Evaluation of Performance and Emission characteristics of Turbocharged Diesel Engine with Mullite as Thermal Barrier Coating

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Abstract— **Tests were performed on a single cylinder, four stroke, direct injection, diesel engine whose piston crown, cylinder head and valves were coated with a 0.5 mm thickness of $3Al_2O_3 . 2SiO_2$ (mullite) (Al_2O_3= 60%, SiO_2= 40%) over a 150 µm thickness of NiCrAlY bond coat. Tests were carried out on standard engine (uncoated) and low heat rejection (LHR) engine with and without turbocharger. This paper is intended to emphasis on energy balance and emission characteristic for standard engine (uncoated) and low heat rejection (LHR) engine with and without turbocharger. Tests were carried out at different engine load and engine speed conditions for standard and low heat rejection engine with and without turbocharger. The results showed that there was 2.18% decreasing on specific fuel consumption value of low heat rejection (LHR) engine with turbocharger compared to standard engine at full load. There was as much as 12% increasing on exhaust gas temperature of LHR engine with turbocharger compared to standard engine at full load. There was as much as 20.64% increasing on NOx emission of exhaust gas, 22.05% decreasing on CO emission of exhaust gas and 28.20% decreasing on HC emission of exhaust gas of LHR engine with turbocharger compared to standard engine at full load.**

Index Terms— **Energy balance; Emissions; Mullite; Turbocharger; LHR; SE.**

I. INTRODUCTION

It is well known fact that about 30% of the energy supplied is lost through the coolant and the 30% is wasted through friction and other losses, thus leaving only 30% of energy utilization for useful purposes. In view of the above, the major thrust in engine research during the two decades has been on development of low heat rejection engines. Several methods adopted for achieving low heat rejection to the coolant were using ceramic coatings [1] on piston, liner and cylinder head and creating air gap in the piston [2] and other components with low- thermal conductivity material like superni, mild steel etc. However, this method involved the complication of joining two different metals. [3] Jabez Dhinagar et al. used different crown materials with different thickness of air gap in between the crown and the body of the piston. Ceramics have a higher thermal durability than metals; therefore it is usually not necessary to cool them as fast as metals. Low thermal conductivity ceramics can be used to control temperature distribution and heat flow in a structure [4-5]. Thermal barrier coatings (TBC) provide the potential for higher thermal efficiencies of the engine, improved combustion and reduced emissions. In addition, ceramics show better wear characteristics than conventional materials. Lower heat rejection from combustion chamber through thermally insulated components causes an increase in available energy that would increase the in-cylinder work and the amount of energy carried by the exhaust gases, which could be also utilized [6-7].

Material	Advantages	Disadvantages
Mullite	(1) High corrosion-resistance (2) Low thermal conductivity (3)Good thermal-shock resistance below 1273 K (4) Not oxygen-transparent	(1) Crystallization (1023-1273 K) (2) Very low thermal expansion coefficient

A major breakthrough in diesel engine technology has been achieved by the pioneering work done by Kamo and Bryzik [8-9]. Sekar and Kemo [10] developed an adiabatic engine for passenger cars and reported an improvement in performance to the maximum extent of 12%. Woschni et al. [11] state that 5% of the input fuel energy cannot be accounted for which is of the order of the expected improvements. Havstad et al. [12] developed a semi-adiabatic diesel engine and reported an improvement ranging from 5 to 9% in ISFC, about 30% reduction in the in-cylinder heat rejection. Prasad et al. [13] used thermally insulating material, namely partially stabilized zirconia (PSZ), on the piston crown face and reported a 19% reduction in heat loss through the piston.

Among possible alternative materials, one of the most promising is mullite. Mullite is an important ceramic material because of its low density, high thermal stability, stability in severe chemical environments, low thermal conductivity and favorable strength and creep behavior. It is a compound of SiO_2 and Al_2O_3 with composition $3Al_2O_3.2SiO_2$. Compared with YSZ, mullite has a much lower thermal expansion coefficient and higher thermal conductivity, and is much more oxygen-resistant than YSZ. For the applications such as diesel engines where the surface temperatures are lower than those encountered in gas turbines and where the temperature variations across the coating are large, mullite is an excellent alternative to zirconia as a TBC material. Engine tests performed with both materials show that the life of the mullite coating in the engine is significantly longer than that of zirconia.[14-15] Above 1273 K, the thermal cycling life of mullite coating is much shorter than that of YSZ.[16] Mullite coating crystallizes at 1023–1273 K, accompanied by a volume contraction, causing cracking and de-bonding. Mullite has excellent thermo-mechanical behavior; however its low thermal expansion coefficient creates a large mismatch with the substrate [17]. To address this problem, a 150 μm thickness of NiCrAlY bond coat was used.

