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Research Paper

Investigation on Yttria Stabilized Zirconiacoated Piston Crown using Different Biodiesels

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The present paper is concentrated on the effect of Yttria Stabilized Zirconia coated with its piston crown on the performance and emission characteristics of a diesel engine. The piston crown top surface was fully coated with 7% YSZ with a thickness of 0.25 mm and in the bond coat NiCrAlY were used with a thickness of 0.05 mm which is deposited on the target surface using plasma spray technique. The present analysis is carried out in a four-stroke single cylinder diesel engine with diesel fuel, Mahua and jatropha biodiesel under different loading conditions. Results of this study reveal that the brake thermal efficiency of a 7% YSZ coated engine with diesel as a fuel is increased by 10.4% along with a decrease of brake specific fuel consumption of a 7% YSZ by 13.1%. In coated engines the Hydrocarbon (HC) emissions and carbon monoxide (CO) emissions were reduced by 16 % and but the Nitrogen oxide (NOx) emission was marginally increased by 18.87%.

Keywords: Yttria-Stabilized Zirconia; Thermal Barrier Coatings (TBC); Low Heat Rejection Engine (LHR); Mahua and Jatropha Biodiesel; Plasma Spray Technique

Introduction

The thermal barrier coating is generally used by many researchers to enhance the heat resistance inside the combustion chamber and thereby enlightening the thermal efficiency of the engines. The approximate heat energy distribution in the conventional engines and in ceramically coated engines is presented in Fig. 1.

The LHR concept has been of awareness since the 1980s when a large number of programs investigated the "adiabatic engine" (Kamo and Bryzik 1979; Wade and Trinker 1984; Thring 1986). Commonly in LHR engines, the TBC coating is done on combustion areas like cylinder head, cylinder liners, piston crowns and valves. Many researchers have determined that the thermal efficiency of TBC coated LHR engines is higher and also better brake specific fuel consumption is reduced in TBC coated engines. At average speeds and effective pressure, the BSFC values of the Low Heat Rejection Engine were found to be 6% lesser than the uncoated engine (Buyukkaya and Cerit 2008). Compared the uncoated piston engine, it is clear that a higher combustion temperature in TBC engine, as a result, the thermal efficiency of the engine increases (Cerit and Coban 2014). The CO and HC emissions show decreasing in TBC engine. There was an interesting reduction of NOx is observed due to coating because nitrogen has absorbed by zirconia tendency (Muthusamy 2016). Smoke

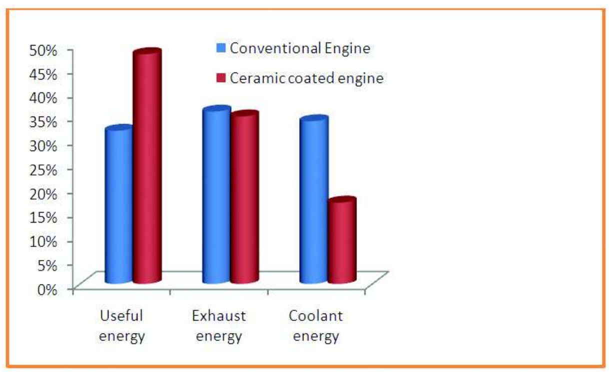


Fig. 1: **Comparison of conventional and ceramic coated engines(Buyukkaya and Cerit 2008)**

**Author for Correspondence: E-mail: vidyasagar041@gmail.com* values were reduced by using 20% AME blended with the 80% of Neat diesel in LHR engine without any modifications (Ramalingam 2016).

Experimental results showed that TBC engines have higher brake thermal efficiency the enhancement extended by 5% to 6% (Kamo and Bryzik 2006). Previous literature revealed that fuel consumption reduced in the LHR engines at the range of 16-37% (Bruns and Bryzik 1997). Experiments carryout on TBC engines the indicated thermal efficiency of the engines are often improved by 14% and 7% for fully adiabatic and for semi-adiabatic conditions respectively (Wallace and Way 1979). Studies on an insulated engine are coated with YSZ on its piston crown and cylinder head with 0.1 mm thickness and also the cylinder liner is coated with YSZ of 0.5 mm thickness has enhanced the fuel efficiency by 6-7% and efficiency increased by 5% to 9% (Havstad and Gervin 1986). Also revealed that Low Heat Rejection engines with YSZ coated on combustion chamber components it improves the Brake thermal efficiency and Brake specific fuel consumption of Internal Combustion engines (Miyairi and Matsuhisa 2009).

