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Performance and Emission Characteristics of Diesel Engine Using Thermal Barrier Coated Cylinder Liner and Piston

K.Thiruselvam[1]*, M.D.Mohan Gift[1]

[1]*Associate Professor, Dept of Mech Engineering, Panimalar Engineering College, Chennai, Tamilnadu, India.*

**Corresponding author E-Mail ID: thirumurugu2014@gmail.com, Mobile: 9443492009*

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ABSTRACT

Improvement in thermal efficiency and reduction in emission from diesel engines are major thrust research work in all around the world. This research work is on the performance and emission characteristics of diesel engine using Low Heat Rejection (LHR) techniques of thermal barrier coated cylinder liner and piston. A piston was coated as 100 micron thickness and three cylinder liners were coated in the thickness of 100,150 and 200 micron. Piston and cylinder liners were coated with equal percentages of Alumina and Yittria Stabilized Zirconia powder using the plasma spraying coating method. The test results compared with base engine showed reduction in the performance parameter of specific fuel consumption (SFC) on an average by 6.11%, 12.78% and 16.89%, while the brake thermal efficiency increased by 1.68%,3.75% and 5.19% in 100,150 and 200 micron thickness coated cylinder liner used engine respectively. There was reduction in Carbon monoxide (CO), unburned hydrocarbon (HC) and smoke emissions levels while Nitrogen Oxide (NOx) emission was slightly higher in the coated engine compared with the uncoated engine in all load conditions. Overall, 200 microns thickness coated cylinder liner showed a better performance parameter and low emission compared with other cylinder liner coated engine.

Keywords: Low Heat Rejection (LHR) engine, Thermal Barrier Coating (TBC), Cylinder liner, Piston, Diesel engine.

1. INTRODUCTION

High thermal expansion coefficient, low thermal conductivity and high thermal shock resistance are the major characteristics of Yittria Stabilized Zirconia (YSZ) but it has sintered above 1473 K, phase transformed at 1443 K, corrosion and oxygen-transparent. On the other hand Alumina posses high corrosion-resistance, high hardness and not oxygen-transparent but it has the disadvantages of phase transformation occurring at 1273 K, high thermal conductivity and very low thermal expansion coefficient [1]. So the individual YSZ and Alumina coating cannot be the best thermal barrier coating materials. Hence the authors used 50% of Alumina and 50% of YSZ as coating material in the cylinder liner and piston. Thermal shock and the thermal torch experiments on various coated materials are proved that zirconia has the best thermal shock properties and can be used in an engine for increased performance [2].

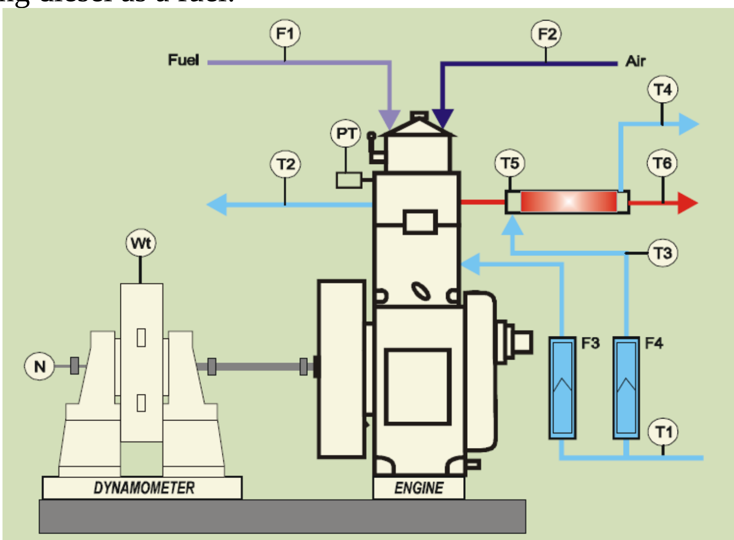
The test results of 0.5mm thickness of thermal barrier coated on piston head using alumina and yittria partially stabilized zirconia in diesel engine showed specific fuel consumption as lower around 15 to 20%, a significant increase in engine performance at high engine speeds and power increase by approximately 8% and torque by 6% [3]. The test results of six cylinders, direct injected, turbocharged, ceramic coated diesel engine that 0.5mm thickness coating in cylinder head, piston and valves reduced heat loss to the coolant around 5-25% [4].

