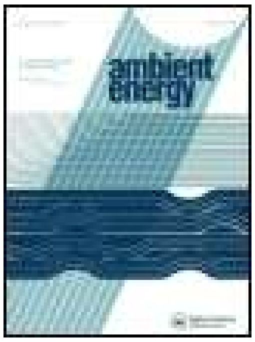

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Analysis on impact of thermal barrier coating on piston head in CI engine using biodiesel

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ABSTRACT

The fossil fuel energy sources over the world are depleting day by day. In this situation, there is a necessity to explore for substitute fuels. Low volatility, filter clogging and high viscosity are main drawbacks of vegetable oils. Due to above said problems, poor combustion and poor performance take place. For the enhancement of above properties, thermal barrier coated engine is adopted. In the present work, an effort is made to use Yttria stabilised zirconia (YSZ) coating applied on a Toroidal geometry piston crown using plasma spray technique. Three thermal barrier coating thicknesses 150, 300 and 450 microns are considered in this study. Experiments are conducted on uncoated piston engine with diesel and coated piston engine fuelled with diesel, Jute methyl ester and Neem methyl ester separately. Increase in thermal efficiency and reduction in emissions were recorded with coated piston engine. Among the fuels used, the best results were obtained by Jute methyl ester with Low Heat Rejection (LHR) engine coated with 300 microns.

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KEYWORDS
Yttria stabilised zirconia; thermal barrier coating; Jute methyl ester; Neem methyl ester; performance; emissions

1. Introduction

Thermal barrier coating (TBC) has been commercially used for jet engines and gas turbines. Several investigations have been carried out on different aspects of applying coating to the combustion chamber walls, piston head, inlet and exhaust valves in compression ignition engines. The main intention was to attain higher thermal efficiencies by reducing the heat rejection from the engine cylinder (Masera and Hossain 2019). The low volatility and high viscosity of vegetable oils were main drawbacks for their use in base engines (Puhan 2005). Guruprakash et al. (2016) conducted experiments on single-cylinder engine with thermal barrier coatings with an intention to overcome these drawbacks. They concluded that thermal efficiency of internal combustion engines increases from 37% to 41% when TBC was used. The experimental results also revealed that the brake thermal efficiency was increased and the fuel consumption was reduced for LHR engine (Ciniviz et al. 2014).

Shrirao et al. (2011) carried out experiments on Mullite coated diesel engine with turbocharger. The 0.5 mm thickness of mullite coating was applied on cylinder head, piston crown and valves. The results observed that specific fuel consumption was reduced about 2.17% at full load condition. The CO pollutant was decreased about 22.01% and the unburnt hydrocarbons were reduced about 28.01% at full load operation compared to base line engine (Gnanamoorthi and Devaradjane 2014).

Karuppasamy et al. (2013) conducted experiments on Ni–Cr and Al–Ti coated engine. They found that the specific fuel consumption (SFC) was decreased about 16.5% correlated to standard engine. From the results, it was also observed that at low and medium load operations the coated piston engine performance was better compared to uncoated piston engines (Datta et al. 2013).

Nitesh Mittal et al. (2013) investigated the performance and emission characteristics of partly coated LHR spark ignition engine. They observed that the CO pollutant was reduced when tested with biodiesels. The nitrogen oxide emission was increased in the LHR engine compared to base engine. It was found that the unburnt hydrocarbon emissions decrease with semiadiabatic concept compared to standard engine (Garud et al. 2017; Powell et al. 2016).

Basavaraj et al. (Shrigiri et al. 2016) carried out investigations with NKOME and CSOME in four-stroke, direct injection, single-cylinder LHR engine. They concluded that brake thermal efficiency (BTE) was increased in LHR engine with NKOME& CSOME as fuels. The SFC was decreased in LHR engine correlated to base engine. The ceramic coatings were applied on valves, cylinder head and top of the piston. It was found that the in-cylinder heat transfer rate was reduced and fuel consumption was minimised when using LHR concept (Rajak and Verma 2018; Aziz et al. 2017; Srikanth et al. 2017).

