Analysis on a thermal barrier coated (TBC) piston in a single cylinder diesel engine powered by Jatropha biodiesel–diesel blends

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Abstract

The objective of the present work is to enhance the performance of a diesel engine using a thermal barrier coated piston operated with Jatropha biodiesel–diesel blends. For thermal barrier coating, Yttria stabilized zirconia (YSZ) is preferred owing to its high heat insulation capabilities in comparison with other insulating materials such as mullite, zirconia, ceramics, magnesium silicate, silicon carbide etc. YSZ is coated via a plasma spray technique at around 200 μm thickness around the piston crown. The test fuel utilized are DF100 (100% diesel fuel), JB20NE (20% Jatropha biodiesel + 80% diesel fuel operated at normal un-coated engine) and JB20CE (20% Jatropha biodiesel + 80% diesel fuel operated at YSZ coated engine). Experimental results revealed that JB20CE has resulted in 10.6% increased brake thermal efficiency and 20.97% lowered brake specific fuel consumption since the YSZ coating acts as a potential insulator in retaining maximum heat inside the combustion chamber, lowering the energy losses followed by improved combustion efficiency, enhanced air–fuel mixture formation and higher performance. Emission wise, JB20CE operation resulted in lowered hydrocarbon and carbon monoxide emissions by about 41.67% and 33.33% due to improved fuel oxidation and effective combustion provided by YSZ insulation.

Keywords Thermal barrier · Yttria stabilized zirconia · Biodiesel · Engine performance · Combustion · Emissions

Abbreviations

TBC	Thermal barrier coated	DI	Direct injection
YSZ	Yttria stabilized zirconia	PSZ	Partially stabilized zirconia
DF100	100% diesel fuel	LTC	Low temperature combustion
JB20	20% Jatropha biodiesel + 80% diesel fuel	DEE	Diethyl ether
JB20NE	20% Jatropha biodiesel + 80% diesel fuel operated at normal un-coated engine	EGR	Exhaust gas recirculation
JB20CE	20% Jatropha biodiesel + 80% diesel fuel operated at YSZ coated engine	H ₂ SO ₄	Sulphuric acid
BTE	Brake thermal efficiency	KOH	Potassium hydroxide
BSFC	Brake specific fuel consumption	ASTM	American society for testing and materials
HC	Hydrocarbon	HRR	Heat release rate
CO	Carbon monoxide	ID	Ignition delay
NO _x	Nitrogen oxides	CAD	Crank angle degree
LHR	Low heat rejection	CD	Combustion duration
		EGT	Exhaust gas temperature

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1 Introduction

In recent years, works were done with various biodiesels [1–4] and various engine optimization techniques [5–9] for reducing fossil fuel consumption and lowering the exhaust emissions. Thermal barrier coating on various engine components has shown interest in recent years owing to resulting higher thermal and mechanical efficiencies as well as minimized emissions and improved fuel consumption. Through insulation, the heat rejected from the engine is subsequently lowered and hence the waste heat can be useful energy in oxidizing the soot precursors in hydrocarbon combustion thereby lowering the hydrocarbon (HC), carbon monoxide (CO) and Nitrogen oxides (NO_x) emissions followed by lowered brake specific fuel consumption (BSFC). The thermal barrier coating (TBC) is effective in formulating the low heat rejection (LHR) engines. So far, several materials such as mullite, alumina, ceramics, spinel forsterite, zirconides, yttria-stabilized zirconia (YSZ) were used as potential coating materials as a thermal barrier coating. These materials were selected based on specific material properties such as higher melting point, minimized transformation between temperatures, lower coefficient of thermal expansion, chemical elements and match with metallic substrate etc. For the current experimentation, Yttria stabilized zirconia (YSZ) of 200 μm thickness is coated for providing thermal insulation in an internal combustion engine. There are various types of coating methods for providing insulation. For the present studies, plasma spray technique is adopted to coat YSZ, where the YSZ enters as powdered jet as the phase at a temperature of 8300 $^{\circ}\text{C}$ (15,000 $^{\circ}\text{F}$), YSZ melts and steers into hot gas towards piston, where it solidifies as a thick coating.

