EXPERIMENTAL INVESTIGATION ON PERFORMANCE OF SINGLE CYLINDER 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 3Al2O3 .2SiO2 (mullite) (Al2O3= 60%, SiO2= 40%) over a 150 µm thickness of NiCrAlY bond coat. The working conditions for the standard engine (uncoated) and low heat rejection (LHR) engine were kept exactly same to ensure a comparison between the two configurations of the engine. This paper is intended to emphasis on energy balance with and without ceramic insulation coating at identical conditions. Tests were carried out at same A/F ratio for both standard and low heat rejection engine at different engine load and engine speed conditions. The results showed that there was 1.07 % decreasing on specific fuel consumption value of low heat rejection (LHR) engine compared to standard engine at full load. However, there was as much as 16 % decreasing on heat amount to coolant of LHR engine compared to standard engine at full load. There was as much as 22 % increasing on heat amount to exhaust of LHR engine compared to standard engine at full load.

***KEYWORDS**: Energy balance, Ceramic coating, Mullite, LHR, SE*

1.0 INTRODUCTION

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 (Alkidas, 1989 and Uzun., 1999). 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 (Hejwowski *et.al*., 2002 and Toyama *et.al*., 1983).

A major breakthrough in diesel engine technology has been achieved by the pioneering work done by (Kamo *et.al*., 1978 and Kamo *et.al*., 1979). Kamo and Bryzik used thermally insulating materials such as silicon nitride for insulting different surfaces of combustion chamber. An improvement of 7% in the performance was observed (Kamo *et.al*., 1978). Sekar *et.al*, 1984 developed an adiabatic engine for passenger cars and reported an improvement in performance to the maximum extent of 12%. The experimental results of (Morel *et.al*., 1985) indicate that the higher temperatures of the insulated engine cause reduction in the in-cylinder heat rejection, which is in accordance with the conventional knowledge of convective heat transfer. (Woschni *et.al*., 1987) state that 5% of the input fuel energy cannot be accounted for which is of the order of the expected improvements. (Havstad *et.al*., 1986) 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*., 1990) 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 Yttria-stabilized zirconia (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 (Kokini *et.al*., 1996 and Yonushonis, 1997). Above 1273 K, the thermal cycling life of mullite coating is much shorter than that of YSZ (Ramaswamy *et.al*., 1999). 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 (Samadi *et.al*., 2005). To address this problem, a 150 μm thickness of NiCrAlY bond coat was used.

TABLE 1 Properties of TBC materials (Cao *et.al*., 2004)

Materials	Properties
Mullite	Melting point (Tm) =2123 K Thermal conductivity(λ) =3.3 W m^{-1} K^{-1} (1400 K) Young's modulus (E)=30 GPa (293 K) Thermal expansion coefficient (α) =5.3x10^{-6} K^{-1} (293–1273 K) Poisson's number (υ) =0.25
NiCrAlY (Bond coat of TBC)	Young's modulus (E) =86GPa(293K) Thermal expansion coefficient (α) =17.5x$10^{-6}$$K^{-1}$ (293–1273K) Poisson's number (υ)=0.3

TABLE 2 Thermal conductivity and thermal resistance for mullite at various temperatures (Gilbert *et.al*.,2008)

Material	Thermal conductivity (W/m k)			Thermal Resistance R_{th} (K/W)		
	296K	773K	1273K	296K	773K	1273K
Mullite	1.05	1.23	1.39	8.8	7.6	6.7

TABLE 3 TBC materials and their characteristics

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

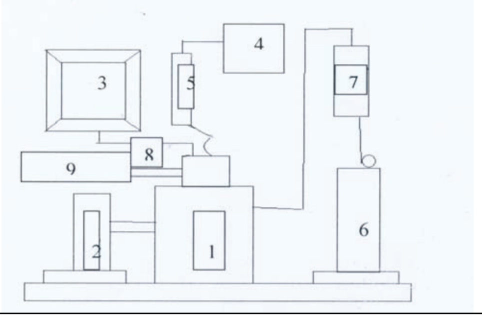
The main purpose of this study was to evaluate the energy balance at different engine loads and speeds with and without ceramic-coated diesel engine. Experiments were conducted with single cylinder, direct injected, inter-cooled diesel engine to evaluate heat losses to oil, ambient and cooling system of ceramic coated engine (LHR).

2.0 EXPERIMENTAL SETUP

A four stroke, direct injected, water-cooled, single cylinder, naturally aspirated diesel engine was used for investigation. Details of the engine specifications are given in Table 4.