Shuang Wang et al. (2020) conducted experiments on Kirloskar make four-stroke single-cylinder DI diesel engine. In this work, pumpkin seed oil methyl ester (25PSOME) 25% blend was considered as fuel. Various performance parameters such as different injection pressures (190, 210, 230 and 250 bar), compression ratios (16.5:1, 17.5:1, 18.5:1 and 19.5:1) and various injection timings (19°, 21°, 23° and 25° bTDC) were evaluated. They concluded that optimum performance parameters were

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found with 19.5:1 compression ratio, 250 bar injection pressure and 25° bTDC injection timing. The investigation also concluded that a reduction in emission parameters viz. smoke, CO and HC parameters were observed.

Karthickeyan et al. (2020) investigated the energy and exergy analysis of 20% pomegranate seed oil methyl ester with thermal barrier coated engine and various operating conditions. The operating conditions were modified in 1500 rpm, 5.2 kW, water-cooled single-cylinder DI engine. The combustion chamber parts were coated with YSZ (Yttria Stabilised Zirconia) material. In this work, various engine parameters were altered such as compression ratio (16.5:1, 17.5:1, 18.5:1 and 19.5:1), injection timings (19°, 21°, 23° and 25° bTDC) and injection pressure (190, 210, 230 and 240 bar). They concluded that the thermal efficiency of the thermal barrier coated engine (TBCE) with B20 (20% pomegranate methyl ester and 80% diesel) was increased compared to base engine. Further it was also observed that smoke emissions were reduced using B20 pomegranate seed oil methyl ester.

Karthickeyan et al. (2020) carried out experiments on direct injection (DI) Diesel engine using diesel and papaya seed methyl ester (POME) as fuels. In this work, Pyrogallol (PY) and 1% of Di-Tertiary Butyl Peroxide (DTBP) were utilised as ignition promoters. The Partially Stablised Zirconia coated combustion chamber with PY and POME blend has given better performance such as 35% of increased thermal efficiency and 2.17% reduced fuel consumption compared to base engine. Further it was noticed that with short ignition delay the combustion efficiency, heat release rate, in-cylinder pressure and combustion duration were improved.

Karthickeyan et al. (2019) conducted performance test experiments on four-stroke diesel engine using diesel and pine oil as fuels. Further investigations were carried out on partially stabilised zirconia coated combustion chamber. The investigations concluded that in both coated and uncoated engines, Pine oil (PO) gives lower fuel consumption than diesel fuel, this was due to chemical and physical properties of fuel. The HC, CO and smoke emissions were decreased with coated piston.

Karthickeyan et al. (2019) studied the impact of new biodiesel namely Pistacia seed oil on diesel engine performance and emission characteristics. From the investigations, it was concluded that Pistacia khinjuk methyl ester (PKME) blends showed lower performance parameters than diesel fuel due to its lower density and calorific value. But the emission characteristics such as brake-specific oxides of nitrogen (BSNO), brake-specific carbon monoxide (BSCO) and brake-specific hydrocarbon (BSHC) were reduced with PKME blends.

Karthickeyan (2019) investigated the effect of combustion chamber bowl geometry on engine performance, combustion and emission characteristics using biodiesel as fuel. From this study, it was reported that Toroidal Combustion Chamber (TCC) showed improved engine performance compared to Hemispherical Combustion Chamber (HCC). The TCC provided high swirl and squish in the combustion chamber, and this leads to better mixing and complete combustion. Further it was concluded that methyl ester of pumpkin seed oil has given 66.51% exergy efficiency in TCC engine.

In the present work, an attempt was made to use YSZ coating applied over a Toroidal piston crown geometry using plasma spray technique. Three thermal barrier coating thicknesses 150, 300 and 450 microns were considered in this study. Experiments were conducted on engine fueled with diesel, Jute methyl ester and Neem methyl ester separately.

2. Experimental setup

A 5.2-kW (4.55 kW was the maximum considered load), four-stroke, water-cooled, single-cylinder, DI diesel engine was used in this experimentation as shown in Figure 1. The engine details are listed in Table 1. The eddy current dynamometer was connected to engine shaft. It was operated at various load conditions at constant speed of the engine. The engine combustion temperatures and pressure were measured using various thermocouples and pressure transducer respectively. K-type thermocouples were used in this experimentation. The quantity of

Figure 1. Engine setup.

Table 1. Specifications of the engine.

