determined to be 35% for 100% PME at full load compared to that of the base engine. However the smoke density of PME is lower than that of diesel for both the engine operations. Lower smoke density of PME may be caused by higher oxygen present in the biodiesel. The oxygen content of fuel can contribute oxidation to improved fuel oxidation in locality fuel rich combustion zones, hence resulting in reduction in smoke density.

The smoke value for the base engine with diesel and 100% PME are 3.6 BSU and 3.2 BSU respectively, whereas for the CE, it is 2.1 BSU at full load. The decrease in smoke for the CE may be due to better vaporization of biodiesel at higher combustion temperature and also more oxygen present in the biodiesel, resulting in complete combustion.

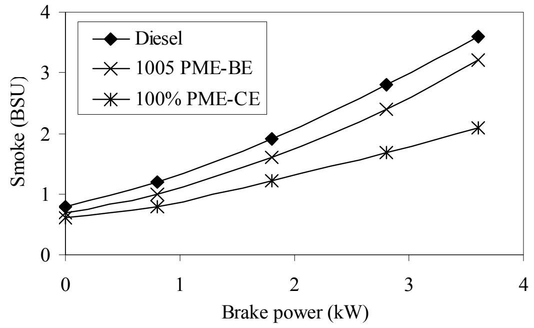

Fig. 12. Variation of smoke emissions with BP.

4. Conclusions

In order to decrease the exhaust emissions of the internal combustion engines and to improve the combustion and thermal efficiency, thermal barrier coatings are applied. In this experimental study, the piston crown has been coated to achieve the semi adiabatic engine feature. The following conclusions have been drawn from the present experimental study.

(1) The peak pressure and heat release rate increased for the test fuels in the CE is compared with the base engine. The ignition delay is decreased for the test fuels in the CE compared with the base engine. The delay period decreased about 2°CA for 100% biodiesel compared with the base engine.

(2) In CE engine due to reduction BSFC, the brake thermal efficiency was increased, the BTE increased about 2.2% for pure biodiesel compared with the base engine.

(3) The BSFC decreases for all the test fuels in the CE compared with the base engine. The BSFC is decreased about 8% for pure biodiesel compared with the base engine.

(4) The exhaust gas temperature increased for all the test fuels in the CE compared with that of the base engine. The exhaust gas temperature increased about 14% for the biodiesel compared with the base engine.

(5) The CO and HC emission decreased about 30% and 23% for pure biodiesel compared with the base engine. The CO_2 emissions are increased for the bio diesel with CE due to higher combustion temperature.

(6) The NO emission increases for the test fuels in the CE compared with the base engine. The NO increase in the CE was determined to be 12% for pure biodiesel compared with

the base engine.

(7) The smoke density decreases for all the test fuels in the CE compared with the base engine. The smoke decrease in the CE was determined to be 35% for pure biodiesel compared with the base engine.

(8) In this study, the TiO_2 ceramic coating may be applied successfully without requiring any modifications in the engines. It is concluded that the ceramic-coated engine with biodiesel may increase the thermal efficiency and reduce the harmful emissions.

Acknowledgment

The authors thank the management to give the necessary facilities to do the experiments successfully.

Nomenclature

PME : Pongamia methyl ester
BE : Base engine
CE : Coated engine
CO : Carbon monoxide
HC : Hydrocarbon
NO : Nitrogen oxide
BTE : Brake thermal efficiency
BSFC : Brake specific fuel consumption
ID : Ignition delay
CA : Crank angle
BSU : Bosch smoke unit
LHR : Low heat rejection engine
EGT : Exhaust gas temperature
TDC : Top dead centre

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