Several ceramic coatings such as TiO_2, Al_2O_3, mullite, CaO/MgO–Zro_2, YSZ have been used in engine application (Cao and Vassen et al. 2004; Mohamed and Sivapirakasam et al. 2011; Lima and Guilemany 2007). Partially stabilized zirconia (PSZ), mostly 6-9% yttria-stabilized zirconia (i.e. YSZ) is the most widely used TBC material and it showed good performance in high-temperature applications like diesel engines, gas turbines etc. But TBCs like mullite, Ca/Mg-PSZ, Al2O3 and TiO2 can be good alternatives to YSZ due to their suitable properties for engine application (Lima and Trevisan 1999; Bengtsson and Ericsson et al. 1998; Hejwowski 2010).

From the literature that stabilized zirconia is also used extensively in aero engines as an ideal TBC material (Vassen and Tietz *et al*., 2004). Literature survey yields that Yttria is the desired stabilizing agent for zirconia. Many investigators have tried successfully the stabilized zirconia as thermal barrier coating agent for piston crown. However, a significant number of the literature revealed that NOx emission levels are improved due to TBC coatings inside the combustion chamber (Morel andKeribar *et al*., 2013). A review on the application of LHR concept in bio-diesel engines, inferred that the energy of bio-diesel can be released more efficiently under LHR operation (Panneerselvam and Murugesan *et al*., 2015).

Many investigations were done to find the effect of biodiesel and in-cylinder insulation in internal combustion engines. Performance and emission characteristics of a diesel engine were studied using rice bran oil methyl esters and its blends with diesel. They reported that the engine runs well with biodiesel (Deepanraj and Sankaranarayanan *et al*., 2012). Rudolf Diesel, the inventor of the diesel engines, used peanut vegetable oil as a fuel for demonstration purpose in 1900 (Demirbas 2007). The effect of cottonseed oil methyl ester in a low heat rejection diesel engine and reported that the performance (6.0% for specific fuel consumption) and emission values (up to 18.0% for CO, 8.0% for smoke density) of the test fuel were improved in the coated engine compared with those in the uncoated engine (Hazar 2011). Studies reported that the cashew nut shell oil blended fuel in low heat rejection engine offers higher brake thermal efficiency, lower specific fuel consumption and lower exhaust emission levels compared to the conventional engine (Santhanakrishnan and Ramani 2015). The diesel engine using mahua oil biodiesel showed that engine performance and emission give higher results compared with diesel (Sukumar and Nagarajan 2007).

This paper describes the findings of experiments conducted on a diesel engine with diesel fuel,mahua and jatropha biodiesel fuel and coats the TBC coatings on piston crown to investigate its performance and emission characteristics. The purpose of using coatings and different biodiesels is to increase brake thermal efficiency and reduces emissions.

Plasma Spray Technique

In the present study, the plasma spray method is implemented for the coating. The present experiments are focused on Yttria-Stabilized Zirconia material is sprayed on the piston crown surface to form a 0.25mm thin TBC coating. Main components of the system are power unit, powder supply unit, gas supply unit, cooling system, spraying gun and control unit. The coating materials are made of 7% YSZ which acts as a top coat to a thickness of 0.25mm andNiCrAlY to a thickness of 0.05mm is the bond coat which is deposited on the target surface using plasma spray technique. Specifications of plasma spray are presented in Table 1. Plasma Coating system is presented in Fig. 2.

Table 1: Specifications of plasma spray coating

Coating parameters	Specifications
Plasma gun	3MB plasma spray gun
Nozzle	GH Type nozzle
Pressure of organ gas	100-120 PSI
Flow rate of organ gas	80-90 LPM
Pressure of hydrogen gas	50 PSI
Flow rate of hydrogen gas	15-18 LPM
Powder feed rate	40-45 g per minute
Spraying distance	3-4 in.

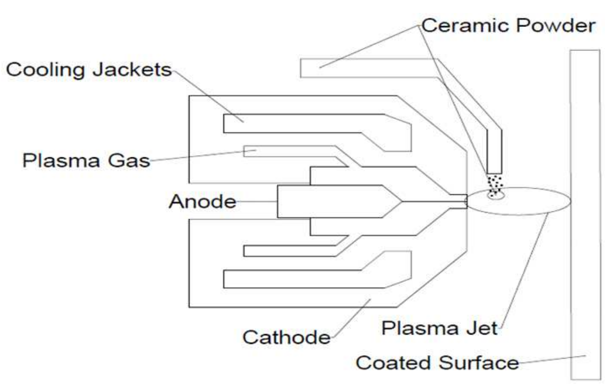


Fig. 2: Plasma spray coating system (Miyairi and Matsuhisa 2009)

Experimental Test Setup

A four stroke, single Cylinder, direct injected, the water-cooled diesel engine is used for examination. The diesel engine specifications are presented in Table 2. The Snapshots of (a) uncoated baseline engine piston (b) 7%YSZ coated piston are presented in Fig. 3. The Snapshots of engine setup and coated piston arrangement are presented in Fig. 4. The Schematic diagram of the experimental setup is presented in Fig. 5.