S. No.	Content	Specifications
1	Engine power	5.2 kW
2	Rated speed	1500 rpm
3	Stroke length	110 mm
4	Connecting rod length	235 mm
5	Cylinder bore	87.5 mm
6	Compression ratio	17.5
7	Stroke type	Four
8	Stroke length	110 mm
9	Number of cylinders	One
10	Speed type	Constant
11	Loading device	Eddy current dynamometer

air flow was measured with the help of air flow sensor. The u-tube manometer was used to measure the fuel flow rate. All temperature and pressure sensors were connected to data acquisition system as shown in Figure 2. The entire test setup was connected with data acquisition system. Initially the experiments were conducted with diesel, Jute Methyl Ester and Neem Methyl Ester as fuels by using uncoated Toroidal piston. Further investigations were carried out with Yttria stabilised zirconia coated piston with different coating thickness as shown in Figure 3. The experimentations were carried out by maintaining the constant engine speed at 1500 rpm. The performance characteristics were analysed with variations in brake power periodically. The emission levels like carbon dioxide, carbon monoxide, hydro carbon and nitrogen oxide were determined using five gas Mars analyser.

3. Results and discussion

In this work, experiments have been conducted with uncoated piston at various loads to analyse performance and emission characteristics using standard diesel, Neem methyl ester (NME) and Jute methyl esters (JME). Further investigations were carried out on thermal barrier coatings with different coating thickness of 150, 300 and 450 microns (Table 2).

3.1. Performance parameters of low heat rejection (LHR) engine using different piston coating thickness with biodiesels

Performance characteristics were evaluated for uncoated piston engine using standard diesel and LHR engine using various piston coating thicknesses and using diesel and biodiesel. The performance characteristics and emissions were compared and analysed.

Figure 4 shows the comparison between engine output power and brake thermal efficiency. It was observed that the brake thermal efficiency (BTE) of low heat rejection with 300 microns coated piston engine using jute methyl ester as fuel (LHR 300 JME) was about 30% higher than Toroidal base engine at maximum load condition. The base engine BTE was about 28% using toroidal combustion chamber without low heat rejection concept. The lowest brake thermal efficiency obtained for LHR 150 NME was 20.1% at 100% load operation. The brake thermal efficiency for Low heat rejection 300 JME engine was about 8.9% higher than the toroidal base diesel (TD) engine at 100% load operation. This may be owing to high temperature of combustion and reduced heat losses from the engine combustion chamber.

The variation of indicated thermal efficiency with respect to Brake power was shown in Figure 5. It was apparent that the ITE was increased from 0% to 100% load condition. The ITE recorded for LHR 300 Jute methyl ester was about 51% at full load condition. The indicated thermal efficiency for toroidal uncoated

