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Low Heat Rejection Engine Coating Materials: A Critical Review

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Abstract— **The Low Heat Rejection Engine (LHR Engine) is a technology, which minimizes heat loss to the coolant by providing heat resistance in the heat flow to the coolant. The use of coating in the automotive industry has been found to yield a significant effect on the efficiency of engines. The challenge for Automobile is present emission norms that demands engine for green environment with high performance and low emission. The depletion of fossil fuel resources at a faster rate in the present world of economic competitiveness is generating an essential demand for increase in efficiency of internal combustion engines. Higher the operating temperature more will be the efficiency of the system. However, such higher temperatures demand for enhanced temperature resistant materials to be used. This paper presents a review on the various aspect and usage of thermal insulating materials (commonly known as thermal barrier coatings).**

Index Terms— **Low Heat Rejection Engine, TBC, ceramic coating, piston, cylinder liner, valves, Diesel Engine.**

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1 Introduction

The first use of Thermal barrier coating (TBC) was for aircraft engine performance. The concept of thermal barrier coating for diesel engines began in 1980s. Insulating the combustion chamber components of LHR engine can reduce heat transfer between in-cylinder gas and cylinder liner. The LHR concept is based on suppressing heat rejection to the coolant and recovering the energy in form of useful work. Some important advantages of LHR engines are improved fuel economy, reduced engine noise, higher energy in exhaust gases and multi-fuel capability of operating low Cetane fuels. The thermal barrier coated engine parts are piston, cylinder head, and cylinder liners and exhaust valves. The engine that thermal barrier coating is applied is called low heat rejection (LHR) engine. Thermal barrier coatings are used to improve reliability and durability of hot section metal components and enhance engine performance and efficiency in internal combustion engines. Thermal barrier coatings are usually composed of a bond coat (NiCrAl) as an oxidation resistant layer and stabilized Zirconia as a top coat that provides thermal insulation toward metallic substrate.

Average in-cylinder gas temperatures increase due to insulation in LHR engines. In compression stroke around TDC in-cylinder gas temperature increases by 250K in LHR engine in comparison to standard engine. This reduce ignition delay period of fuel injected to cylinders. So combustion starts before sufficiently mixing of air and fuel. Sun et al. reported that combustion characteristics of LHR diesel engines are different from standard diesel engines in four ways:

(a) Ignition delay period shortens
(b) Diffusion burning period increases while premixed burning period decreases
(c) Total combustion duration increases
(d) Heat release rate in diffusion burning period decreases.

Thermal barrier coatings offer the possibility of reducing particulate emissions Thermal barrier coatings decrease the amount of condensable hydrocarbons. Under low load and speed conditions the base engines produces plate like particles, the TBC engine produces smaller spherule particles.

The petroleum crisis and the subsequent increase in the cost of fuels, the improvement of fuels and the improvement of fuel economy of the I.C Engines has become a high priority to the researchers. Numerous investigations have modelled and analysed the effects of in-cylinder thermal insulation. Reducing heat rejection in reciprocating engines is a possible way of reducing fuel consumption. This may be possible by eliminating a part of the cooling system and incorporating high-temperature insulting materials in the combustion chamber to withstand the higher combustion gas temperature. The advent of high temperature, high performance ceramics has tempted engine researchers to strive for higher operating temperatures with subsequent higher engine thermal efficiency by reducing fuel consumption.

Problematic pollutants in emission of various vehicles are:

1. SO_2
2. NO_X, Nitrogen oxides
3. CO
4. CO_2
5. Certain hydrocarbons
6. Particulates.

2. Ceramic Coated Combustion Chamber

The engine exhaust temperature has increased in the case of TBC engine (from 4100C to 4280C) which promotes better energy recovery .The insulation of the combustion chamber with ceramic coating influences the performance and exhaust emissions of the CI engine. The insulation modifies the boundary

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conditions for the combustion process which in turn shortens the ignition delay period hence lowers the fuel consumption, reduces the heat loss and increases the exhaust temperature, which in turn influences the engine performance and emissions. Ceramic coatings provide potential for higher engine thermal efficiencies, longer life and higher reliability of engine components..ZrO2 stabilized with Y2O3 over NiCrAlY binding layer as a coating material gives good results for aluminium alloyed pistons. As ceramic coating material, ZrO2 stabilized with Y2O3 is expensive for practical usage. Cylinder walls also can be coated to reduce heat rejection.