NOx emission was higher in the ceramic coated diesel engine with the usual injection timing because of the higher heat energy in the chamber. But this could be reduced by retarding injection timing by 4^0 BTDC [5]. Test results of cerium oxide stabilized zirconia coated diesel engine cylinder liner, the reduction in specific fuel consumption by 4% but NOx was high [6]. Analysis of thermal shock behavior between plasma sprayed nano structured and the conventional zirconia thermal barrier coatings and concluded that plasma sprayed zirconia provided better performance in thermal shock test [7]. Thermal efficiency of diesel engine increased by 2% in low load,5% in medium load and 3% in high load of ceramic coated thermal barrier coating of piston compared with a standard engine at 20^0CA [8]. Theoretically evaluated two different ceramic coated pistons of Mg-PSZ and Y-PSZ are showed top surface of piston providing increase in temperature by 18% - 48% in both the coatings. However the Y-PSZ coating material made knocking free engine in petrol engine [9]. Analyzed thermal and temperature stress of thickness range 0.2 mm to 1.6 mm and found magnesium stabilized ceramic coated aluminum alloy piston of diesel engine using ANSYS software and clearly showed increase in combustion temperature as the thickness of coating increased, thereby increasing the thermal efficiency of the engine [10]. Ten years of experience for the role of ceramic coatings on a diesel engine in reducing automotive emissions and improving combustion efficiency [11-12]. The selection of TBC materials are considered as high melting point, low thermal conductivity, low density, high resistance to thermal shock, corrosion resistant, high surface emissivity, ability to withstand mechanical erosion and high coefficient of thermal expansion [13]. Alumina and 40% Titania ceramic coated piston in diesel engine produced low specific fuel consumption, high brake thermal efficiency and low NOx and HC emission [14]. Piston head coated with a combination of Al_2O_3+40%TiO_2 showed that Al_2O_3 had thermal growth of oxides and decompositions which provided better diesel engine performance [15]. The ceramic coated engines produced better thermal efficiency and low emission level [16,17]. The authors found that most of the thermal barrier coatings showing the coating on piston head and valves head only. Hence this experimental work was a novel method for analyze the cylinder liner coating along with piston head. The liners are tested with thickness of 100,150 and 200 microns and piston head coated 100 microns of yittria stabilized zirconia and alumina using plasma spraying method. The figure 2 and 3 shows that piston and cylinder liner before and after coating.

2. EXPERIMENTAL SETUP ENGINE

Performances and emission characteristics were tested in the single cylinder four stroke direct injection diesel connected to an eddy current type dynamometer for loading. It was provided with necessary instruments for combustion pressure and crank-angle measurements. These signals were interfaced to a computer through engine indicator for Pθ−PV diagrams. Figure 5 shows that engine setup with various measuring sensors fitted on it. Table 3 shows technical specifications an engine and table 4 indicated that accuracy and range of measuring devices used in an engine. Cylinder pressure data of 50 successive cycles with accuracy of 1^0 CA (crank angle) measured by the piezoelectric pressure transducer. The measured pressure data were recorded and utilized for heat release rate and maximum pressure rise rate analysis. Eddy current dynamometer fitted with load sensor which was used to measure the load applied on an engine. Provision was also made for interfacing airflow, fuel flow and temperatures measurement. The set up has stand alone panel box consisting of air box, fuel tank, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator and engine indicator. Rota meters are provided for cooling water and calorimeter water flow measurement. Engine connected with computer which was enabled Lab view based Engine Performance Analysis software package “Engine soft” for on line performance evaluation. The software evaluates power, efficiencies, fuel consumption and heat release. It is configurable as per engine set up. Various graphs are obtained at no load, 25%, 50% and 100% load condition.

The performance of the uncoated engine and combustion parameters were initially noted. The base engine cylinder liner and piston were then replaced by a thermal barrier coated cylinder liner and piston. The 100,150 and 200 micron coating thickness of cylinder liner were separately used in the engine and their performances and combustions parameters noted. All the performances and combustion parameters were recorded in an engine with compression ratio 17.5 and using diesel as a fuel.