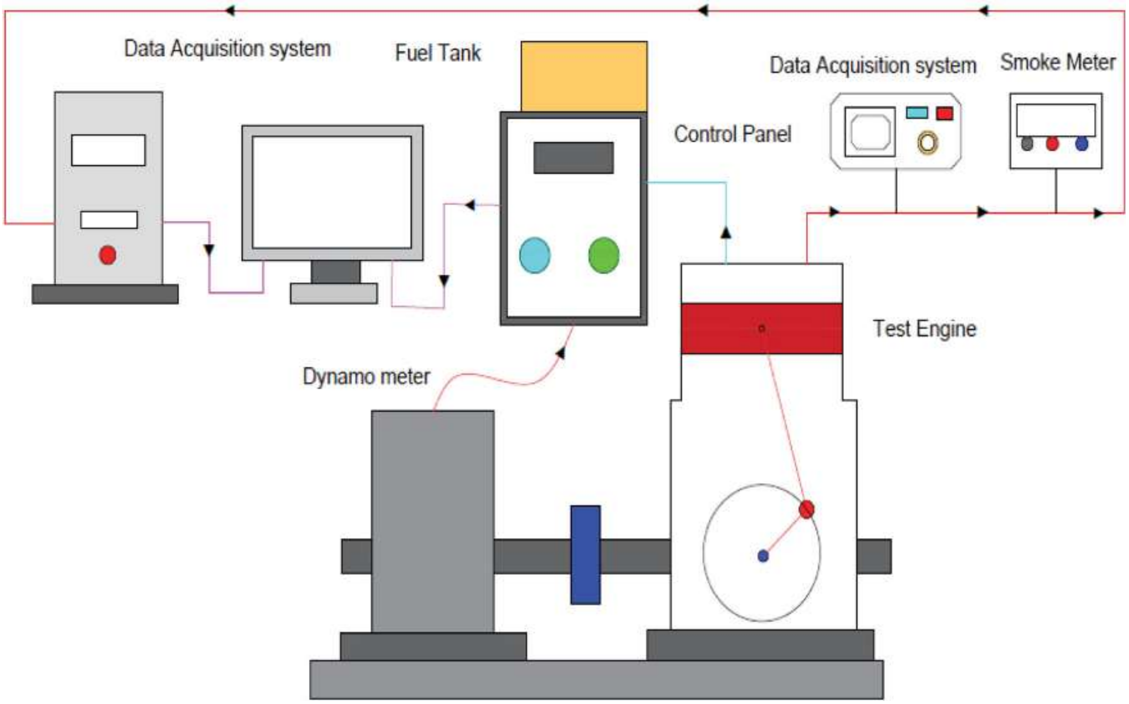

Figure 2. Layout of the experimental engine setup.

(a) LHR 150 TCC (b) LHR 300 TCC c) LHR 450 TCC d) Uncoated piston

Figure 3. Coated and uncoated toroidal combustion chamber (TCC) piston.

Table 2. Comparison of properties of diesel, JME and NME.

Properties	Unit	Diesel fuel	Jute methyl ester	Neem methyl ester	Test method
Specific gravity	–	0.83	0.85	0.88	–
Density	kg/m^3	830	978	948	ASTM D1298
Kinematic viscosity@ 40°C	CST	3.01	3.8	13.05	ASTM D 445
Heating value	MJ/kg	42.5	38	34	ASTM D 5865
Flash point	°C	50	166	175	ASTM D 92
Fire point	°C	60	179	191	ASTM D 92
Cetane number	–	47	44–48	45–47	ASTM D 613

piston configuration engine was about 46% at 100% load condition. The ITE for Low heat rejection 300 JME engine was 10.5% higher than toroidal base diesel engine. This was caused due to higher temperature of combustion chamber walls. The ITE for LHR 150 engine with NME was minimum in comparison to other piston coatings and was 32.95% at maximum load condition.

The variation of mechanical efficiency with respect to brake power was plotted in Figure 6. The similar performance of the plotted graph was observed for different coated piston configurations. The mechanical efficiency (ME) for low heat rejection 300 engine with JME was 78% at maximum load condition. At 100% load operation, the mechanical efficiency obtained for toroidal uncoated piston with diesel fuel was 75.54%. It was practically observed that mechanical efficiency for LHR 300 Jute methyl ester was high correlated to toroidal base diesel.

The specific fuel consumption (SFC) was decreased from zero load to 36% of full load condition. But after 36% of full load condition little deviation was found. This variation was shown in Figure 7. The SFC for low heat rejection 300 JME was 0.25 kg/kWh at 100% load operation. The SFC for base diesel with toroidal combustion chamber was 0.302 kg/kWh at 100% load condition. It was concluded that SFC for low heat rejection 300 JME was lower than TD and was 13.5% at rated load operation. This was occurred due to increased pressure and temperature of combustion gases. The maximum SFC for low heat rejection 150 NME was 0.418 kg/kWh at 100% load condition.

3.2. Emission parameters of low heat rejection engine using different piston coating thicknesses with diesel and biodiesels

The pollution characteristics were analysed on low heat rejection with various biodiesels using different piston coating