TABLE 4 Engine specifications

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 Before Top Dead Center(BTDC) static



Note:
1. Engine 2. Rope break dynamometer 3. Damping box with orifice 4. Fuel Tank
5. Burette with measuring scale 6.Water Tank 7. Rotameter
8. Reciprrocating compressor as pressure booster 9. Calorimeter

FIGURE 1 Experimental Set up

The first stage tests were performed at different engine loads. The experiments were conducted at five load levels, viz. 0, 25, 50, 75% of full load and full load. The required engine load percentage was adjusted by using the rope break dynamometer. The second stage concerned an investigation of heat losses when combustion chamber insulation was applied. A piston crown, cylinder head and valves were coated with ceramic material over super alloy bond coating (NiCrAlY). The bond coat was first applied to these engine components to avoid mismatch in thermal expansion between substrate and ceramic material. 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. The engine were insulated and tested at baseline conditions to see the effect of insulated surfaces on engine heat losses. The ceramic-coated engine (LHRE) was compared to standard engine.

3.0 PLASMA SPRAY TECHNIQUE

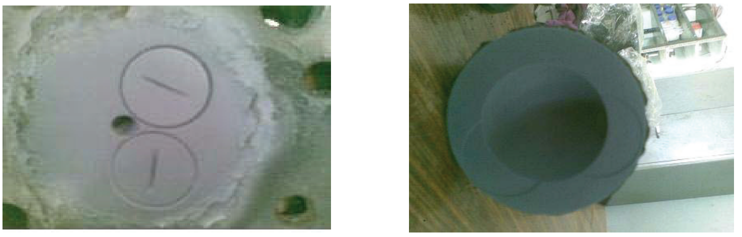


FIGURE 2 Photographic view of Cylinder head, Cylinder valves and Piston crown after ceramic coating.

The gas tunnel type plasma spraying torch was used. The experimental method to produce ceramic coating by means of the gas tunnel type plasma spraying is as follows. After igniting plasma gun, the main vortex plasma jet is produced in the low pressure gas tunnel. The spraying powder is fed from central inlet of plasma gun. The coating was formed on the substrate traversed at the spraying distance L. The power input to the plasma torch was about P= 25 KW. The current and voltage applied was about 837 amp and 37.3 volts respectively. The inputs were given by Miller Thermal, lnc. Model 3702. The power input to the pilot plasma torch, which was supplied by power supply PS1, was turned off after starting of the gas tunnel type plasma jet. The spraying distance was short distance of L=40 mm. The working gas was Argon gas, and the flow rate for gas tunnel type plasma spraying torch was Q= 180 l/min, and gas flow rate of carrier gas was 10 l/min (Arata *et.al*., 1986).

4.0 RESULT AND DISCUSSION

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

Table 5 and 6 shows energy balance at various loads for standard and low heat rejection diesel engine respectively. It can be observed from the tables that the percentage of heat lost to the coolant and miscellaneous heat losses are less for LHR engine as compared with standard engine due to coating of low thermal conductivity material on substrate. The percentage of heat lost to the exhaust gases is more for LHR engine as compared with standard engine due to increase of combustion temperature.

TABLE 5 Energy balance at various loads for standard diesel engine (SE)

	No load	¼ load	½ load	¾ load	Full load
Energy supplied, kW	4.28	6.83	8.93	10.49	17.29
Brake power,kW	0	0.68	1.65	2.4	2.8
Heat lost to Exhaust gases, kW	0.6206	1.1935	1.5979	2.525	3.35205
Heat lost to coolant, kW	1.7976	2.8686	3.2148	3.3568	4.8412
MiscellaneousLosses, kW	1.8618	2.0879	2.4673	2.2082	6.29675
BSFC, Kg/kWh	0	0.860924	0.463896	0.374643	0.529286

TABLE 6 Energy balance at various loads for low heat rejection (LHR) diesel engine

	no load	¼ load	½ load	¾ load	full load
Energy supplied, kW	4.28	6.83	8.93	10.49	17.29
Brake power,kW	0	0.685	1.6665	2.427	2.83
Heat lost to Exhaust gases,kW	0.6448	1.3243	1.9646	3.21	4.31
Heat lost to coolant, kW	1.7976	2.8686	3.0362	2.9372	4.1496
Miscellaneous Losses, kW	1.8376	1.9521	2.2642	1.9158	6.0004
BSFC, Kg/kWh	0	0.85464	0.459717	0.370475	0.523675

At all load levels, the reduction in heat rejection mostly resulted in an increase in exhaust energy. The exhaust energy was increased by 9, 18, 21 and 22% with LHR engine at 25, 50, 75% of full load and full load condition respectively compared to standard engine.