Symbol	meaning
F1	Fuel flow sensor
F2	Air flow sensor
F3	Engine Water flow sensor
F4	Calorimeter Water flow sensor
T1	Cooling water inlet temp sensor
T2	Cooling water outlet temp sensor
T3	Calorimeter water inlet temp sensor
T4	Calorimeter water outlet temp sensor
T5	Calorimeter gas inlet temp sensor
T6	Calorimeter gas outlet temp sensor
PT	Pressure sensor
N	Engine speed sensor
Wt	Load sensor

Fig 1. Engine Dynamometer setup

Table 1. Technical specifications of Engine

Parameters	Values
Engine make	Kirloskar
Model	TV 1
No.of Cylinder	1
No.of strokes	4
Fuel	Diesel
Rated Power	5.2 KW @ 1500 RPM
Cylinder diameter	87.5 mm
Stroke length	110 mm
Compression ratio	17.5:1
Ignition type	Compression ignition
Cooling	Water cooled
Loading type	Eddy current dynamometer
Combustion chamber injector nozzle	Three holes with 0.3mm diameter each
Combustion chamber shape	Hemi spherical shape
Injection timing	230 BTDC
Injection pressure	200 bar

Fig 2. Piston before and after coating

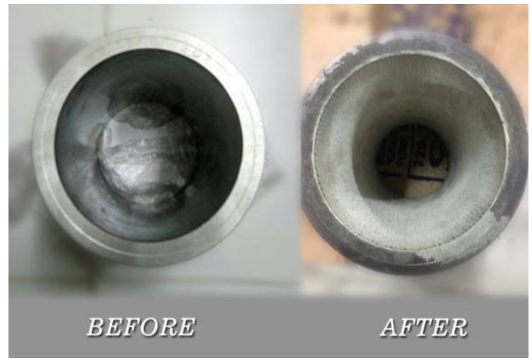


Fig 3. Cylinder liner before and after coating

3. RESULTS AND DISCUSSION

The results of the performance and combustion parameters of thermal barrier coated engine compared with under different load conditions of 0, 25%, 50% and 100%. In forthcoming all figures base engine meant uncoated engine, 100 micron, 150 micron and 200 micron meant corresponding thickness of thermal barrier coated cylinder liner used engine.

3.1. Specific Fuel Consumption (SFC)

Figure 4 shows that the specific fuel consumption at 25% load condition decreased as 4.29%, 11.82% and 15.36% respectively in 100,150 and 200 micron coated cylinder liner compared with a base engine. Under 50% load (part load) condition, the SFC decreased by 8.39%, 13.38% and 19.88% in the respective coated liners with the base engine. Under 75% load condition, the decrease as 7.14%, 13.36% and 16.29% respectively. Under 100% load (full load) condition, the SFC is decreased by 4.60%, 12.53% and 16.06% in respective coated cylinder liner compared with a base engine. There was a decrease in the rate of fuel consumption due to the time taken for decrease the fuel consumption as the thickness of cylinder liner coating increased. The increase in thermal barrier coating thickness in the cylinder liners produced the maximum mean effective pressure and maintained high combustion chamber temperature due to reduction in the amount of heat flow outside the combustion chamber which might be the cause for the decrease in the fuel consumption rate. This decrease in the specific fuel consumption rate showed the efficient use of the supplied fuel by the thermal barrier coated engine for the accomplishment of the work. The 200 micron coated cylinder liner resulted in a low amount of fuel consumption compared to other coated cylinder liners.