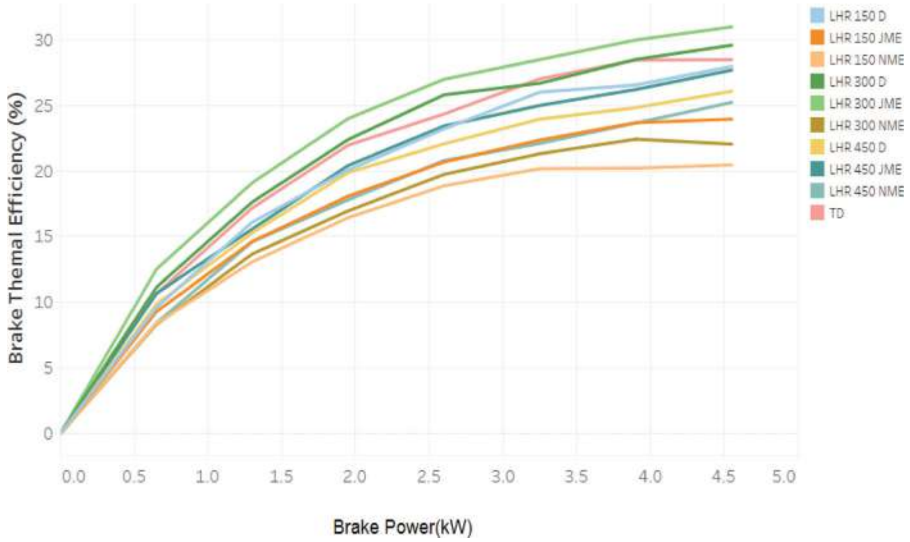

Figure 4. BTE variation with respect to BP.

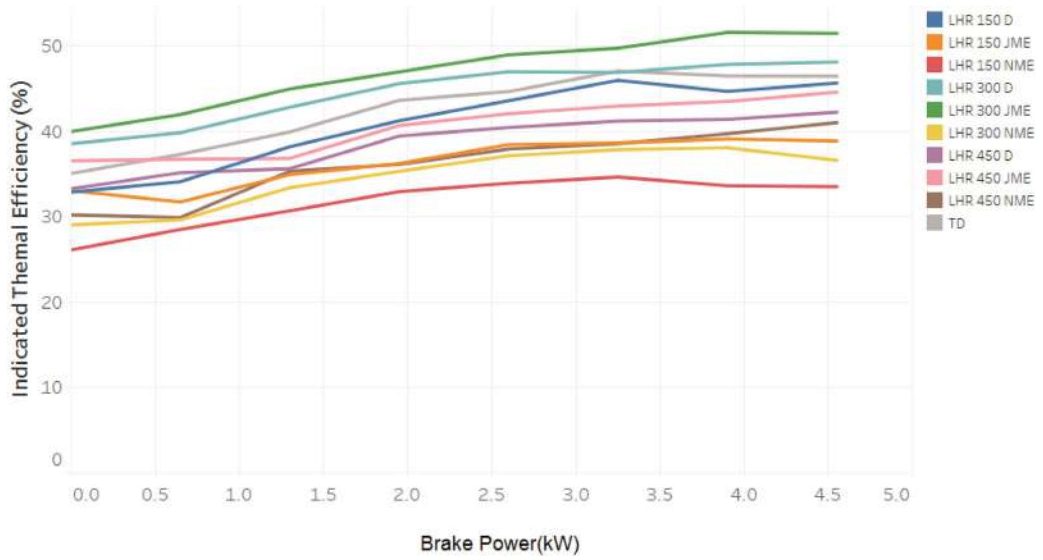

Figure 5. ITE variation with respect to BP.