This paper describes the findings of experiments conducted on a diesel engine using a mahua and jatropha biodiesel. The purpose of using biodiesels is to enhance the combustion and lower the engine exhaust emissions. The Properties of biodiesel are shown in Table 3.

Table 2: Specifications of the test engine

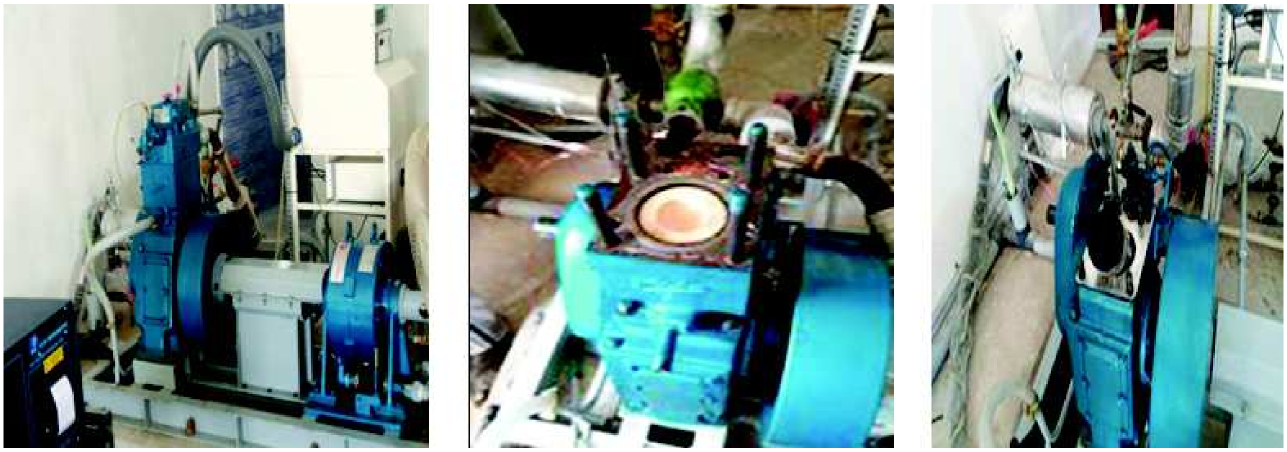
Type	Specifications
Engine	4-Stroke, Single Cylinder water-cooled Diesel Engine
Rated Speed	1500 rpm
Bore Diameter	87.5mm
Stroke	110 mm
Compression ratio	17.5:1
Loading	Electric loading
Orifice Diameter	29.6 mm
Coefficient of Discharge	0.6

Fig. 3: Snapshots of (a) uncoated baseline engine piston (b)7% YSZ coated piston

Experiments were conducted at different loads, viz. 25%, 50%, 75% and 100% with at constant speed of 1500 rpm and loading by eddy current type dynamometer. A piezoelectric pressure transducer is used to measure the In-cylinder pressure. Chromel-Alumel thermocouples were used to measure the exhaust gas temperature at the exit pipe. The measurement of fuel flow was carried out by using a 100 cc graduated burette and stopwatch. The AVL DI GAS 444-5 five gas analyzer is used to measure the tailpipe emissions (Rashmi 2017).

Table 3: Properties of fuels

Properties	Diesel	Jatropha Biodiesel (B 100)	Mahua Biodiesel (B 100)
Kinematics viscosity at 40^{o}C (cst)	2.74	4.89	5.78
Density at 15^{o}C (kg/m^3)	850	870	880
Flash Point (^{o}C)	68	165	157.6
Fire Point (^{o}C)	72	170	165.4
Calorific value (MJ/kg)	42	39	38



(A) (B) (C)

Fig. 4: Snapshots of (A) Engine set up; (B) Coated pistion arrangment and (C) After experiment

Experimental Procedure

Sample Preparation and Deposition Works

Thermal barrier coating system consists of a bond layer (NiCrAlY) which is an oxidation-resistant to serve as a substrate material and for insulation. NiCrAlY powder, 7% YSZ are selected to coat the piston. To maintain the compression ratio of the air-fuel mixture before and after the TBC the piston crown is to be machined before applying the TBC. The amount of material removed by machining should be equal to the amount of TBC applied on the piston by volume. Once the machining is over, the piston crown is grid blasted, and then Piston crown is first coated with NiCrAl as a bond coat thickness of 50 microns, and over 7% YSZ is coated as a top coat thickness of 250 microns. Spray coating restores the original dimensions of the engine. The complete details of the coating material and its compositions used are presented in Table 4.