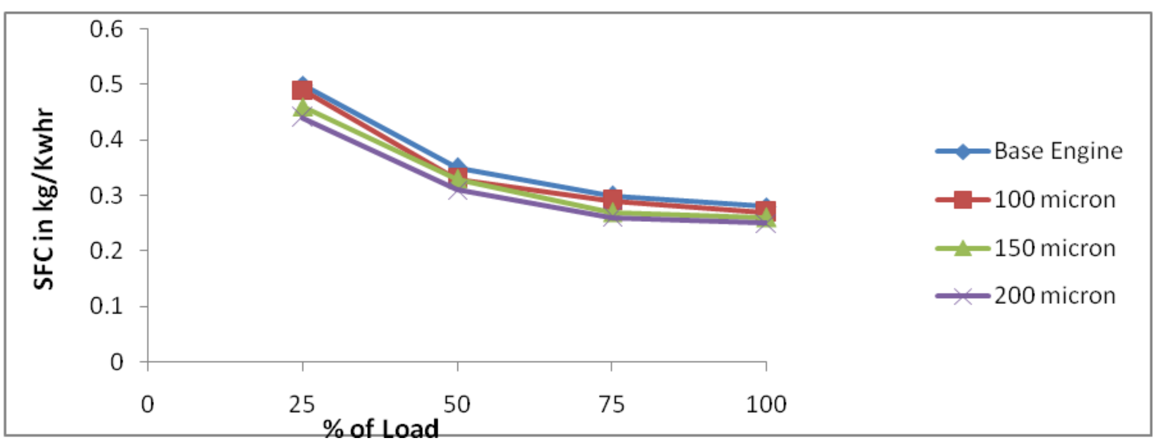


Fig 4. Specific fuel consumption variation with load

3.2 Brake Thermal Efficiency

The brake thermal efficiency of thermal barrier coated cylinder liners was found to be higher than that of the base engine. This is shown in Figure 5. The increase in cylinder liner coating thickness caused increase in the combustion chamber temperature, thereby causing a reduction in the total amount of fuel consumption followed by increased brake thermal efficiency which was 0.762%,2.279%,and 3.08% under 25% load condition,2.212%,3.731% and 5.99% under 50% load condition(part load),2.25%,4.511% and 5.69% under 75% load condition,1.511%,4.485% and 6.0% under 100% load condition(full load) respectively for 100,150 and 200 micron coated cylinder liner used engine compared with base engine. Figure 7 also indicates the higher thickness coated i.e 200 micron thermal barrier coated cylinder liner having high brake thermal efficiency under all load condition. This result showed that partially Yittria Stabilized Zirconia having low thermal conductivity and high thermal expansion coefficient which provided better insulation to the combustion chamber, thereby reducing the amount of heat transfer to cooling water resulting in increase in thermal efficiency.

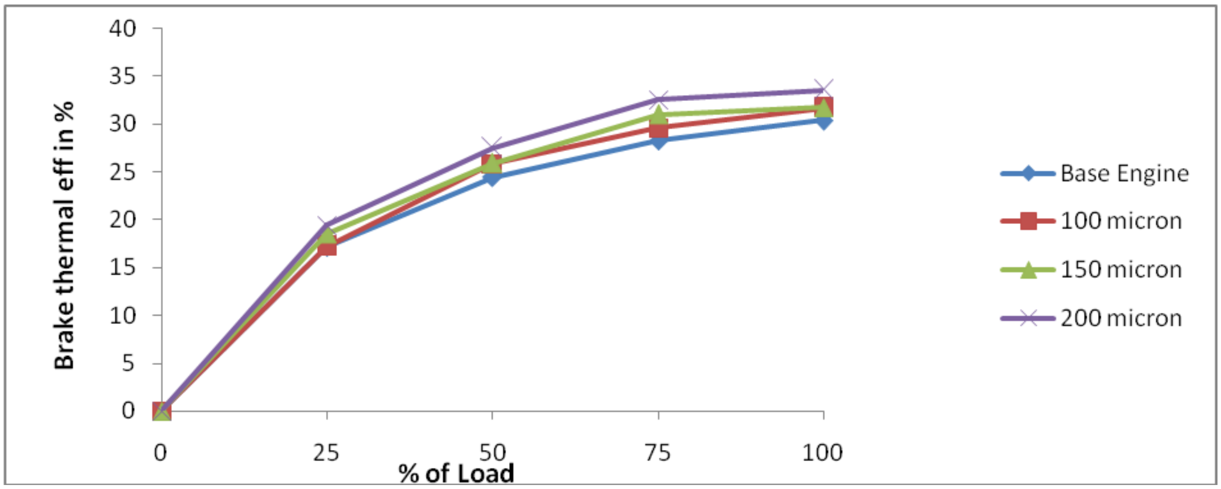


Fig 5. Brake Thermal Efficiency Vs Load

3.3 Variation of pressure rise and heat release rate

Figure 6 indicated pressure variation with crank angle at full (100%) load condition. It was found that peak pressure of 100,150 and 200 micron thickness coated cylinder liner used engine is 71.16, 72.1, and 72.77 bar respectively. It was correspondingly 3.8, 5.06 and 5.2 bar higher than base engine. Thermal barrier coated cylinder liner and piston maintained high thermal insulation to the chamber thereby combustion rate is increased. It caused to increase cylinder pressure in the combustion chamber.