Materials	Properties
Mullite	Tm=2123 K
	λ=3.3 W m^{-1} K^{-1} (1400 K)
	E=30 GPa (293 K)
	α =5.3x10^{-6} K^{-1} (293–1273 K)
	υ=0.25
NiCrAlY (Bond coat of TBC)	E=86GPa(293K)
	α =17.5x10^{-6} K^{-1} (293–1273K)
	υ=0.3

TABLE I: PROPERTIES OF TBC MATERIALS [18]

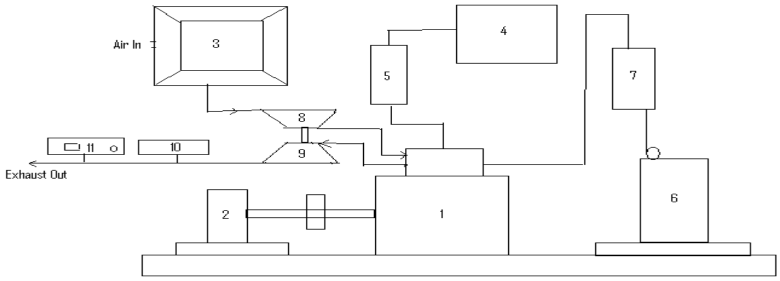
TABLE II: TBC MATERIAL AND ITS CHRACTERISTICS

II. EXPERIMENTAL SETUP

A four stroke, direct injected, water-cooled, single cylinder, naturally aspirated diesel engine will be used for investigation. Details of the engine specifications are

Engine type	Kirloskar AV1, DI
Stroke number	4
Cylinder number	1
Bore (mm)	80
Stroke (mm)	110
Compression ratio	16.5:1
Maximum engine power (KW)	3.7
Maximum engine speed (rpm)	1500
Specific fuel consumption (g/Kwh)	245
Injection timing	20 BTDC static

III. EXPERIMENTAL SETUP



Note: 1.Engine; 2. Dynamometer; 3. Damping box with orifice; 4.Fuel tank; 5. Burette with measuring scale; 6.Water tank; 7.Rotameter; 8.Centrifugal Compressor; 9. Radial flow Turbine; 10.Calorimeter; 11.AVL 444 Di-gas analyzer.

The experiments were conducted at five load levels, viz. 0, 25, 50, 75% of full load and full load. Nitrous oxides (NO_x), carbon monoxide (CO), hydrocarbon (HC), and carbon dioxide (CO_2) were measured by an AVL 444 Di-gas analyzer.

IV.PLASMA SPRAY TECHNIQUE

A piston crown, cylinder head and valves were coated with 0.5 mm coating of Mullite is commonly denoted as $3Al_2O_3 . 2SiO_2$ (i.e. 60 mol% Al_2O_3). However it is actually a solid solution with the equilibrium composition limits of 60 – 63mol % Al_2O_3 below 1600^o C. The ceramic material was coated by using plasma-spray technique [20].

V. RESULT AND DISCUSSION

A long term experimental study has been conducted on a single cylinder, direct injection Diesel engine. The standard engine (without TBC) and its LHR version with and without turbocharger have been used in the experiments. For LHR engine without turbocharger a compressor has been installed between air box and engine to boost the air pressure and to maintain constant A/F ratio as in standard engine. A comparative evaluation has been made based upon engine performance, brake specific fuel consumption (BSFC), exhaust gas temperature and energy balance for SE and LHR engine with and without turbocharger.

The increase in combustion pressure and temperature values of LHR engine with turbocharger compared to LHR engine without turbocharger are mainly due to introduction of air into an engine cylinder at higher density than ambient at higher operating temperature. This allows a proportional increase in the fuel that can be burned and hence raises the in cylinder gas pressure and temperature of LHR engine with turbocharger. Domkundwar et al

[21] reported, in his textbook, increase in maximum pressure for supercharged engine is about 26.66% higher than the unsupercharged engine.

Ceramic coated combustion chamber reduced heat transfer to the coolant. In case of LHR engine with turbocharger, the heat transfer rate is lower as compared to conventional engine. However, in case of LHR engine, the heat flow is restricted than conventional engine due to effect of thermal insulation coating. This leads to lower the temperature difference between cylinder surfaces and the combustion gas. Finally, it leads to lower the heat transfer. Kamo R, et al [22] reported 70% reduction in heat transfer in case of LHR engine with turbocharger and Morl et al [23] reported, in their investigation for turbocharged truck engine, about 60% reduction in heat transfer through LHR engine.