Table 4: Details of the coating material and the compositions used

TBC Layers	Coating material	Composition	Thickness	Particle size
Bond Coat	NiCrAlY	(67%Ni, 22%Cr,10%Al, 1%Y)	50 microns	56-106 microns
Top Coat	7YSZ	(7%Y,93% ZrO_2)	250 microns	56-106 microns

Testing Condition

This work is focused on different engine conditions with biodiesel as fuel. The total number of experiments planned is divided into four categories. The details of each study are presented in Table 5.

Table 5: Details of the six different engine tests

Type of engine	Testing condition
Baseline Engine (Diesel fuel)	Test 1
Baseline Engine (Mahua Biodiesel B-100)	Test 2
Baseline Engine (Jatropha Biodiesel B-100)	Test 3
LHR Engine with coating 7% YSZ (Diesel fuel)	LHR 1
LHR Engine with coating 7% YSZ (Mahua Biodiesel B-100)	LHR 2
LHR Engine with coating 7% YSZ (Jatropha Biodiesel B-100)	LHR 3

Results and Discussion

The result of these tests will bring out the comparison of the performance between the normal engine and TBC coated engine with mahua and jatropha biodiesel.

In this study the performance parameters like BTE, BSFC and emission parameters are compared between different tests. The details of the variation of each parameter under different load conditions are

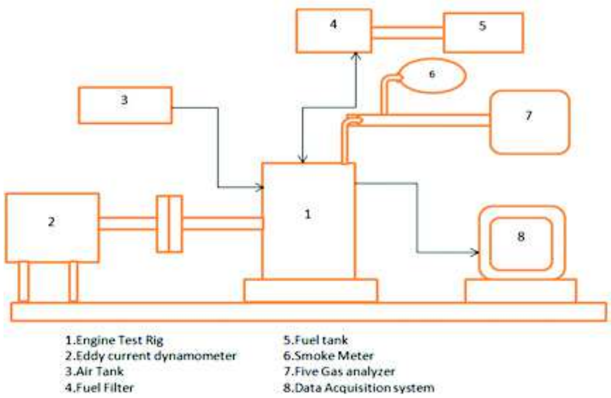


Fig. 5: Engine schematic diagram

discussed in the following sections.

Brake Thermal Efficiency

Figure 6 shows the variation of brake thermal efficiency with the brake power in both the baseline and LHR engines. It shows that an LHR engine has higher brake thermal efficiency than that of baseline engines at full load condition. This may be due to providing YSZ coating in LHR engines. It reduces the overall thermal conductivity of the TBC materials and which leads to increase the thermal resistance on the piston surface, this resisted heat increases the thermal efficiency further (Raghavan and Wang *et al*., 2001). The results obtained that the brake thermal efficiency for Test-1, Test-2, Test-3, LHR 1, LHR 2 and LHR 3 were found to be 30.06%, 2 8.16%, 29.6%, 34.87%, 30.9% and 31.42%. The highest brake thermal efficiency was obtained for LHR 3. This TBC coated materials resistance to the heat inside the cylinder and tries to go out of the engine cylinder. This resisted heat increases the thermal efficiency further.

Brake Specific Fuel Consumption

Figure 7 shows the variation of brake specific fuel consumption with the brake power in both the baseline and LHR engines. It shows that LHRengineshave lower brake specific fuel consumption than that of baseline engines at full load condition. This is may be due to higher gas and wall temperature in the combustion chamber (M. Mohamed Musthafa and. Sivapirakasam *et al*., 2011). The results obtained that the brake specific fuel consumption for LHR 1, LHR 2 and LHR 3 decreases in compare to Test-1, Test-2, Test-3 in all load conditions. The lowest BSFC were obtained for LHR 1 it has been decreased to 13.1% compared to that of the baseline engine. In LHR engines YSZ will resist the more heat, thus increases the temperature of the combustion chamber, which leads to increase the temperature of the fuel present in the combustion chamber (Kamo and Mavinahally *et al*., 1999).