Thermal barrier coating with NiCrAlY of 150 μm resulted in improvement of power, efficiency and lowering of fuel consumption as well as improvement in engine lifetime as a result of lowered surface temperature [10]. Sharma [11] reviewed literature pertaining to the influence of coating materials in LHR engine of ceramic materials. It was observed that the ceramic coating has shown better as thermal barrier coating owing to its improved porosity and minimized stress in coating. Funatani et al. [12] examined the effect of Ni–Cr–Ce coating in the piston crown on diesel engine emissions and performance. They observed that CO and HC emissions were lowered while BTE increased with coating. Moreover, they found that Ni–Cr–Ce coating as TBC helps in increasing the engine brake power. Sivakumar and Kumar [13] examined the influence of YSZ coating as TBC in a single-cylinder direct injection (DI) compression

ignition engine. Results revealed that, with coating, the heat loss is lowered by 10%, thermal efficiency increased by 5% and BSFC is lowered by 28%, HC and CO emissions were lowered by about 35.2% and 2.7% while NO_x emissions increased up to 5.6%.

Taymaz et al. [14] reported improved fuel economy, minimized HC and CO emissions as well as lowered noise emissions as a result of lowered pressure rise rate and exhaust gas high energy content as a result of TBC. Kamo et al. [15] predicted that the ceramic-based TBC can enhance the BTE by 6% in comparison with the uncoated engine. Similar results with TBC has revealed that there was an increase in fuel economy by 37% [16], increase in indicated thermal efficiency by 14% [17], increase in indicated specific fuel consumption by 9% [18]. Kamo et al. [15] experimented with diesel engine fuelled with TBC of YSZ around 0.1 mm thickness in piston and cylinder, 0.5 mm thickness coating of YSZ in cylinder liner and found that the fuel efficiency is increasing by about 6% at all the engine loads. Dhana Raju and Kishore [19] studied the diesel engine characteristics of operated with various tamarind biodiesel blends when the piston crown coated with zirconium of 150 μm thickness using a plasma spray method. The experimental test results revealed positive diesel engine characteristics than the uncoated piston at the same engine operating conditions.

Yao and Qian [20] studied the thermal analysis of a natural gas-powered diesel engine with nano-ceramic coated piston at different load conditions. They used aluminium alloy-piston coated through partially stabilized zirconia (PSZ) ceramic layer of 200- μm thickness. They found with a TBC of the piston, significant enhancement in temperature of combustion chamber, thermal efficiency and a considerable decrease in harmful emissions at all load conditions. Selvam et al. [21] examined the effectiveness of ceramic-coated piston on the performance and combustion characteristics of a direct injection diesel engine. Yttria-stabilized zirconia (YSZ) was applied as TBC material over the piston top surface with the use of a plasma spray coating technique. They noticed higher thermal efficiency and lower brake specific fuel consumption with the coated piston than the non-coated piston at full load condition for tested fuel samples. However, they also observed that an increase in NO_x emissions with the coated piston.

Agarwal et al. [22] reviewed about the fundamental aspects of low temperature combustion engines evaluation, its origin of thermal barrier approach and future challenges with respect to internal combustion engines. They also revealed the detailed insights for fuel requirements and fuel injection systems for low temperature combustion (LTC) engines. The authors also provided an in-depth review of emission characteristics of LTC engines and suggested the LTC engine technology was a promising

option for future automobile applications. Jena et al. [23] examined performance, emission and combustion characteristics of a DI diesel engine with YSZ coated on the piston crown and engine valves. They used ferric chloride as a fuel catalyst to diesel with coated piston and also non-coated piston. The application of ferric chloride on zirconia coated piston shown 2.7% enhancement in BTE and 8.3% decrease in BSFC when compared to the normal piston at full load operation. Further, they found significant reductions in CO, HC and smoke opacity with marginal increment in NO_x emission.