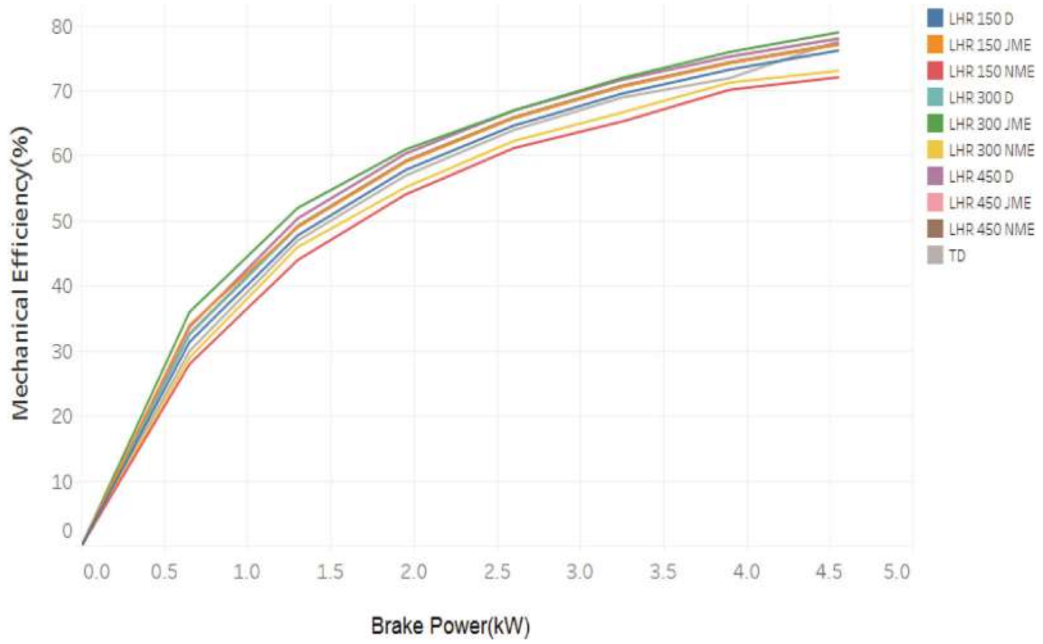

Figure 6. ME variation with respect to BP.

thicknesses. The pollution characteristics such as nitrogen oxides, CO_2, HC and CO emissions were determined.

The results were plotted between brake output power and CO emissions as shown in Figure 8. It was found that the carbon monoxide emission levels were small from zero load to 70% of full load condition. The pollutants were rapidly increased after 70% of full load condition. The CO emissions for LHR 450 Jute methyl ester were about 0.21% at 100% load operation. The CO emissions for TD were 0.26% at full load condition. The carbon monoxide pollutants for LHR 450 JME were about 14.5% low correlated to Toroidal combustion chamber with base diesel. The better combustion of bio-fuel in coated combustion chamber was the main reason.

The variation of unburnt hydrocarbon emission with respect to brake power was shown in Figure 9. It was observed that the HC emissions were not deviated from zero load to 50% load condition. The HC emissions were increased from 50% load condition to the maximum considered test load. The HC pollutants for low heat rejection 300 JME was about 83 ppm at 100% load operation. The HC emission for low heat rejection 150 base diesel was 102 ppm. At full load, low heat rejection engine 300 JME hydrocarbon pollutants were minimum correlated to LHR 150 D and was 19.18% lower. The high combustion chamber temperature was the main reason for less HC pollutants.

The variation of carbon dioxide pollutant vs. brake output power was shown in Figure 10. It was identified that CO_2 emissions were progressively raised from zero load to 100% load condition for all coating thicknesses of the piston. The carbon dioxide emission for LHR 300 JME was 9.2% at 100% load. The CO_2 pollutants for TD were about 11.12% at full load. The CO_2

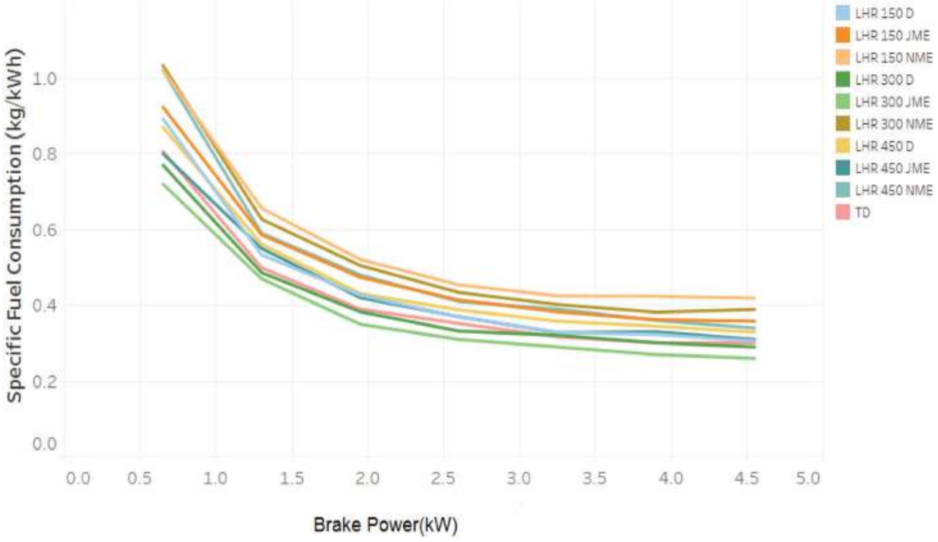

Figure 7. SFC variation with respect to BP.