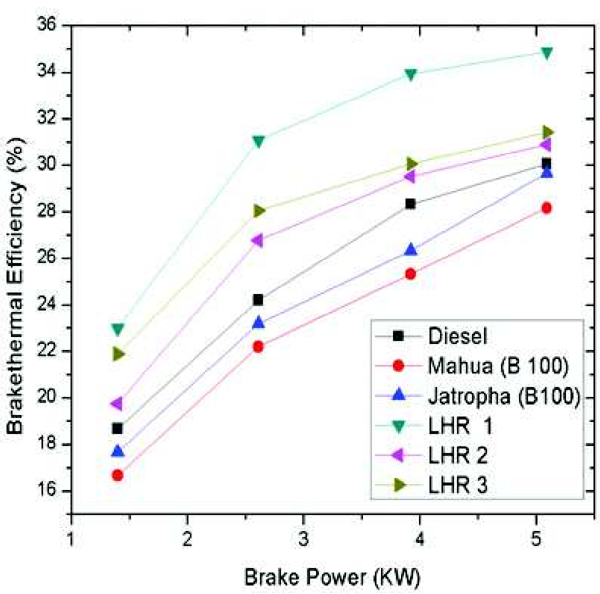


Fig. 6: Variation of brake thermal efficiency with brake power

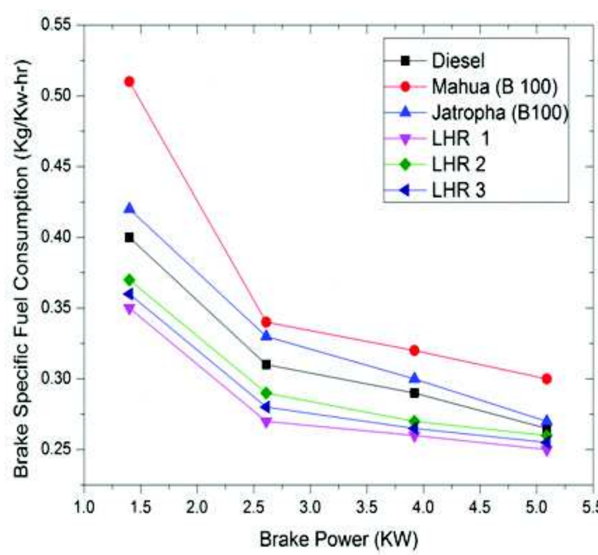


Fig. 7: Variation of brake specific fuel consumption with brake power

Exhaust Gas Temperature (EGT)

Figure 8 shows the variation of exhaust gas temperature with brake power in both the baseline and LHR engines. It shows that an LHR engine has higher exhaust gas temperature than that of baseline engines at full load condition. The results obtained that the exhaust gas temperature forTest-1, Test-2, Test-3, LHR 1, LHR 2 and LHR 3 were found to be 290.16^{0}C, 305^{0}C, 298^{0}C, 300.27^{0}C, 325.895^{0}C and 315.32^{0}C. The increase in the EGT was prominent in LHR engine as a minimal loss in heat rejection to the surroundings this could be thermal barrier coating (Hazar 2009). Results clearly indicate that the ceramic coating LHR 1, LHR 2 and LHR 3 shows the high exhaust gas temperature compare to that of baseline engines.This is due to more amount of heat present inside the engine cylinder.

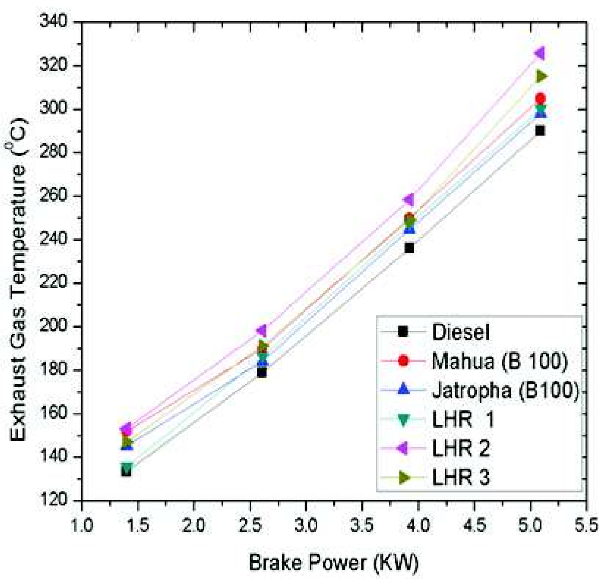


Fig. 8: Variation of exhaust gas temperatures with brake power

Emission Characteristics

Hydrocarbon Emissions

Figure 9 shows variations in HC emissions with varying brake power in both the baseline and LHR engines. Previous researchers reported that biodiesel produces less HC emission in comparison to that of diesel (Nwafor and Rice 2008; Pradeep and Sharma 2005). The results obtained that the hydrocarbon emission in TBC engines LHR 1, LHR 2 and LHR 3 decreases