Heat release rate per degree of crank angle of thermal barrier coated cylinder liner and base engine results are plotted in the figure 7. The results were obtained that the maximum heat release rate as 43.39, 43.89 and 44.94 KJ/deg CA in the respective 100,150 and 200 micron thickness coated cylinder liner used engine. It was correspondingly 1.22, 1.82, 2.87 KJ/deg CA higher than base engine. The thermal barrier coated cylinder liners produced higher heat energy under the all load conditions compared to the base engine due to the coated liner acting as an insulator and enabled almost complete combustion in the chamber and also the heat transfer rate to the walls are less. Hence the net heat transfer rate of the thermal barrier coated engine was high compared with base engine. The 200 micron coated cylinder liner used engine had higher heat release rate compared with other coated cylinder liner used engine.

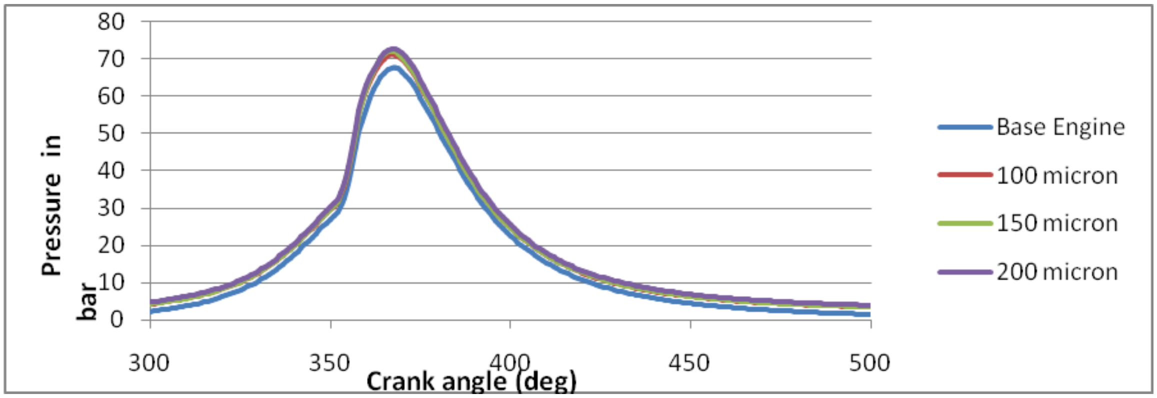


Fig 6. pressure – crank angle at 100% load

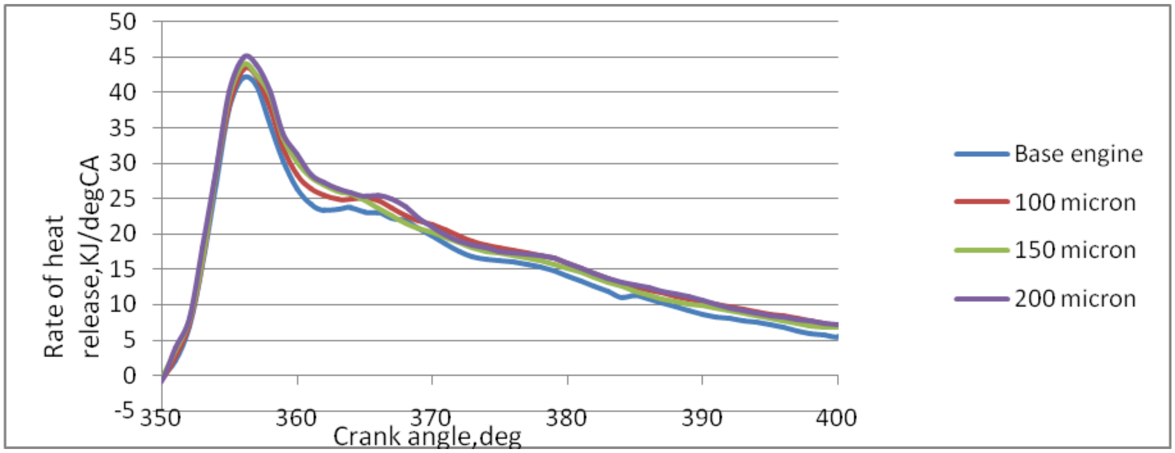


Fig 7. Rate of heat release at 100% load

3.4 Carbon Monoxide (CO)

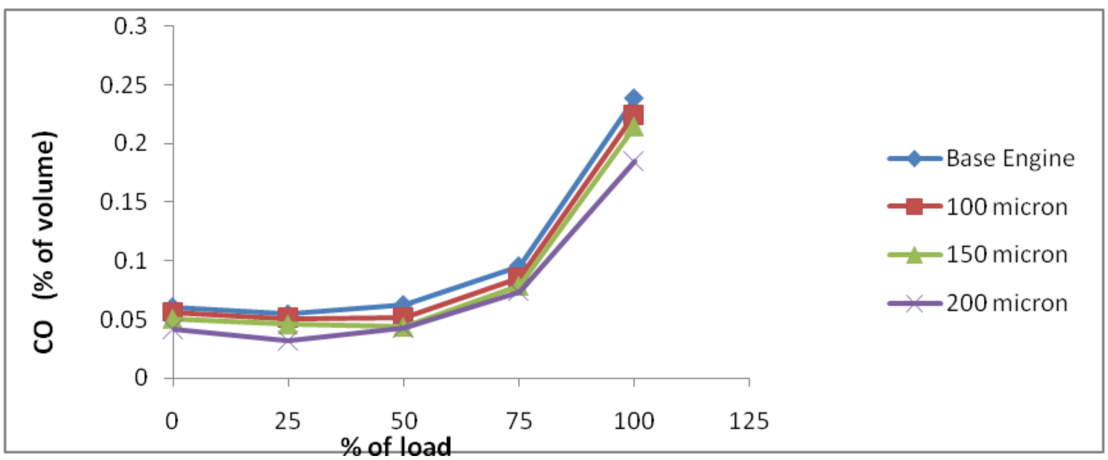


Fig 8. Carbon monoxide emission versus load

Carbon monoxide (CO) emission occurred due to insufficient oxygen in the combustion chamber during the combustion process in the engine. Poor mixing and incomplete combustion are the main sources of CO emission. The yittria stabilized zirconia and alumina coated cylinder liner and piston used engine maintain high temperature in the combustion chamber causing a complete combustion in the chamber. This resulted in low carbon monoxide emission compared to the base