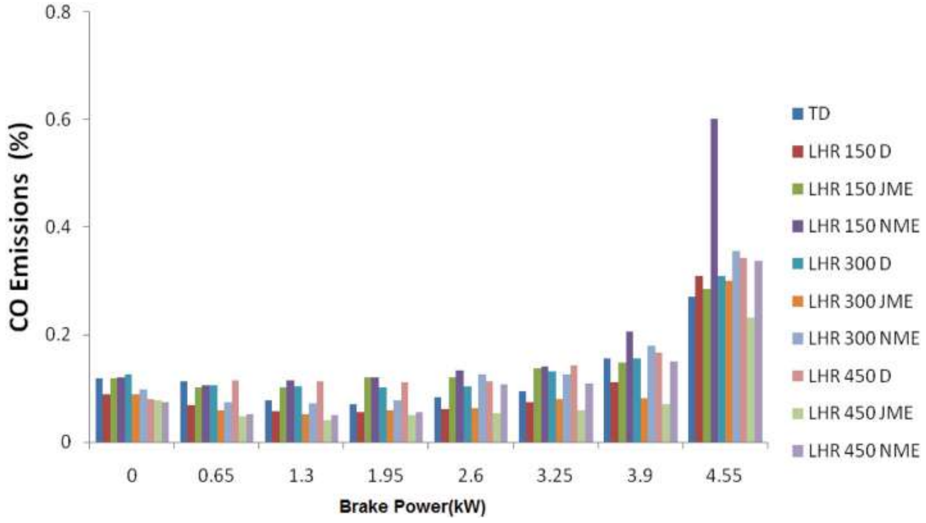

Figure 8. CO variation with respect to BP.

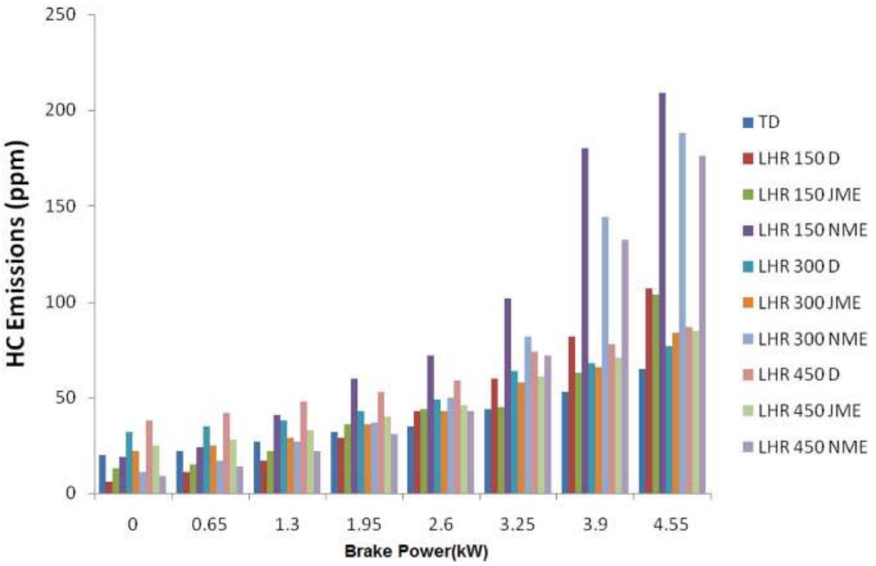

Figure 9. HC variation with respect to BP.

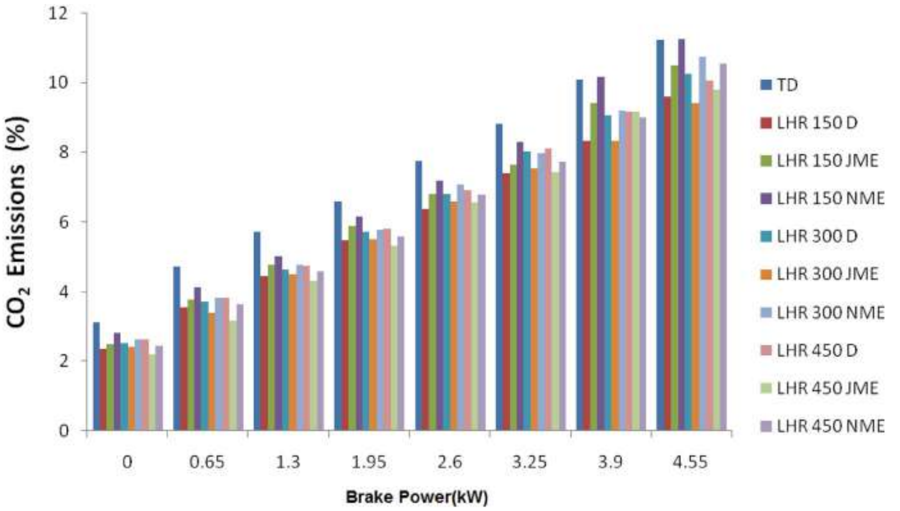

Figure 10. CO_2 variation with respect to BP.