Zirconia ceramics have attracted much attention since their discovery, and the materials, which are very strong and tough at room temperature, can be made by control of the phases. Understanding of the phase transitions is crucial to appreciate the properties of zirconia ceramics. Zirconium dioxide (ZrO 2) has a monoclinic crystallographic structure at ambient temperatures. Upon raising the temperature, the oxide undergoes the phase transitions from monoclinic to tetragonal with a transitional temperature of 1170 °C. From tetragonal to cubic, the transition temperature is 2370 °C. At 2680 °C and above, the material melts. The transformation from tetragonal to monoclinic phase with decreasing temperature at approximately 1170 °C is quite disruptive and renders pure ZrO2 unusable as a high-temperature structural ceramic. This disruption is caused by a 6.5% of volume expansion upon transformation from tetragonal to monoclinic phase, a change which could cause structural failure of any ceramic coating. The effects of Thermal barrier coating in internal combustion engine are listed below.

3. Methods Of Coating In I.C Engines.

Usage of tribological coatings in internal combustion engines have been increasing every day. Metal and metal alloy are needed in many fields due to fast developing technology. One of these fields is engines. With various methods combustion chamber elements are coated with coating materials in internal combustion engines. Thermal barrier coatings are used in order to increase reliability and strength of hot parts of metal components, increase yield and performance of engines. Engine parts which are coated with thermal barrier are; piston, cylinder head cylinder sleeve and exhaust valves. Engines with thermal barrier coating are called low heat loss engines

Different methods are used to coat the surface of metals. These methods differ according to characteristics of material to be used; suitable to the intended use.

1. Physical Vapour Decomposition (PVD)
2. Chemical Vapour Decomposition (CVD)
3. Ion Coating
4. Splash Coating
5. Electron Beam Evaporation Coating (EBE)
6. Flame Spray (FS)
7. Plasma Spray (PS)
8. Sol-gel (SG)
9. Detonation Gun (DG)
10. Reactive ion coating (IP)
11. Hot izostatical press coating (HIP)

Although several systems have been used as TBC for different purposes, Partially- Stabilized Zirconia has received the most attention. Plasma spray is the most common method of depositing TBCs for diesel engine applications.

Properties	Variation Type	Maximum variation amount (%)
Fuel consumption	Decrease	11
Engine lifetime	Increase	20
Engine power	Increase	10
Emission	Decrease	20-50
Particle	Decrease	52
Oil consumption	Decrease	15
Engine noise	Decrease	3 (db)
Reliability	Increase	----
Components temperature	Decrease	100 (°C)
Valves lifetime	Increase	300
Costs	Decrease	20

Table.1.The effects of Thermal barrier coating

From table 1 it is clear that the valves lifetime increases by 300 percent and the overall cost decreases by 20 percent. The decrease in oil consumption is around 15 percent. The engine which is the heart of internal combustion engine can be operated 10 percent more than the traditional engine. There will be an increase engine life time by 20 percent the overall fuel consumption decreases by 11 percent.

4. Thermal Barrier Coating Materials

The following are the requirements of thermal barrier coating for use in internal combustion engines. 1

1. High melting point
2. No phase transformation between room temperature and operation temperature,
3. Low thermal conductivity,
4. Chemical inertness,
5. Thermal expansion match with the metallic substrate,
6. Good adherence to the metallic substrate
7. Low sintering rate of the porous microstructure.

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So far, only a few materials have been found to basically satisfy these requirements. There are some ceramics which are used for thermal barrier coating below.

Zirconates

The main advantages of zirconates are their low sintering activity, low thermal conductivity, high thermal expansion coefficient and good thermal cycling resistance. The main problem is the high thermal expansion coefficient which results in residual stress in the coating, and this can cause coating delamination.

Yittria Stabilized Zirconia

7-8% yittria stabilized zirconia has high thermal expansion coefficient, low thermal conductivity and high thermal shock resistance.Disadvantages of yittria stabilized zirconia are sintering above 1473 K, phase transformation at 1443 K, corrosion and oxygen transparent.