engine. Figure 8 showed that at part load condition overall CO emission is low and in full load condition it reaches high. A comparison of CO emission from the thermal barrier coated engine showed it was low with base engine in percentage of volume as 0.035,0.036 and 0.044 under 25% load condition,0.043,0.051 and 0.06 under 50% load condition,0.063,0.054 and 0.079 under 75% load condition and 0.04,0.11 and 0.209 under 100% load condition. It clearly indicated the action of 200 microns coated cylinder liner as a good thermal barrier producing complete combustion, thereby resulting in low CO emission.

3.5. HC emission

The unburned hydro carbon emission in the thermal barrier coated engine was in reduced lower level in all load condition compared to base engine. This is shown in Figure 9. Under 50% load condition there was reduced level of the HC emission in the respective 100,150 and 200 micron thickness coated cylinder liner engine are 7, 8 and 10 ppm, under the 100% load condition, the reduced levels in the respective cylinder liner were 21, 24 and 28 ppm compared to the uncoated engine. This reduced HC emission occurred due to smaller incomplete combustion produced by the usage of one of the coating elements of alumina powder promoting the oxidation process with hydrocarbon in diesel fuel and insulation coating maintained higher combustion temperature in the combustion chamber. The coating powders did not to allow the deposit of oil in the combustion chamber wall which might be one of the reasons for low HC emission. The 200 micron thickness coated cylinder liner engine caused a reduced low level as 28 ppm as compared to the uncoated engine.