Kumar and Veerabhadhrappa [24] studied the TBC over engine cylinder head, valves and piston crown to minimize the heat losses and improve the performance parameters of the diesel engine. Plasma spray method was used for coating ceramic material over the hot spot engine components. From the experimental test results, they found considerable enhancement in thermal efficiency with the coated piston than the normal piston at all load operations of the diesel engine with significant reductions in exhaust emissions. Krishnamani et al. [25] performed tests on LHR diesel engine powered by rapeseed biodiesel and diethyl ether to improve the performance parameters and reduce the exhaust emissions. They reported that overheated engine components such as inlet valve, piston crown, exhaust valve, cylinder head of diesel engine coated with lanthanum zirconate with the application of plasma spray technique. They noticed from the experimental test results that substantial improvement in thermal efficiency for the test specimens and also greater reductions in emissions such as CO and HC by 10% and 18% respectively for diethyl ether (DEE) addition at 10% concentration to 20% rapeseed methyl ester than the neat rapeseed methyl ester at full load condition. Kulkarni et al. [26] studied the characteristics of the diesel engine when the combustion surfaces like a piston, cylinder head and engine valves were coated with ceramic material making the combustion chamber as fully adiabatic or low heat rejection diesel engine. They conducted tests on a DI diesel engine powered with mahua oil biodiesel at different exhaust gas recirculation (EGR) rates such as 0%, 5%, 15% and 20% with and without ceramic coating. The low heat rejection yielded considerable enhancement in thermal efficiency as well as significant reductions in engine tailpipe emissions than an uncoated diesel engine.

Rao et al. [27] examined the influence of a thermal barrier coating on the dual fuel diesel engine when hot engine parts of the combustion chamber were coated with Mullite (a mixture of aluminium oxide and silicon oxide). They were used diesel as pilot fuel and compressed natural gas was used as a primary fuel at different flow rates such as 5, 10 and 15 l per minute to investigate the performance, combustion and emission characteristics. They

found mullite coating on combustion chamber parts revealed a positive effect on the characteristics of the dual-fuel diesel engine. Also, they noticed greater reductions in exhaust emissions with a coated piston of dual-fuel engine at operating conditions except nitrogen oxide emissions. Similar test results reported by Senthil et al. [28] about the emission and performance characteristics of PSZ coated diesel engine powered with nerium biodiesel blends. The insulation effect of coating over engine components increased the thermal efficiency of 3.8% than the uncoated diesel engine with nerium biodiesel blend. Babu et al. [29] stated the use of 20% mahua oil biofuel as a viable alternative fuel for low heat rejection of diesel engine applications. The insulating material of aluminium oxide coated over piston, valves and cylinder walls with a thickness of 0.3 mm by plasma spray technique. They inferred that 6.2% increase in thermal efficiency and 8.5% reduction in fuel consumption with the coated engine than the unmodified diesel engine with neat diesel. The engine tailpipe emissions were also reduced with the coated engine at all operating conditions.

Based on the critical literature analysis, it is observed that the LHR engines with TBC on engine components with YSZ coating are effective in improving the BTE and BSFC. However, certain literature pointed out that with TBC coating, the NO_x emissions were prone to increase due to higher in-cylinder temperatures prevailing inside the combustion chamber. In the present experimental work, the piston crown is coated with YSZ (at a thickness about 200 μm) using plasma spray coating method and analyzed in diesel engine powered by JB20 (20% Jatropha biodiesel + 80% diesel fuel) for combustion, performance and emission characteristics.

2 Experimental material and methods

2.1 Yttria stabilized zirconia coating

Zirconia material is capable of being stable at different temperatures and transforms itself from monoclinic phase at 1200 °C to transformed phase beyond 1200 °C and at temperatures above 2370 °C, it is reported to have transformed to cubic phase. During the transformation from monoclinic to tetragonal phase, a severe decline in particle volume occurs (around 4%) when it is subjected to higher temperatures such as gas turbines. Hence, in order to prevent the associated cracking of materials at volume change, stabilizers are added to zirconia into its tetragonal/cubic phase. Full stabilization of zirconia requires 20% Yttria addition, however, fuel stabilization results in the poor thermal cycling process. However, partial stabilizing by (7–9 wt%) of Yttria ensures phase stability of the coated