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. Compared with yittria stabilized zirconia, mullite has a much lower thermal expansion coefficient and higher thermal conductivity, and is much more oxygenresistant than yittria stabilized zirconia. The low thermal expansion coefficient of mullite is an advantage relative to yittria stabilized zirconia in high thermal gradients and under thermal shock conditions. However, the large mismatch in thermal expansion coefficient with metallic substrate leads to poor adhesion.The other disadvantage of mullite is crystallization at 1023-1273K.

Alumina

It has very high hardness and chemical inertness. Alumina has relatively high thermal conductivity and low thermal expansion coefficient compared with yittria stabilized zirconia. Even though alumina alone is not a good thermal barrier coating candidate, its addition to yittria stabilized zirconia can increase the hardness of the coating and improve the oxidation resistance of the substrate.

The disadvantages of alumina are phase transformation at 1273K, high thermal conductivity and very low thermal expansion coefficient.

Spinel

Although spinel has very good high temperature and chemical properties, its thermal expansion coefficient prevents its II-176 usage as a reliable choice for thermal barrier coatings.

Forsterite

The high thermal expansion coefficient of forsterite permits a good match with the substrate. At thicknesses of some hundred microns, it shows a very good thermal shock resistance.

5. TBC Coating In Piston

The performance and emission effects of thermal barrier coating used in piston investigated experimentally by laksmanan. Thermal barrier coating used in piston increasing the brake thermal efficiency and decreasing the specific fuel consumption for Light heat Rejection engine with thermal coated piston compared to the standard engine. There was increasing the NOx emission and O2 for thermal barrier coated engine. However there was decreasing the CO and HC emissions for thermal coated piston engine compared to the standard engine.

TBC, using PSZ, applied to the combustion chamber of the internal combustion engine showed some improvement in fuel economy with a maximum of up to 4% at low engine power.

The peak cylinder pressures were increased by a magnitude of eight to ten bars in the TBC piston engine, in particular at high engine power outputs, though the exhaust gas temperatures were generally lower, indicating good gas expansion in the power stroke. The unburned hydrocarbon concentrations were increased most seriously at low engine speed and/or low engine power output with a TBC piston engine. The authors suspected that this could be due to the porous quenching effect of the rough TBC piston crowns, where oxidation of hydrocarbons was unable to be achieved by the combustion air. Sampling of cylinder pressures in the cylinders showed that the ignition point of the TBC piston engine advanced slightly relative to the baseline engine, indicating the improvement in ignitability and heat release before the top dead center, which caused the peak cylinder pressure to rise.

6. TBC Coating In Cylinder Liner

At present TBCs are applied to combustion components of IC engines, mainly for pistons crow, valves, cylinder cover, and cylinder liner. However, the extended application of TBC to cylinder liner has not been explored practically. Cylinder liner is one of the important components of IC engine which severely under goes wear and tear due to reciprocating motion of piston. At the same time, linear as subjected to thermal stresses caused by hot gasses of combustion. TBC in the place of linear has to play very important role in minimizing wear and tear, heat transfer from cylinder to surroundings. The problem presently faced in implementing of TBC as engine cylinder is thermal mismatch which mainly occurs due to improper adhesion and difference in thermal expansion coefficient between bond coat and cylinder materials. TBC must also withstand wear and tear.There is a need to overcome these problems for employing TBC to engine cylinder as a liner the present work is undertaken with the following main objects.

1. To search a proper bond coatings and top coat materials based on composition of substrates.
2. Selection of proper coatings techniques.
3. Preparation of plasma sprayed coated samples for various tests.

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4. To check the microstructure and Topology of coating.
5. To check the surface texture parameter of coating.
6. To determine the bond strength of coating.
7. To determine micro hardness of coating.
8. To determine abrasive wear of coating.
9. To determine erosion wear of coating.
10. To establish the suitability of coatings for its application in internal combustion Engine as a linear.