A. *Specific fuel consumption*

It is observed that, in case of LHR engine with turbocharger at all loads; the brake specific fuel consumption is lower than the LHR engine without turbocharger. In case of LHR engine with turbocharger, brake specific fuel consumption is lower by about 2.18% than conventional engine without turbocharger at full load. It is due to fact that, engine with turbocharger exhibits higher pressure and temperature resulting lower specific fuel consumption for entire load operation. Kamo R, et al [22] reported 10% improvement in BSFC in case of adiabatic turbo-compound engine. Hoag et al [24] have shown 2% decrease in BSFC for turbocharged engine. Tovell et al [25] reported, 7.5% improvement in ISFC, French et al [26] reported, 9% improvement in BSFC for LHR turbocharged engine over base line engine.

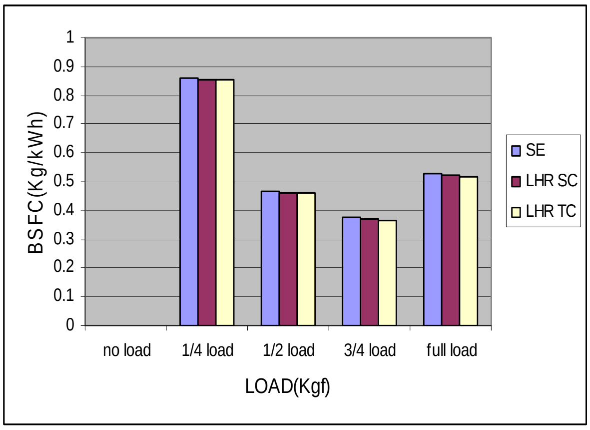


FIG.1 LOAD VS BSFC

B. *Nitrogen oxide (NO_x) emissions*

Figure 2 shows NO_x variations depending on the load of the engine. An increase in after-combustion temperature causes an increase in NO_x emission. All factors facilitating and accelerating the reaction between oxygen and nitrogen increase NO_x formation. The main factor in the NO_x formation is temperature. However, engine speed, combustion chamber content, combustion chamber homogeneity, and mixture density in the combustion chamber are also factors. Fig. shows NOx emission increases with increasing engine load. The increase of NO_x for in the LHR engine may be a result of an increase in after-combustion temperature due to the ceramic coating. Most of the earlier investigations showed that NO_x emission from LHR engines is generally higher than in water cooled engines. This is due to higher combustion temperature and longer combustion duration. A noticeable increase in the NOx emission was observed in the LHR engine with the turbocharger operation. This is due to the fact that application of turbocharger provides more air to the engine and causes a higher combustion temperature which yields an increase in the formation of NOx emission.

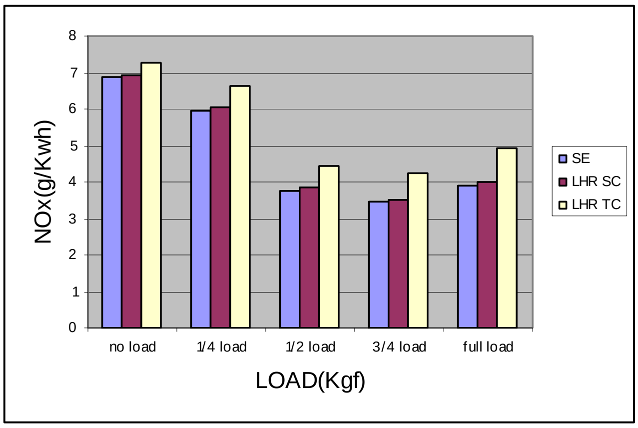


FIG.2 Load Vs NOx emission

C. *Hydrocarbon (HC) emissions*

Figure 3 shows variations of HC emissions depending on the load of the engine. HC emission is low in the LHR engine with turbocharger compared with the standard engine. The decrease in HC emission in the LHR engine with turbocharger may be due to an increase in after-combustion temperature as a result of the decrease in heat losses going to cooling and outside due to the ceramic coating, causing more unburned HC to be added to the combustion. Thus, the results clearly indicate that the ceramic coating improves local conditions specifying temperature, pressure, mixture ratio, and amount of oxygen, affects combustion, and makes the combustion continuous in diesel engines. The emission of unburned hydrocarbon from the LHR engine with turbocharger is more likely to be reduced because of the decreased quenching distance and the increased lean flammability limit. The higher temperatures in the gases and at the combustion chamber walls of the LHR engine assist in permitting the oxidation reactions to proceed close to completion. Most of the investigations reported reduction in HC level.