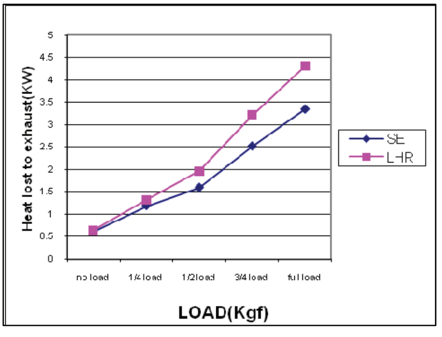


FIGURE 3 Load vs Heat lost to exhaust gas

Ceramic coated combustion chamber reduced heat transfer to the coolant. LHR engine resulted 0, 5, 14 and 16% reduction in heat transfer to the coolant for 25, 50, 75% of full load and full load condition respectively compared to standard engine. This is due to fact that ceramics have a much lower thermal conductivity than metals so that the energy flow to the coolant will be reduced which results in higher combustion temperature.

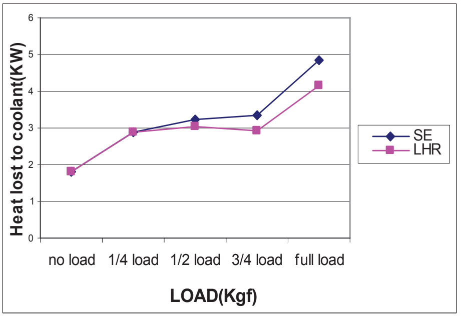


FIGURE 4 Load vs Heat lost to coolant

The higher combustion temperature will lead to more expansion work. The increase of combustion temperature causes the brake power to increase up to 1.06% with LHR engine at full load condition compared to standard engine. It can be seen that the values of brake power are slightly higher for LHR engine as compared to standard engine.

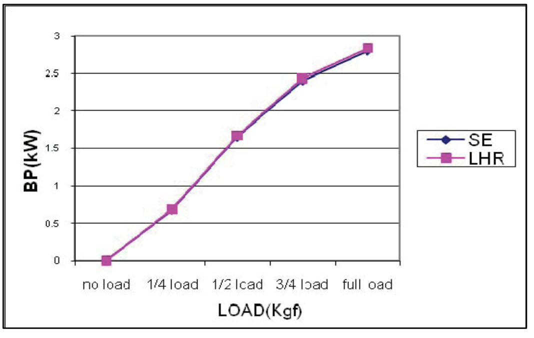


FIGURE 5 Load vs BP

A comparison of BSFC for standard and LHR engine for all loads is as shown in fig. Because of higher surface temperatures of combustion chamber of LHR engine, the BSFC values of LHR engine were lower than those of standard engine. It was observed that BSFC value was decreased by 1.07% for LHR engine as compared to standard engine at full load.

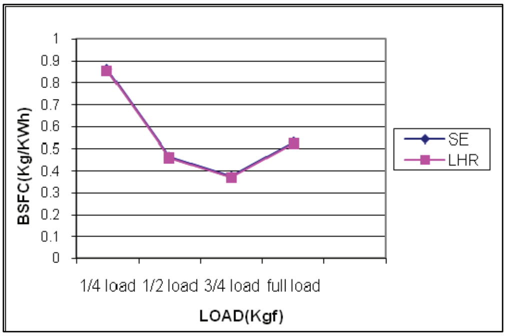


FIGURE 6 Load vs BSFC

The combustion chamber insulation causes the Qmisc (heat rejected to the oil plus convection and radiation from the engine's external surface) to drop at medium and high load conditions for the LHR engine. Percentage heat rejection to ambient and oil decreases from 1-8% for LHR engine as compared to standard engine.

5.0 CONCLUSION

The following conclusions were drawn from this investigation that used a single cylinder, direct-injected, inter-cooled LHR diesel engine (mullite coated).

1. In case of standard engine (without coating), the heat loss to exhaust gas was about 22 % higher than that of the LHR engine at full load.
2. The heat loss to the coolant gas was about 16 % less for LHR engine than the standard engine at full load.
3. Thermal efficiency was slightly more for LHR engine than the standard engine.
4. Insulation increases the cylinder wall temperature which increases exhaust gas energy. It can beharnessed to increase the net power output of the system, thus raising the thermal efficiency and decreasing specific fuel consumption. Turbo compounding can be incorporated in order to effectively recover the exhaust energy increased by heat insulation, as the shaft output.
5. Drop in volumetric efficiency for LHR engine than the standard engine. It can be increased by using turbocharger.

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