7. Thermal Barrier Coating In Diesel Engine

The major advantages of thermal barrier coatings for diesel engines are low cetane fuels can be burnt, improvements occurs at emissions except NOx, waste exhaust gases are used to produce useful shaft work, increased effective efficiency, increased thermal efficiency, using lower-quality fuels within a wider distillation range, ignition delay of the fuel is considerably reduced, faster vaporization and the better mixing of the fuel, reduced specific fuel consumption, multi-fuel capability, improved reliability, Smaller size, lighter weight, decreased the heat removed by the cooling system, first start of engine on cold days will be easier, decreasing knocking and noise caused by combustion.

The below figure 1 show that possibilities of thermal barrier coating are used in diesel engine combustion chamber.

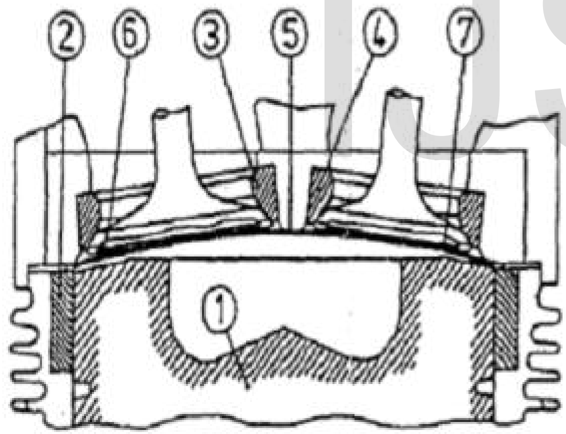

Fig.1. Diesel engine combustion chamber

1. piston head, 2 cylinder liner, 3. Seating of intake valve, 4. Seating of exhaust valve, 5. Cylinder head, 6.intake valve and 7.exhaust valve

Thermal barrier coating with fuel additive drastically reduce the exhaust emission, it proves by following experimental results (32).

1. The thermal efficiency slightly improves due to the effect of thermal barrier coating. The fuel additive with 1.0% shows better performance than other concentration.
2. Smoke level is found higher in thermal barrier coated engine. At the maximum brake power, the smoke level was slightly increased in the fuel additive plus thermal barrier coated engine.
3. Comparing with standard engine the NOx will be reducing about 500 ppm for TBC engine. By introduction of fuel additives to the TBC engine, it was further reduced by 100 ppm of NOx emission.
4. The heat release rate slightly decreases due to the effect of coating and coating plus fuel additives.

8. Surface Ignition System

Methyl alcohol and Ethyl alcohols can also be ignited in a diesel in a diesel engine with the help of surface ignition. In this type of ignition, the injected fuel ignites not by compression ignition but by contact with the hot surface maintained within the engine. Since Methanol and Ethanol are very susceptible to surface ignition {pre-ignition in SI engines), this method is suitable to these fuels. The hot surface ignition engine is reported to have better multi fuel capability than its spark assisted counterpart.

9. Modification of test engines

Use of ethanol in diesel engines is associated with problems on account of their low cetane numbers, low viscosity and poor miscibility with diesel, higher latent heat of evaporation and also need a compression ratio of 23:1 for starting and 20:1 for normal running. To use ethanol in diesel engine assistance in the form of a timed spark or a hot surface is needed. In the present investigation, glowplug was used for ignition assistance. Ethanol was used as a sole fuel in the normal and LHR engine to study the characteristics of glowplug assisted ceramic coated engine.

Plasma spray process

Material in the form of powder is injected into very high temperature plasma flame, where it is rapidly heated and accelerated to a high velocity. The hot material impacts on the substrate surface and rapidly cools forming a coating. Plasma gun comprises a copper anode and tungsten cathode, both of which are water cooled. Plasma gas (argon, helium, nitrogen, hydrogen) flows around the cathode and through the anode which is shaped as a constricting nozzle. Atmospheric plasma spray coating method was used to coat the combustion chamber components. As for plasma gas, a mixture of argon (Ar) and nitrogen (N2) was used. The coating materials and the parameters of plasma spray are given in Table 2. The conventional combustion chamber of a diesel engine was insulated with yttria stabilized zirconia of 0.3 mm thickness. Thermal insulation of the combustion chamber was provided to have a hotter environment for the combustion of ethanol in order to avoid the problems that will occur due to the low ignition