Table 1 Advantages and disadvantage of insulating materials

Material	Advantages	Disadvantages
Alumina	Higher hardness Corrosion-resistant No Oxygen transparency	Phase transformation occurs at 1273 K Higher thermal conductivity Lower coefficient of thermal expansion
Mullite	No Oxygen transparency Improved corrosion resistance Low thermal conductivity	Crystallization occurs between 1023 and 1273 K Lower coefficient of thermal expansion
MgZrO ₂	Higher Young's modulus Low thermal conductivity (2 W/(mK)) Higher toughness fraction	Lower coefficient of thermal expansion Lower melting point (1600 °C)
YSZ	Higher melting point (2800 °C) Lower thermal conductivity (2 W/mK) Higher coefficient of thermal expansion (10 ⁷ /°C)	Sintering occurs above 1473 K Phase transformation occurs at 1443 K

Table 2 Plasma coating specifications

Parameter	Specifications
Spray gun	Metco 3 MB plasma spray
Powder feed rate (gpm)	46–48
Hydrogen flow rate (Psi)	50
Organ gas flow rate (lpm)	85–90
Organ gas pressure (Psi)	110–120
Spraying distance (inches)	4 (max)
Nozzle type	GH nozzle

Fig. 1 Thermal barrier coated (TBC) piston and valve using a plasma coating method

part, due to effective sintering. YSZ has several advantages in comparison with other insulating materials which are briefed in Table 1. The YSZ is coated by plasma spray coating method at a thickness of 200 μm . The specifications of the plasma spray coating were detailed in Table 2. The thermal barrier coated piston with a plasma spray coating is shown in Fig. 1.

Fig. 2 a Transesterification equipment, b funnel separator

2.2 Jatropha biodiesel preparation

Jatropha biodiesel was produced by using 2L batch reactor, condenser, magnetic stirrer, thermometer, sampling outlet unit. The biodiesel preparation was done by adopting the procedure of acid–base catalyst. The raw Jatropha oil was heated up to 60 °C for moisture removal using a rotary evaporator under vacuum condition. The transesterification equipment along with funnel separator as shown in Fig. 2.

For esterification, a mixture of methanol to raw oil of 10:1 molar ratio and 1.5% (v/v) sulphuric acid (H_2SO_4) was added with preheated oil and stirred for 4 h at 60 °C at 700 rpm. Then, alcohol, H_2SO_4 and other impurities were separated using a funnel separator. The separated esterified Jatropha oil was now heated up to 60 °C for 1 h using rotary evaporator for removing methanol and water. The transesterification process was carried out after esterification to reduce the viscosity since the raw Jatropha oil is highly viscous (4.2cSt). During transesterification, a

mixture of methanol to oil ratio 4:1 molar ratio and 1% (m/m) of potassium hydroxide (KOH) were mixed with the esterified Jatropha oil and stirred about 2 h at 60 °C at 700 rpm, then the obtained solution is transmitted to a funnel separator and permitted to settle for 24 h. The required Jatropha biodiesel was obtained at the top layer and glycerol was settled in the bottom of the funnel which was drained later. The properties of Jatropha oil, Jatropha biodiesel and diesel fuel were determined as per American Society for Testing and Materials (ASTM) standards and were illustrated in Table 3. JB20 is prepared by blending 20% Jatropha biodiesel along with 80% diesel fuel using magnetic stirrer.

2.3 Selection of test engine

Experimentation was done on single-cylinder, four-stroke, vertical, naturally-aspirated diesel engine. The test engine specifications are given in Table 4. The test engine gives a power of 4.4 kW which works at a constant speed of 1500 rpm. This direct-injection diesel engine has a fuel capacity of 0.661 litres, bore diameter and a stroke length of 87.5 mm and 110 mm along with 203 mm long connecting rod. The schematic of the experimental setup is sketched in Fig. 3.