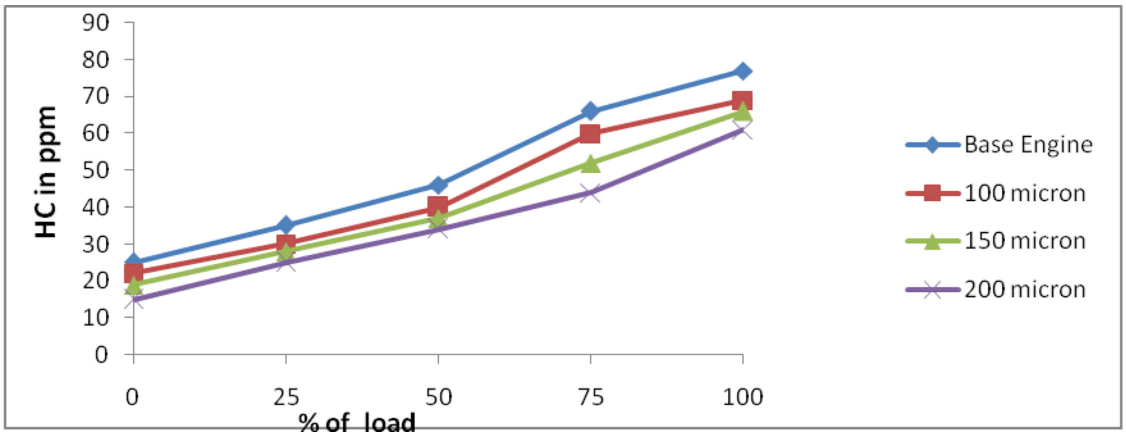


Fig 9. Variation of Hydro Carbon (HC) emission with load

3.6. Nitrogen Oxide (NOx) emission

As per the Zeldovich kinetics of NO formation mechanism, maintenance of high temperature in the combustion chamber is the main causes for molecular nitrogen which reacts with oxygen to form nitrogen oxide.The combustion reaction is less at low load condition produces a temperature in the combustion chamber which is not enough for higher NOx emission. But it increases is more with increase in the load. In this test results also showed that below the part load condition the NOx emission is low and its level is high above the part load condition. This is shown in the figure 10. Under part load condition, the increases of NOx in the 100,150 and 200 micron coated cylinder liner engine respectively as 98, 25 and 115 ppm compared with base engine. Under full load condition, the increase of NOx in the coated cylinder liner engine is as 188,216 and 275 ppm compared to uncoated engine. This increased NOx emission is due to increase in gas temperature by 40 to 50^0c in the combustion chamber of thermal barrier coated engine compared with uncoated engine. The 200 micron thickness of yittria stabilized zirconia and alumina coated cylinder liner used engine produced more nitrogen oxide level compared with other thickness of cylinder liner. The NOx emission is usually high in the thermally insulated diesel engine [5,6].

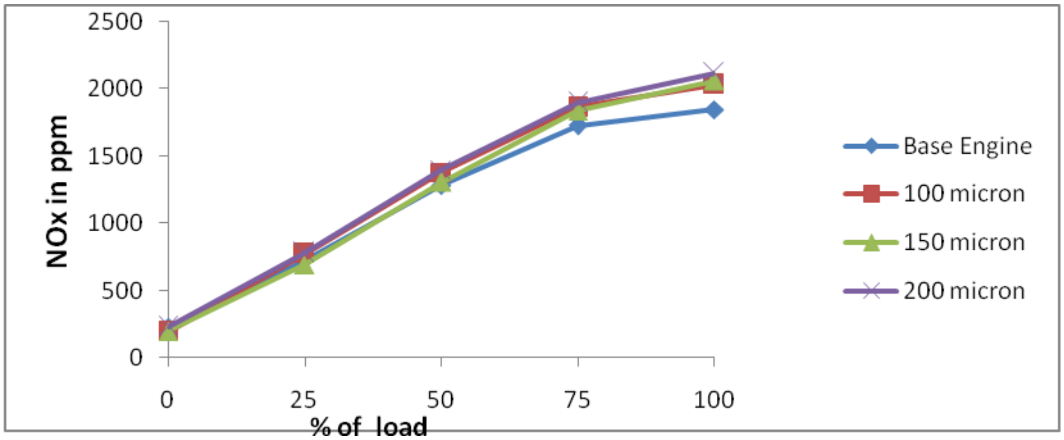


Fig 10. Variation of Nitrogen Oxide (NOx) emission versus load

3.7 Smoke emission

Smoke level is measured by AVL smoke meter 437C with the measuring range of 0-100% and resolution of 0.1%. The smoke level under all the load conditions the thermal barrier coated engine produced lower than uncoated engine. It is due to higher combustion efficiency maintained by the coated engine under all load condition. Figure 11 shows the decrease in 100,150 and 200 micron thickness coated of cylinder liner used engine as 2%,3.4% and5.4% in part load (50%) condition,9.7%,13.2% and 17% in full load (100%) condition compared with uncoated engine. This result also indicated a lower level of smoke for higher thickness coated (200 micron) cylinder liner compared with other coated (100 and 150 micron) cylinder liner.