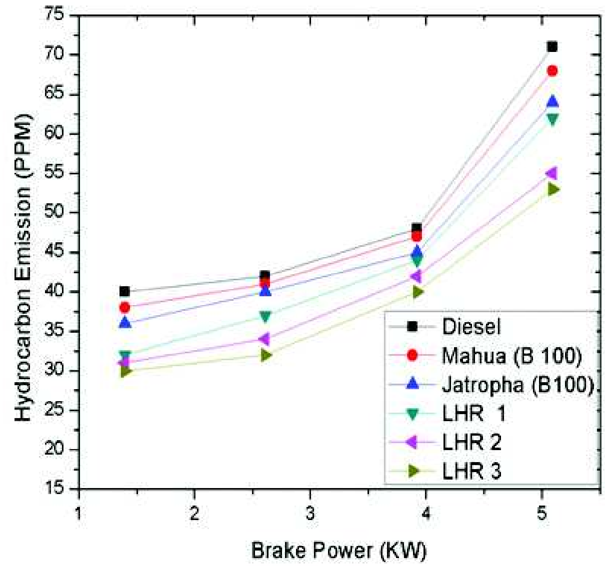


Fig. 9: Variation of hydrocarbon emission with brake power

in compare to Test-1, Test-2, Test-3 in all load conditions. The lowest HC were obtained for LHR 3 it has been decreased to 16.1% compared to that of baseline engine with diesel. The decrease in the HC emission in the LHR 3 engine is due to the rise in combustion temperature which indications to burn the hydrocarbon present in the fuel. Previous researchers reported that HC emission was decreased in LHR engines using bio-diesels because of more oxygen content in bio-diesels leads to complete and proper combustion(Pradeep and Sharma. 2005).

Carbon Monoxide Emission

Figure 10 shows that CO variations with respect to varying brake power in both the baseline and LHR engines. The results obtained that the CO emission in TBC engines LHR 1, LHR 2 and LHR 3 decreases in compare to Test-1, Test-2, Test-3 in all load conditions. The lowest CO were obtained for LHR 3 it has been decreased to 14.5% compared to that of baseline engine with diesel. In LHR 3 engine due to the addition of TBC coating and additional oxygen content in the jatropha bio-diesel which makes to lead the better combustion and it decreases CO emission. Previous researchers reported that due to ceramic coating compression temperature increases which decrease the CO emission in LHR engines this could be complete combustion of the fuel due to more amount of heat present in the combustion chamber (Karabektas and Murat, 2009).