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quality of ethanol and its latent heat of vaporization. Figure 1 shows the photographic view of insulated engine components. Cylinder head, piston, exhaust and inlet valves of the diesel engine used in the tests were coated with yttria stabilized zirconia ($Y2O3–ZrO2$). Engine piston, cylinder head and valves were coated by plasma spraying technique. The thickness of coating was selected as 0.3 mm, within the optimum range of thickness 0.1–1.5 mm. Cylinder liner was not coated because of very negligible area. Combustion chamber geometry was maintained by machining the components before ceramic coating. In the conventional diesel engine the hot air that prevails at the end of compression stroke is sufficient for igniting the diesel fuel. But due to higher self-ignition temperature of ethanol (695 K) ignition assistance must be provided. In the present work, a glowplug of MICO 12 V single pole sheathed type has been installed in the cylinder, so as to increase the temperature in the cylinder by passing electric current through the glow plug, thereby improving starting characteristic of the engine. A helical heating wire is embedded in a powder of heat resistant electric insulation packed tubular sheath made of heat resistant metal in the glowplug. The glowplug is screwed into the combustion chamber to supply additional heat to air during compression stroke and to vaporize the fuel which impinges on it. The protrusion of the standard glowplug into the combustion chamber is not sufficient for the fuel spray to impinge on the glow plug. So, the glow plug was machined in such a way that the protruding part of the glow plug could be increased for better impingement of the fuel spray. Fig. 2 shows the location of the glow plug in the cylinder head and the combustion chamber configurations.

Figure 2: Zirconium Oxide coated piston and head

Key Properties of Zirconium Oxide:

- Use temperatures up to 2400°C
- High density
- Low thermal conductivity (20% that of alumina)
- Chemical inertness
- Resistance to molten metals
- Ionic electrical conduction
- Wear resistance
- High fracture toughness and high hardness.

Table 2: Engineering Properties:

Density	6	gm/cc
Elastic Modulus	200	GPa
Hardness	1300	Kg/ mm^2
Thermal Conductivity	2	W/m°K
Coefficient of Thermal Expansion	10.3	10^{-6}/°C

10. Low heat rejection (LHR) Engine:

Energy conservation and emissions have become of increasing concern over the past few decades. As automobiles are one of the major sources of energy consumption and urban emissions, engineers concerned are under significant pressure to improve their energy efficiency and reduce exhaust emission levels. While tremendous effort has been devoted in improving performance and reducing emissions of current engines, new technologies are also getting attention. One example is the Low Heat Rejection Engine (LHRE). A technological thrust is currently in progress to develop insulated, low heat rejection engines which exhibit higher thermal efficiency and improved exhaust emissions. The low heat rejection engine concept is not new. For the past two decades many have conducted experiments on low heat rejection engines. Although promising, the results of the experimental investigations have been somewhat mixed.

The concept of low heat rejection (LHR) engine aims to reduce the heat transferred to cooling system. So this energy can be converted to useful work. Some of the major advantages of LHR engines are as follows: Better fuel economy, increased engine life, reduction in HC, CO and PM emissions, and lower combustion noise due to reduced pressure increasing rate, increased exhaust gases energy and ability of operating low Cetane fuels.

Various forms of LHR:

- Ceramic coated piston- low degree of insulation.
- Ceramic coated piston, cylinder head and liner.

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- Air gap insulated piston engine.
- Air gap insulated piston, air gap insulated liner engine.
- Air gap insulated piston, air gap insulated liner and ceramic coated cylinder head engine- high degree of insulation.

Alcohols in LHR engine

The plain engine is modified by fitting with a PSZ coated cylinder head and liner. Then the existing aluminum piston is replace by a cast iron piston with an air gap. These air gap surface are coated with PSZ. Also the crown of the piston is coated with PSZ. These tests are conducted with Methanol and ethanol as fuels in GHSI engines as usual.

11. Experimental Analysis

Experiments were conducted on the standard Diesel engine in various combinations of piston crown matrial.

The engine was operated under no load for the first 20 minutes and for each load the engine was operated long enough to stabilize the condition.

All the tests were conduct at the rated speed of 1500 rpm. From the observed readings, the parameters of brake power, brake thermal efficiency, brake specific consumption, peak pressure, rate of pressure rise and ignition delay and emission parameter were evaluate.