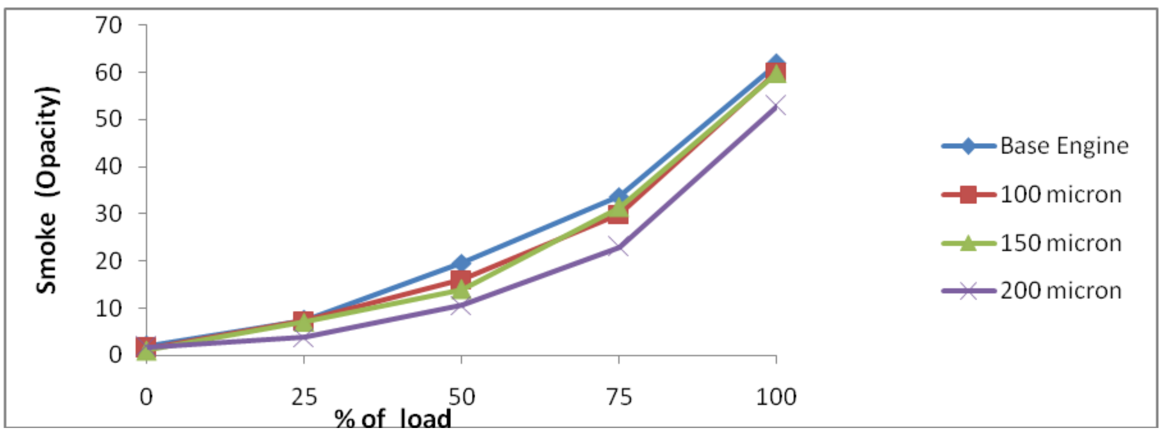


Fig 11. Variation of Smoke Opacity versus load

4. CONCLUSION

The following single cylinder diesel engine performance and emission characteristics were obtained using thermal barrier coated cylinder liner and piston used low heat rejection engine and it's compared with uncoated engine.

1. Decrease in Specific Fuel Consumption (SFC) was seen in all load conditions on an average as 6.11% in 100 micron coated cylinder liner engine, 12.78% in 150 micron coated cylinder liner engine and 17.65% in 200 micron coated cylinder liner engine as compared to the uncoated engine which showed efficient utilization of fuel to produce work by thermal barrier coated engine.

2. Brake Thermal Efficiency increase in the 100,150 and 200 micron thickness coated cylinder liner engine respectively under all load condition was 1.68%,3.75% and 5.19% as compared to an uncoated engine due to the use of yittria stabilized zirconia with low thermal

conductivity, thereby acting as better thermal insulation to combustion chamber to reduced heat dissipation rate.

3. Heat release rate increased compared to the uncoated engine under all load condition subject to a maximum of 4.98, 6.53 and 8 KJ/deg CA as difference in value in 100,150 and 200 micron thickness coated cylinder liner used engine respectively.

4. Carbon monoxide (CO) and unburned hydrocarbon (HC) emissions were very low level in all thickness of thermal barrier coated cylinder liner used engine compared with uncoated engine under all load conditions. It was due to the maintenance of higher temperature and thermal barrier coated materials which promoted the oxidation reaction with fuel in the combustion chamber. Hence, incomplete combustion was smaller.

5. Nitrogen Oxide (NOx) emission was slightly high in the thermal barrier coated engine due to increase in gas temperature by 400c to 500c in the combustion chamber compared with uncoated engine.

6. The smoke density was low compared with uncoated engine as a result of the production of higher combustion efficiency in the coated engine under all load conditions.

Overall, the performance and the combustion analysis of three different thickness of cylinder liner used engine, the 200 micron thickness coated cylinder liner used engine had better performance and low emissions.

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Conflict of Interest

None of the authors have any conflicts of interest to declare.

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