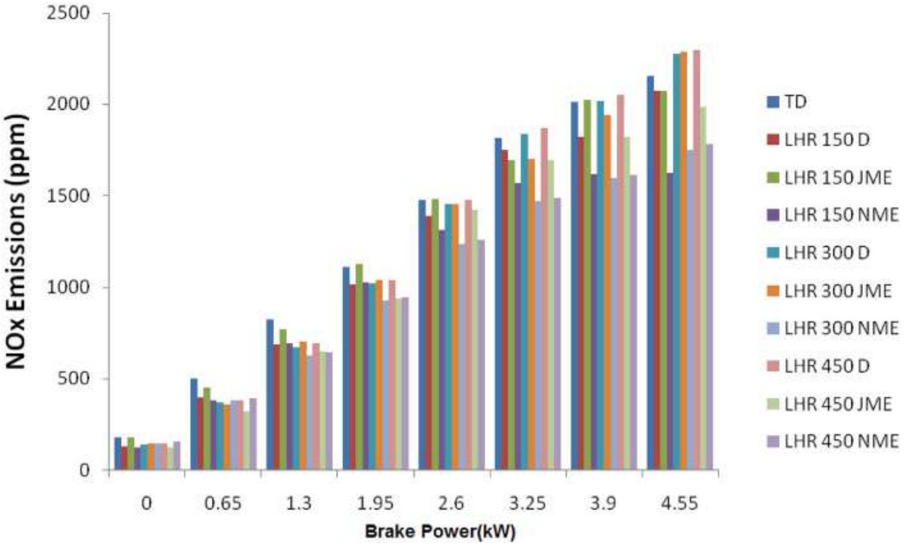

Figure 11. NO_x variation with respect to BP.

pollutant was low with low heat rejection 300 jute methyl ester correlated to other piston configurations. The oxygen molecules were high in combustion gases at full load condition.

The deviation of NO_x pollutants with brake output power was indicated in Figure 11. The NO_x pollutants were increased from zero load to 70% of full load condition. After 70% load condition, the oxides of nitrogen pollutant were increased vastly for all piston coatings. The NO_x pollutants were less for low heat rejection 300 JME and were 2290 ppm at 100% load. The nitrogen oxide pollutants for TD were 2100 ppm at 100% load condition. The nitrogen oxide pollutant for low heat rejection 300 JME was higher than Toriodal diesel and was about 6.22% high compared to Toroidal diesel at full load condition. The high combustion temperature causes increased NO_x pollutant levels with semiadiabatic concept.

4. Conclusion

In this work, experiments were carried out on single-cylinder four-stroke direct injection water-cooled engine by varied combustion chamber configuration with Diesel, Neem and Jute methyl ester as fuels. Further investigations were conducted on low heat rejection engine using different piston head coating thicknesses.

The conclusions were summarised below.

Based on experiments conducted using 3 different fuels (diesel, JME and NME) and 3 different piston coating thicknesses (150, 300 & 450 microns), JME 300 fuel-coating thickness combination showed maximum benefit in performance when compared to uncoated piston engine with diesel as fuel.

(1) BTE of JME 300 was high compared to other fuels in LHR and also compared to uncoated engine piston.
(2) ME of JME 300 was high compared to other fuels in LHR and also compared to uncoated engine piston.
(3) SFC of JME 300 was low compared to other fuels in LHR and also compared to uncoated engine piston.
(4) CO_2 of JME 300 was low compared to other fuels in LHR and also compared to uncoated engine piston.

(5) CO of JME 450 was low compared to other fuels in LHR and also compared to uncoated engine piston.
(6) HC of TD was low compared to other fuels in LHR.
(7) The nitrogen oxide emission with LHR 150 NME was lower compared to diesel at 80% load condition.

Scope for future work

- The experiments may be extended with different injection pressures and different injection timings.
- The same experiments may be extended using various thermal barrier coating materials.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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