Comparative Study of Performance and Combustion Characteristics of Conventional and Low Heat Rejection (Mullite Coated) Diesel Engines

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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 $3\text{Al}_2\text{O}_3\cdot2\text{SiO}_2$ (mullite) $(\text{Al}_2\text{O}_3 = 60\%, \text{SiO}_2 = 40\%)$ over a 150 µm thickness of NiCrAlY bond coat. The working conditions for the conventional engine (without coating) and LHR (mullite coated) engine were kept exactly same to ensure a comparison between the two configurations of the engine. This paper is intended to emphasis on performance and combustion characteristics of conventional and LHR (Mullite coated) diesel engines under identical conditions. Tests were carried out at same operational constraints i.e. air-fuel ratio and engine speed conditions for both conventional engine (without coating) and LHR (mullite coated) engines. The results showed that, there was as much as 1.8 % increasing on brake power for LHR (mullite coated) engine compared to conventional engine (without coating) at full load. The average decrease in brake specific fuel consumption in the LHR engine compared with the conventional engine was 1.76 % for full engine load. However, there was increasing on cylinder gas pressure and net heat release rate for LHR engine compared to conventional engine. Also the results revealed that, there was as much as 22% increasing on exhaust gas temperature for LHR engine compared to conventional engine at full engine load.

Keywords: Performance characteristic; ceramic coating; Mullite; LHR; SE

1. 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 supermi, 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]. A major breakthrough in diesel engine technology has been achieved by the pioneering work done by Kamo and Bryzik [8-9]. Kamo and Bryzik used thermally insulating materials such as silicon nitride for insulating different surfaces of combustion chamber. An improvement of 7% in the performance was observed [10]. Sekar and Kamo [11] developed an adiabatic engine for passenger cars and reported an improvement in performance to the maximum extent of 12%. The experimental results of [12] 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 [13] state that 5% of the input fuel energy cannot be accounted for which is of the order of the expected improvements. Havstad [14] 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 [15] 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 has 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$_2$O$_3$ with composition $3\text{Al}_2\text{O}_3.2\text{SiO}_2$. 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 [16-17]. Above 1273 K, the thermal cycling life of mullite coating is much shorter than that of YSZ [18]. 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 [19]. To avoid the mismatch with the substrate, a 150 µm thickness of NiCrAlY bond coat was used.

| Table 1: Properties of Bond coat material and mullite material was used as thermal barrier coating (TBC) for diesel engine |
|---------------------------------------------------------------|
| **Material Properties**                                      | **NiCrAlY** | **Mullite** |
| Modulus of elasticity (GPa)                                  | 64.5        | 19         |
| Poisson’s ratio                                              | 0.30        | 0.25       |
| Thermal conductivity (W/mK) @ RT                            | 3.88        | 1.29       |
| Coefficient of thermal expansion ($\times 10^{-6}$K$^{-1}$) @ RT | 10.3        | 5.1        |
| Density (Kg/m$^3$)                                           | 6290        | 2710       |
| Specific heat (J/kg K) @ RT                                  | 460         | 760        |
2. 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 2.

| 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 Centre(BTDC) static |

Note: T1, T3-Inlet Water Temperature, T2- Outlet Engine Jacket Water Temperature, T4-Outlet Calorimeter Water Temperature, T5-Exhaust Gas Temperature before Calorimeter, T6- Exhaust Gas Temperature after Calorimeter, F1-Fuel Flow DP (Differential Pressure) unit, F2- Air Intake DP unit, PT- Pressure Transducer, N- RPM Decoder, EGA- AVL Di-Gas Analyzer (5 gas), SM - AVL Smoke meter.

The first stage tests were performed at different engine loads for conventional engine. 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 eddy current dynamometer. At each of these loads, engine performance and combustion characteristics such as brake power, brake thermal efficiency, brake specific fuel consumption, exhaust gas temperature, cylinder gas temperature and net heat release rate were recorded. The second stage tests were conducted on engine 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 3Al₂O₃ 2SiO₂ (i.e. 60 mol% Al₂O₃). The ceramic material was coated by using plasma-spray technique. The engine was insulated and tested at baseline conditions to see the effect of insulated surfaces on engine performance and combustion characteristics. In present investigation, a centrifugal blower was used for LHR (mullite coated) diesel engine to maintain air-fuel ratio nearly same as in conventionally cooled (without coating) diesel engine. Thus the working conditions for the conventional engine (without coating) and LHR (mullite coated) diesel engine were kept exactly same to ensure a comparison between the two configurations of the engine.

The results of performance and combustion characteristics of LHR engine were compared with the conventional engine.

3. Plasma Spray Technique:

![Figure 2: Photographic view of Cylinder head, Cylinder valves and Piston crown after ceramic coating.](image)

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, Inc. Model3702. 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 [20].

4. Results and Discussions:

After conducting long-term experimental investigations on a single cylinder, four stroke, direct injection, conventional (without coating) and LHR (mullite coated) diesel engines, the engine performance and combustion characteristics such as brake power, brake thermal efficiency, brake specific fuel consumption, exhaust gas temperature, cylinder gas temperature and net heat release rate for both the Conventional and LHR engines are evaluated. The engine performance and combustion characteristics are evaluated for 25, 50, 75% of full engine load and full engine load condition for both conventional and LHR diesel engines.
Figure 3 Shows the comparison of brake power as a function of engine load for conventional and LHR (mullite coated) diesel engines. It is observed that, the values of brake power are slightly higher for LHR (mullite coated) engine as compared to conventional engine. This is due to effect of insulation; the heat free flow is restricted, which leads to reduction in heat transfer in case of LHR engine. The reduction in heat transfer leads to increase in combustion temperature, which leads to better combustion. The higher combustion temperature will lead to more expansion work. The increase of combustion temperature causes the brake power to increase up to 1.8 % with LHR engine at full engine load condition compared to conventional engine.