2.4 Instrumentation and measuring methods

The present experimental setup uses fuel injection of MICO and a pressure transducer of piezo-electric mounted on cylinder head for recording the heat release rate and the in-cylinder pressure during the operation. Exhaust gas analyser (QRO-402) measures the CO, HC, and NO_x emissions. Smoke meter (AVL437C) measures the smoke opacity. The engine load is connected with eddy current dynamometer. The engine load changed from lower to higher load by varying the current supply. Experimentations were done with different engine loads ranges from 0

Table 4 Engine specification

Make	Kirloskar-TAF 1
Rated power	4.4 kW @ 1500 rpm
Type	Four stroke, vertical diesel engine
Number of cylinder	1
Bore diameter and stroke length	87.5 mm and 110 mm
Displacement volume	660 cm ³
Compression ratio	16.5:1
Injection pressure	20 MPa
Injection timing	23 deg bTDC (rated)
The diameter of the nozzle hole	0.3 mm
No. of nozzle holes	3
Combustion chamber geometry	Hemispherical chamber

to 100%. The air-cooled diesel engine uses SAE40 lubricating oil with a capacity of 3.7 litres.

3 Results and discussion

Experiments were done on DF100 (100% diesel fuel), and JB20 (20% Jatropha biodiesel + 80% diesel fuel) in a normal engine and were compared with that of YSZ coated engine fuelled with JB20. The engine load is varied from 0 to 100% at intervals of 25%. The heat release rate and in-cylinder pressure were analyzed at 100% load condition. The maximum pressure rise is recorded at every load so that the peak pressure rise at every load can be analyzed.

3.1 Combustion characteristics

3.1.1 In-cylinder pressure

In diesel engines, the maximum in-cylinder pressure developed by the fuel depends mainly on the amount of

Table 3 Fuel properties of diesel and Jatropha biodiesel

Fuel properties	ASTM method	ASTM limits	Diesel (DF100)	Jatropha biodiesel (JB100)
Density @ 20 °C (kg/m ³)	ASTM D1298	860–890	838	873.4
Lower heating value (kJ/kg)	ASTM D270	46,000 max	44,650	42,563
Kinematic viscosity at 35 °C (mm ² /s)	ASTM D445	1.8–5.9	2.83	4.35
Cetane number	ASTM D613	47 min	47	51.7
Flash point (°C)	ASTM D92	130 °C min	67	128
Carbon residue (% by wt)	ASTM D524	0.050 max	0.1–0.13	0.22–0.25
Iodine value (g I ₂ /100 g)	ASTM D5554	0.5 max	0.1	0.26
Sulphur (mg/kg)	ASTM D5453	15 max	28	0.0031
C/H ratio (by v/v)	–	–	6.51	6.92

Fig. 3 Schematic representation of test installation

fuel burnt during the combustion (premixed combustion phase). In-cylinder pressure is a vital factor in examining the combustion characteristics of test fuel. The other

various factors influencing the in-cylinder pressure variation include viscosity, air–fuel mixing rate and cetane number. Figure 4 shows the variation of in-cylinder pressure

Fig. 4 Variation of in-cylinder pressure with crank angle

with a crank angle for DF100 and JB20 at normal and coated engines. It is observed that the highest cylinder pressure is perceived for JB20CE (71.69 bar), followed by DF100 (69.23 bar) and JB20NE (67.2 bar) at full engine load condition. When the same engine is coated with YSZ and fuelled with JB20, the cylinder pressure increases by 4.49% which can be attributed to higher cylinder temperatures retained by YSZ coated piston lowering the delay period and subsequently causing higher cylinder pressure. This is also observed from the peak cylinder pressure rise diagram shown in Fig. 5, where it is clear that the JB20CE exhibits highest peak pressure by about 55.99 bar, 56.63 bar, 62.89 bar, 66.96 bar and 71.69 bar at the engine loads of 0%, 25%, 50%, 75% and 100% respectively. This can be attributed to improved combustion of biodiesel at YSZ coated piston resulting in elevated in-cylinder temperatures which cause lowered delay period and higher peak pressures.