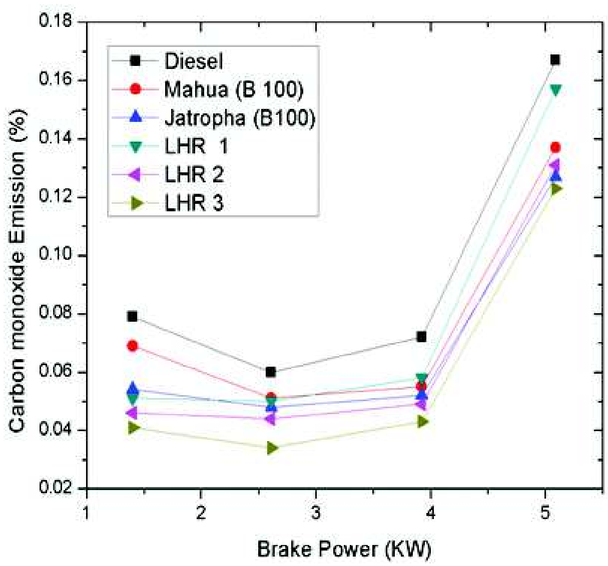


Fig. 10: Variation of Carbon monoxide emission with brake power

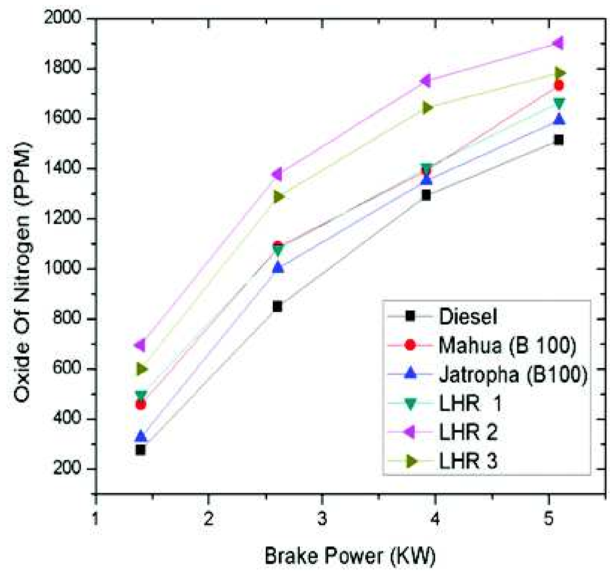


Fig. 11: Variation of oxides of nitrogen with brake power

Oxides of Nitrogen Emission

Figure 11 shows variations in oxides of nitrogen (NOx) emissions varying with brake power in both the baseline and LHR engines. The results obtained that the NOx emission in TBC engines LHR 1, LHR 2 and LHR 3 increases in compare to Test-1, Test-2, Test-3 in all load conditions. NOx emission in LHR engines with Biodiesels is higher than that in the baseline engine with diesel fuel. The highest NOx emission were obtained for LHR 2 it has been increased to 18.87% compared to that of baseline engine. In LHR 2 engine due to high combustion temperature and higher oxygen content in the mahua bio-diesel which leads to increase the NOx levels. Most of the previous surveys also showed that NOx emissions from TBC engine are commonly higher. This might be due to the advanced combustion temperature and lengthier combustion duration (Azadi and Baloo *et al*., 2013).

Conclusion

Conventional single cylinder diesel engine with Mahua and Jatropha biodiesel fuels are used in Test-1, Test-2 and Test-3 conditions and convert the diesel engine has been converted to a LHR Engine by coating Yttria Stabilized Zirconia on its piston crowns by a 250 micron layer of 7%Y+93% ZrO_2 by plasma spray method in LHR 1, LHR 2 and LHR 3. Engine parameters like brake thermal efficiency, brake specific fuel consumption, exhaust gas temperature and emissions like HC, CO and NOx are measured in this investigation.

(i) Brake thermal efficiency is enhanced at all loads in the TBC coated engines in LHR 1, LHR 2 and LHR 3. The highest brake thermal efficiency was obtained for LHR 3 and it is lower in case of baseline engines with pure biodiesels.

(ii) The brake specific fuel consumptions is reciprocal of BTE so that the TBC coated engines in LHR 1, LHR 2 and LHR 3 conditions reduce the specific fuel consumption, respectively compared to the baseline engines in Test-1.

(iii) Hydrocarbon emissions are reduced drastically in the TBC coated engines in LHR 1, LHR 2 and LHR 3 conditions, whereas Carbon monoxide emission is reduced in LHR 1, LHR 2 and LHR 3 conditions, respectively compared to the baseline engines in Test-1.

(iv) Exhaust gas temperature improved at all loads which in turn lead to increase in the NOx emissions of the TBC coated engines in LHR 1, LHR 2 and LHR 3. The highest NOx was increased for LHR 2 engine with mahua biodiesel.

References

Azadi M, Baloo M, Farrahi GH and Mirsalim SM (2013) A review of thermal barrier coating effects on diesel engine performance and components lifetime *Int J Autom Eng* **3** 305-317

Bengtsson P, Ericsson T and Wigren J (1998) Thermal shock testing of burner cans coated with a thick thermal barrier coating *J Therm Spray Technol* **7** 340-348

Bruns L, Bryzik W and Kamo R *et al.* Performance assessment of U.S. army truck with adiabatic diesel Engine. *SAE Paper No. 890142A*

Buyukkaya E and Cerit M (2008) Experimental study of NOx emissions and injection timing of a low heat rejection diesel engine *Int J Therm Sci* pp. 1096-1106

Cao X, Vassen R and Stoever D (2004) Ceramic materials for thermal barrier coatings *J Eur Ceram Soc* **24** 1-10.

Cerit M and Coban M (2016) Temperature and thermal stress analyses of a ceramic-coated aluminium alloy piston used in a diesel engine, compression ignition engine *Thermal Science* **20** S1189-S1196

Deepanraj B, Sankaranarayanan G and Lawrence P (2012) Performance and Emission Characteristics of a Diesel Engine Fueled with Rice Bran Oil Methyl Ester Blends. Daffodil International University *Journal of Science and Technology* **7** 51-55

Demirbas A (2007) Recent developments in biodiesel fuels *International Journal of Green Energy **4*** 15-26

Havstad PH, GervinI J and Wade WR (1986) A ceramic insert uncooled diesel engine *SAE paper* No. 860447

Hazar H (2011) Characterization and Effect of using Cotton Methyl Ester as Fuel in a LHR Diesel Engine *Energy Conversion and Management* **52** 258-263

Hazar H (2009) Effects of biodiesel on a low heat loss diesel engine *Renewable Energy* **34** 1533-1537

Hejwowski T (2010) Comparative study of thermal barrier coatings for internal combustion engine *Vacuum* **85** 610-6

Kamo R and Bryzik W (1979) Ceramics for adiabatic turbo compound engine. In: Lenoe EM, Katz RN, Burke JJ, editors. *Ceramics for high- performance applications*, vol. III. New York: Plenum Press