A comparison of BSFC for conventional and LHR engine for all loads is as shown in figure 4. Because of higher surface temperatures of combustion chamber of LHR engine, the BSFC values of LHR engine are lower than those of conventional engine. The improvement in fuel economy achieved by LHR engine may be attributed to: higher premixed combustion, lower diffused combustion, reduced heat transfer loss and higher rate of heat release in the main portion of combustion. It is observed that BSFC value is decreased by 1.76 % for LHR (mullite coated) engine as compared to conventional engine at full engine load.
It is also evident from figure 5 that, the amount of increase in thermal efficiency for LHR engine with 0.5 mm thickness of mullite insulation is 1.8 % compared to conventional engine at full engine load while at low and medium loads thermal efficiency shows slight variation for LHR engine when compared to the conventional engine. The reason is heat recovered by the insulation, which is normally lost to the cooling, is converted into indicated work. But all the heat recovered by the insulation perhaps may not be able to get converted into useful work. Hence, the rate of increasing thermal efficiency for LHR engine is marginal compared to conventional engine.

![Figure 5: Engine Load Vs Brake Thermal Efficiency](chart)

Figure 6 shows the comparison of cylinder gas pressure as a function of crank angle for conventional and LHR engines with 0.5 mm coating of mullite thermal insulation on combustion chamber. It is observed that, the peak of gas pressure curve occurs 58.0 bars for conventional engine while for LHR (mullite coated) engine the peak of gas pressure curve occurs 58.88 bars. The increase in peak of gas pressure for LHR engine is due to elevated temperature of the insulated engine and better combustion of fuel.

![Figure 6: Crank Angle Vs Cylinder Gas Pressure](chart)
Figure 7 shows the comparison of instantaneous heat release rate as a function of crank angle for conventional and LHR engines with 0.5 mm insulation coating of mullite on combustion chamber. The trend shows that, the LHR engines are exhibiting a higher rate of heat release. The reason for high rate of heat release is due to insulation, the higher heat retainment inside the combustion chamber is exhibited. This leads to evaporate the fuel at faster rate, which helps possibly to better premixing, reduced diffused combustion. Further, it results in complete combustion of fuel. Hence, it releases more amount of heat.

![Figure 7: Crank Angle Vs Heat Release Rate](image)

Figure 8 shows variations of exhaust gas temperature depending on the load of the conventional and LHR (mullite coated) engines. As seen in figure exhaust gas temperature increases as the engine load increases for both engines. This is due to the amount of fuel per unit time increases as the engine load increases, and consequently, more heat energy is produced. As a result, exhaust gas temperature increases. The increase in exhaust gas temperature in the LHR engine, compared with the conventional engine is 22% at full engine load. The increase in exhaust gas temperature for the LHR engine compared with the conventional engine may be due to the decrease in heat losses going into the cooling system and outside due to the coating and the transfer of this heat to the exhaust gas.
5. Conclusions:

The main conclusions drawn from present experimental investigation on LHR (mullite coated) and conventional diesel engines are as follows:

- **LHR engine with 0.5 mm of mullite** \(3\text{Al}_2\text{O}_3.2\text{SiO}_2\) insulation coating on piston crown, cylinder head and valves of diesel engine exhibits lower brake specific consumption than the conventional diesel engine. This insulation coating exhibits the brake specific consumption very close to conventional engine with deviation by about 1.76% higher at full engine load. This is due to effect of insulation; the heat free flow is restricted, which leads to reduction in heat transfer in case of LHR engine. The reduction in heat transfer leads to increase in combustion temperature, which leads to better combustion. The higher combustion temperature will lead to more expansion work.

- **LHR engine with 0.5 mm of mullite** \(3\text{Al}_2\text{O}_3.2\text{SiO}_2\) insulation coating on piston crown, cylinder head and valves of diesel engine gives marginal rise in brake thermal efficiency when compared with conventional diesel engine. The brake thermal efficiency for LHR engine is higher by about 1.8% than the conventional diesel engine at full engine load level. The insulation coating reduces the heat loss through combustion chamber resulting in increase in the charge temperature. This higher charge temperature leads to better combustion. However, this increased heat release is not converted into useful work in direct proportion but leaves with exhaust as seen from the rise in the exhaust temperature. It is observed that, the peak of gas pressure curve occurs 58.0 bars for conventional engine while for LHR (mullite coated) engine the peak of gas pressure curve occurs 58.88 bars. The increase in peak of gas pressure for LHR engine is due to elevated temperature of the insulated engine and better combustion of fuel.

- The LHR engines are exhibiting a higher rate of heat release compared with conventional engine. The reason for high rate of heat release is due to insulation, the higher heat retention inside the combustion chamber is exhibited. This leads to evaporate the fuel at faster rate, which helps possibly to better premixing, reduced diffused combustion. Further, it results in complete combustion of fuel. Hence, it releases more amount of heat.
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7. References:

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