3.1.2 Heat release rate

The variation of heat release rate (HRR) for the test fuels in with engine load is shown in Fig. 6. It is observed that the highest HRR is obtained for JB20CE (66.2 J/degCA), followed by DF100 (63.6 J/degCA) and JB20NE (58.57 J/degCA). This is because, JB20NE has lowered ignition delay period in comparison with JB20NE which causes an increase in premixed combustion phase (PCP), accounting for excessive heat retainment with YSZ coated piston thereby resulting in the higher quantum of heat energy released (especially for JB20CE). This is also evident from the peak heat release rate shown in Fig. 7, where JB20CE

Fig. 6 Variation of heat release rate with crank angle

exhibits peak HRR of 52.17 J/degCA, 57.107 J/degCA, 59.11 J/degCA, 64.16 J/degCA and 69.52 J/degCA at the engine loads of 0%, 25%, 50%, 75% and 100% respectively.

3.1.3 Ignition delay

Figure 8 shows the variation of ignition delay (ID) with respect to engine load for DF100 and JB20 blend at the normal and coated engine. It is observed that the ID is highest for JB20NE, followed by DF100 and JB20CE. ID of JB20NE are 13 crank angle degree (CAD), 11CAD, 8CAD,

Fig. 5 Variation of peak in-cylinder pressure with engine load

Fig. 7 Variation of peak heat release rate with engine load

Fig. 8 Variation of ignition delay (ID) with engine load

7CAD and 6CAD at engine loads of 0%, 25%, 50%, 75% and 100% respectively. This can be attributed to YSZ coating making faster combustion of biodiesel blends as a result of improvement in in-cylinder temperatures thereby leading to lowered ID. YSZ coating in piston lowers the heat energy exhausted and subsequently it improves the combustion of fuel charge which lowers the physical delay period (mixing and evaporation) as well as a chemical delay (slower chemical reactions), thereby lowering the mass of fuel entering the combustion chamber during the injection. All these factors result in lowered ID period for JB20CE.

3.1.4 Combustion duration

Figure 9 shows the variation of combustion duration (CD) with engine load for DF100 and JB20 blend at the normal and coated engine. It is observed that JB20NE has the highest CD, followed by JB20CE and DF100. At 100% engine load, the CD of DF100, JB20NE and JB20CE were 51CAD, 54CAD and 50CAD respectively. YSZ coated engine has lowered CD owing to enhanced air–fuel mixing rate, enhanced evaporation and higher combustion temperature which altogether have a profound influence on lowering the CD significantly.

3.1.5 Brake thermal efficiency

Figure 10 shows the variation of brake thermal efficiency (BTE) with engine load for DF100 and JB20 blend at the normal and coated engine. JB20CE shows highest BTE for all engine load conditions followed by DF100 and JB20NE. BTE of JB20CE are 15.91%, 25.52%, 31.96% and 33.12% at

Fig. 9 Variation of combustion duration (CD) with engine load

engine loads of 25%, 50%, 75% and 100% loads respectively. YSZ coated engine exhibits higher BTE owing to improved vaporization and atomization of the air–fuel mixture, retained the higher in-cylinder temperature in the chamber, improved combustion efficiency and uniform combustion rate. Moreover, due to YSZ coating, reduced heat rejection rate from the combustion chamber via insulated components (thermal insulation) improves the available energy is sufficient to produce a unit kW of brake

Fig. 10 Variation of brake thermal efficiency with engine load

power at a limited quantity of fuel supplied thus leading to improved BTE. The test results were in close agreement with outcomes of Krishnamani et al. [25].

3.1.6 Brake specific fuel consumption

Figure 11 shows the variation of brake specific fuel consumption (BSFC) with engine load for DF100 and JB20 blend at the normal and coated engine. Highest BSFC is observed for JB20NE followed by DF100 and JB20CE. This is because, the biodiesel blend is slightly higher in viscosity than diesel fuel which influences the atomization and vaporization characteristics of the air–fuel mixture, thereby increasing the delay period followed by lowered combustion efficiency and higher quantum of fuel consumed by the engine to maintain a constant speed (1500 rpm). However, with YSZ coating, the BSFC reduces significantly. JB20CE exhibits lowered BSFC of about 0.634 kg/kWh, 0.38 kg/kWh, 0.27 kg/kWh and 0.247 kg/kWh at engine loads of 25%, 50%, 75% and 100% respectively. This can be attributed to YSZ coating which has a positive effect in higher in-cylinder temperatures as a result of improved heat retainment characteristics (due to thermal insulation), which provides sufficient oxidation of JB20 blend causing betterment in atomization and vaporization followed by lowered fuel supplied in maintaining the engine speed constant thus consuming less fuel. Balkrishna et al. [30] reported that aluminium coated piston has shown lower specific fuel consumption when compared to the normal engine at all load conditions.