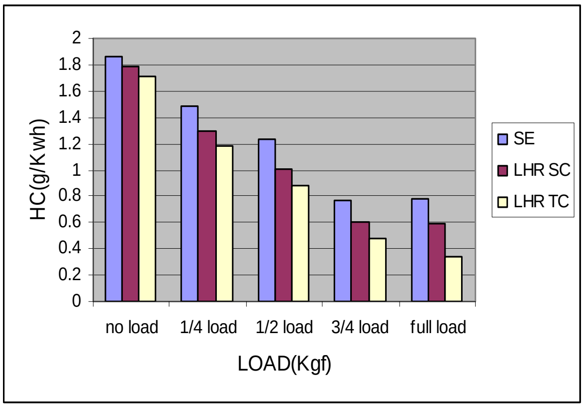


Fig.3 Load Vs HC emission

D. *Carbon monoxide (CO) emissions*

Figure 4 shows CO variations depending on the load of the engine. CO emission from diesel engine is related to the fuel properties as well as combustion characteristics. It is well known that better fuel combustion usually resulted in lower CO emission. It was experimentally determined that LHR engine with turbocharger causes a noticeable reduction in CO emission. This is due to the fact that application of turbocharger provides increased air in the engine and enables mixing of fuel-air easily in the combustion chamber, thereby causing better combustion and lower CO emission values.

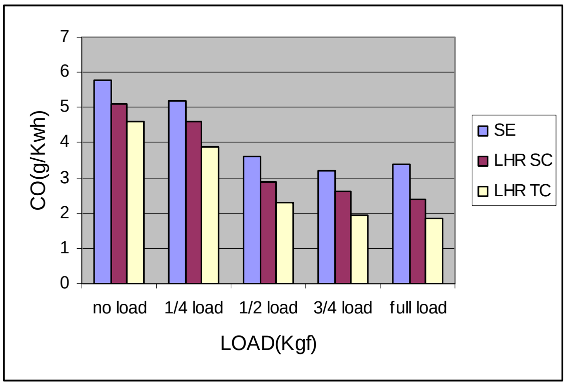


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Fig.4 Load Vs CO emission

D. *Exhaust gas Temperature*

Figure 5 shows variations of exhaust gas temperature depending on the load of the engine. As shown in Fig. exhaust gas temperature increases as the engine load increases for SE and LHR engine. The increase in exhaust gas temperature in the SE compared with the LHR engine with turbocharger may be due to decrease in heat losses going into the cooling system and outside due to the coating and due to increase in amount of fuel burnt per unit time.

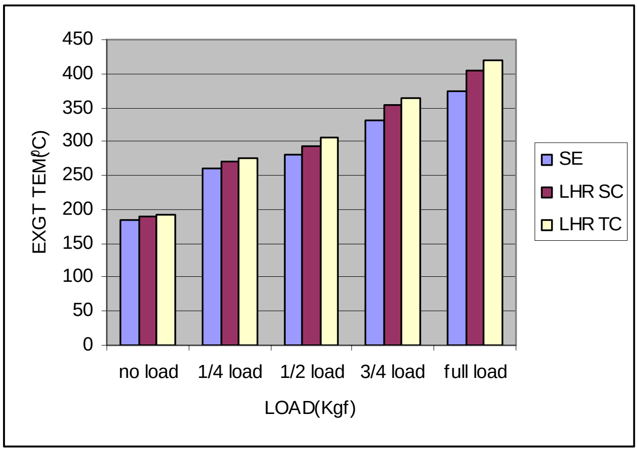

FIG.5 LOAD VS EXHAUST GAS TEMPERATURE

VI. CONCLUSION

The results showed that, increasing the brake thermal efficiency and decreasing the specific fuel consumption for LHR engine with turbocharger compared to the standard engine. There was increasing the NOx emission and exhaust gas temperature for LHR engine with turbocharger. However there was decreasing the CO and HC emissions for LHR engine with turbocharger compared to the standard engine.

APPENDIX

Tm : melting point;
υ : Poisson’s number;
E : Young’s modulus;
α : thermal expansion coefficient;
λ : thermal conductivity;
SC : supercharger;
LHR : low heat rejection;
SE : standard engine;

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