Kamo R, Bryzik W *et al.* (2006) Adiabatic turbo compound engine performance prediction *SAE* Paper No.780068

Kamo R, Mavinahally NS, Kamo, Bryzik W and Schwartz EE (1999) Injection characteristics that improve performance of ceramic coated diesel engines, *SAE* Paper No. 1999-01-0972

Karabektas and Murat (2009) The effects of turbocharger on the performance and exhaust emissions of a diesel engine fuelled with biodiesel *Renewable Energy, Elsevier,* **34** 989-993

Lima C and Guilemany J (2007) Adhesion improvements of thermal barrier coatings with HVOF thermally sprayed bond coats *Surf Coat Technol* **4** 694-701

Lima C and Trevisan R 1999 Temperature measurements and adhesion properties of plasma sprayed thermal barrier coatings *J Therm Spray Technol* **8** 323-7

Miyairi Y, Matsuhisa T, Ozawa T, Oikawa H and Nakashima N (2009) Selective heat insulation of combustion chamber walls for a DI diesel engine with monolithic ceramics *SAE* Paper No. 890141.engine cycle, SAE Paper No. 790823

Mohamed M, Sivapirakasam S and Udayakumar M (2011) Comparative studies on fly ash coated low heat rejection diesel engine on performance and emission characteristics fueled by rice bran and pongamia methyl ester and their blend with diesel *Energy* **36** 2343-51

Mohamed Musthafa M, Sivapirakasam SP and Udayakumar M (2011) Comparative studies on fly ash coated low heat rejection diesel engine on performance and emission characteristics fueled by rice bran and pongamia methyl ester and their blend with diesel *Energy* **36** 2343e2351

Morel T, Keribar R and Blumberg EF (*2013*) Fort, Examination of key issues in low heat rejection engines *SAE* Paper No. 860316

Muthusamy J, *et al.* (*2016*) Experimental investigation of thermal barrier (8YSZ-TiO2-Al2O3) coated piston usedin direct injection compression ignition engine *Thermal Science* **20** pp. S1189-S1196

Nwafor OMI, Rice G and Ogabinna AL (2008) Effect of advance injection timing on the performance of rape seed oil in diesel engines *Journal of Renewable Energy* **21** 433-44

Panneerselvam N, Murugesan A, Vijayakumar C, Kumaravel A, Subramaniam D and Avinashd A (2015) Effects of injection timing on bio-diesel fuelled engine characteristics—Anoverview *Renew Sustain Energy Rev* **50** *http://dx.doi.org/10.1016/j.rser.2015.04.15*

Pradeep V and Sharma RP (2005) Evaluation of Performance, emission and combustion parameters of a CI engine fuelled bio-diesel from rubber seed oil and its blends *SAE* **26** 353

Raghavan S, Wang H, Porter WD, Dinwiddie RB and Mayo MJ (2001) Thermal Properties of Zirconia Co-doped with Trivalent and Pentavalent Oxides *Acta Materialia* **49** 169-179

Ramalingam S *et al.* (2016) Application of thermal barrier coating for improving the suitability of annona biodiesel in a diesel engine *Thermal Science* **20** S973-S979

Rashmi U (2017) Indian Emission Regulations. *The Automotive Research Association of India, Booklet.https://www. araiindia.com / pdf / Indian_Emission_ Regulation_ Booklet.pdf.SAE Paper No.890142A*

Santhanakrishnan S and Ramani BKM (2015) Performance Emission and Combustion Characteristics of A Low Heat Rejection Engine Fuelled with Diesel-CNSO-EEA Blend *Journal of Advanced Engineering Research* **2** 29-33

Sukumar P, Nagarajan G, Vedaraman N and Ramabramhmam BV (2007) Mahua oil (MadhucaIndica oil) derivatives as a renewable fuel for diesel engine systems in India: A performance and emissions comparative study *International Journal of Green Energy* **4** 89-104

Thring RH (1986) Low heat rejection engines *SAE* paper no. 860314; http:// dx.doi.org/10.4271/860314

Vassen R, Tietz F, Kerkhoff G and Stoever D (2004) New Materials for Advanced Thermal Barrier Coatings; pp. 1627-1635 *in Proceedings of the 6th Liege Conference on Materials for Advanced Power Engineering*

Wade WR and Trinker FH (1984) Fuel economy opportunities with an uncooled di diesel engine *SAE* paper no. 841286

Wallace FJ, Way RJB and Vollmert H *et al.* (1979) *Effect of partial suppression of heat loss to the coolant on the high output diesel engine cycle SAE* Paper No.790823.