Fig. 11 Variation of brake specific fuel consumption with engine load

3.1.7 Exhaust gas temperature

Exhaust gas temperature (EGT) from diesel engines depends on the amount of heat released during the combustion process within the engine cylinder for some extent; EGT has also influence over the formation of pollution. EGT can also give a strong insight into the performance, air–fuel ratio, the heat generated during combustion and available oxygen content. Figure 12 shows the variation of Exhaust Gas Temperature with engine load for DF100 and JB20 blend at the normal and coated engine. Highest EGT is observed for JB20CE, followed by JB20NE and DF100. At 100% engine load, the EGT exhibited by JB20CE were 209 °C, 228 °C, 279 °C, 329 °C and 387 °C respectively. This is because of the lowered amount of heat utilized for cooling and delivered outside and this heat is transferred to exhaust gases due to YSZ coating acting as an effective thermal barrier.

3.2 Emission characteristics

3.2.1 Carbon monoxide

Figure 13 shows the variation of carbon monoxide (CO) with engine load for DF100 and JB20 blend at the normal and coated engine. It is inferred that DF100 shows the highest CO emissions followed by JB20NE and JB20CE. The CO emissions of JB20CE were about 0.04%, 0.03%, 0.025%, 0.02% and 0.03% at engine loads of 0%, 25%, 50%, 75% and 100% respectively. This reduction could be attributed to improvement in combustion chamber temperature owing to lowered heat losses and amount of O₂ content

Fig. 12 Variation of exhaust gas temperature (EGT) with engine load

Fig. 13 Variation of carbon monoxide with engine load

in biodiesel which helps in transformation of more CO to CO₂ molecules thereby resulting in lowered CO emissions. Moreover, YSZ coating increases the combustion efficiency of JB20 blend as a result of higher cylinder temperatures which causes local factors (pressure–temperature, air–fuel mixing, O₂ content and sustainability) to be improved significantly paving way for partial oxidation of CO to CO₂ molecules.

3.2.2 Hydrocarbon

Figure 14 shows the variation of hydrocarbon (HC) with engine load for DF100 and JB20 blend at the normal and

Fig. 14 Variation of hydrocarbon with engine load

coated engine. It is deceivable that, JB20NE exhibits highest HC emissions throughout the engine load condition followed by DF100 and JB20CE. HC emissions of JB20CE were about 35 ppm, 32 ppm, 31 ppm, 30ppn and 28 ppm at engine loads of 0%, 25%, 50%, 75% and 100% engine loads respectively. This could be attributed to improved vaporization of Jatropha biodiesel at the presence of YSZ coating resulting in higher in-cylinder temperatures which boosts the oxidation of soot as well as mitigates the unwanted fuel accumulation in engine cylinder especially the nozzle sac volume, crevice areas, cylinder piston interface, etc. which are the sole reason for HC emissions, thereby lowering the possibility of unburnt HC formation during the combustion of JB20. Moreover, as a result of coating, the obtained heat energy, which was delivered out and utilized in cooling was lowered and consequently, the ID is shortened and combustion efficiency is tremendously improved which causes the oxidation of unburnt fuel particles thereby lowering the HC emissions throughout the engine load.

3.2.3 Nitrogen oxides

Nitrogen oxides (NO_x) emission occurs through the oxidation process of atmospheric N₂ at higher in-cylinder temperatures. O_x formation kinetics is certainly governed through zeldovich mechanism and oxygen availability. More the combustion temperature, more the formation of NO_x, provided the factors favouring the reaction between N₂ and O₂ molecules. Various factors influencing NO_x formation are temperature, engine speed, fuel mixture density and homogeneity of the combustion chamber. Figure 15 shows the variation of oxides of Nitrogen (NO_x)

Fig. 15 Variation of nitrogen oxides with engine load

Fig. 16 Variation of smoke opacity with brake power

with engine load for DF100 and JB20 blend at the normal and coated engine. It is observed that JB20CE exhibits the highest NO_x formation followed by JB20CE and DF100. JB20CE has higher NO_x than DF100 because of the presence of O_2 in the molecular structure of biodiesel which favours the zeldovich mechanism of NO_x formation. NO_x emissions of JB20CE are 106 ppm, 204 ppm, 393 ppm, 504 ppm and 659 ppm at engine loads of 0%, 25%, 50%, 75% and 100% respectively. This is due to higher cylinder temperatures and after burning in the combustion chamber occurring due to the presence of a thermal barrier with YSZ coating. A similar pattern of NO_x characteristics of lower heat rejection diesel engine was reported by Arunkumar et al. [31].

3.2.4 Smoke opacity

Smoke formation in engines ensues during the diffusion combustion phase where all the atomized droplets of fuel are splintered to elemental carbon particles which are later oxidized in the reaction zone. Smoke emissions from diesel engine also occur due to deficiency of air in the combustion rich zone, higher C/H ratio, higher fuel viscosity, poor atomization and excessive fuel accumulation in the engine combustion chamber. Figure 16 shows the variation of smoke opacity with respect to engine load for DF100 and JB20 blend at the normal and coated engine. It is observed that the DF100 shows the highest smoke emissions throughout the engine load condition, followed by JB20NE and JB20CE. Smoke emissions of JB20CE are 13.5%, 19.7%, 23.3%, 35.4% and 47.9% at engine loads of 0%, 25%, 50%, 75% and 100% respectively. Smoke emissions are the result of carbon particles generated via an incomplete combustion process. Even though the viscosity of

JB20 is higher than DF100, the presence of YSZ coating delineates the negative effect by generating higher cylinder temperature which subsequently helps in breaking down the higher mean droplet size of biodiesel blend, thus lowering the ignition centres followed by lowered smoke. Lowest smoke emission for JB20CE can be attributed to higher combustion chamber temperatures due to the presence of thermal barrier and hence, more amount of carbon particles takes part in reaction and oxidation of soot precursors occurs which causes the smoke to be lowered significantly.

4 Conclusions

The present study is to investigate the effect of Yttria stabilized zirconia coated piston operated with JB20 (20% Jatropha biodiesel + 80% diesel fuel). YSZ coating was done to cylinder piston crown with a plasma spray coating method for about 200 μm thickness. The test fuels subjected to experimentation are DF100 (100% diesel fuel), JB20NE (20% Jatropha biodiesel + 80% diesel fuel operated with non-coated engine) and JB20CE (20% Jatropha biodiesel + 80% diesel fuel operated with coated engine). Performance characteristics such as BSFC, BTE and EGT, emission characteristics such as HC, CO, NO_x and smoke, combustion characteristics such as cylinder pressure, heat release rate, ID, CD were analyzed at engine loads of 0%, 25%, 50%, 75% and 100% respectively. Based on experimentation, the major inferences observed were as follows:

- In comparison with JB20NE, the JB20CE exhibits 20.97% lowered BSFC and 10.6% higher BTE owing to the pooled effect of improvement in air–fuel mixture formation, improved combustion efficiency and lowered heat loss provided by YSZ coating thereby maximum in-cylinder pressure retained in the combustion chamber.
- Emission wise, JB20CE has lowered HC (by 41.67%), lowered CO (by 33.33%), lowered NO_x (by 15.94%) and lowered smoke (by 15.08%) respectively as a result of improved oxidation of soot precursors and higher in-cylinder temperature inside the combustion chamber.
- Combustion wise, JB20CE has higher in-cylinder pressure of about 71.69 bar and improved heat release rate of about 69.52 J/degCA which could be attributed to lowered delay period and combustion duration favouring the increase in premixed combustion phase due to YSZ coating providing maximized heat retainment inside the engine.

Author contributions The authors have been equally contributed for this research work.

Compliance with ethical standards

Conflict of interest The authors declare no competing financial interest and non-financial interest.

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