The Aluminium piston engine is chosen as a base engine. Then four piston crown material (**Bronze, T**itanium**, Copper, Nimonic alloy**) are tried by changing different pistons. In all these engines **alcohols are use** as fuel in order to evaluate the performance characteristics.

The Experiments are Carrying out in the Following Types.

1. With Different Piston Crown Materials.
   - Normal Aluminium piston
   - Bronze Crown Aluminium Piston
   - Copper Crown Aluminium Piston
   - Nimonic alloy Crown Aluminium Piston
   - Titanium Crown Aluminium Piston
2. Five fuel additives used in the best performed **(Glow Plug Surface Ignition)** GHSI engine
3. Conversion of best performed GHSI test engine in to LHR Engine With best additive

Piston: The total height of the standard piston was 110 mm and this height had to be maintained in the insulated piston. The height of the standard piston was reduced by 7mm in order that the total height of the modified piston including the crown (7 mm).

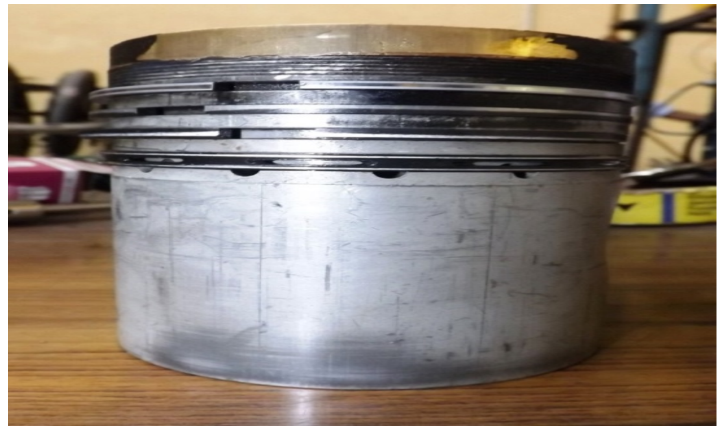

Figure 3: Photographic view of Normal Aluminum piston

Properties of Deferent Piston Crown Materials

Materials	Density Kg/m³	Thermal conductivity (k) W/mk	Melting point ⁰C
Bronze	3.93	34	660
Copper	8.94	339	900-950
Titaniumalloys	8.33	11.2	1390-1423
Nimonic alloys	8.52	121	900-950

The below figure 4-8 shows that thermal barrier coated with bio diesel engine has high thermal efficiency and volumetric efficiency and low exhaust gas temperature. NOX emission slightly high compared with uncoated engine.

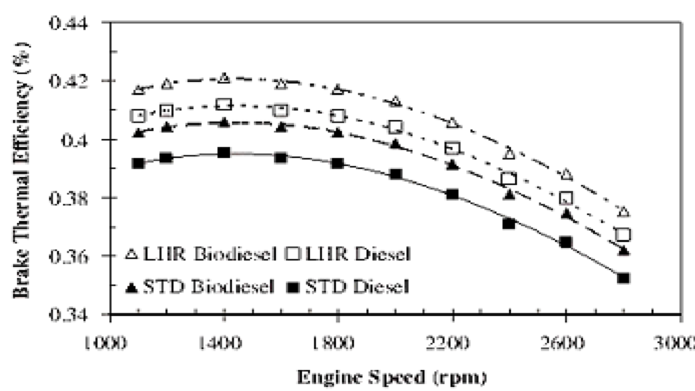

Fig.4 Changes of brake thermal efficiency according to engine speed

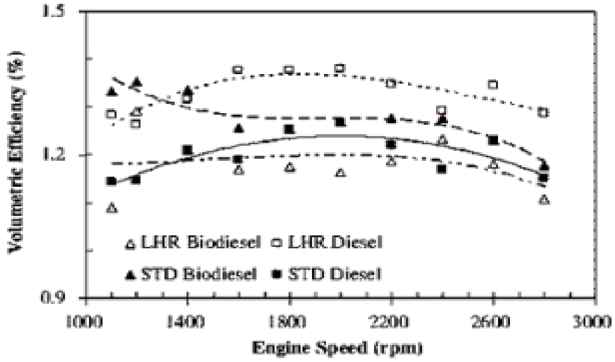

Fig.5 Changes of volumetric efficiency according to engine speed

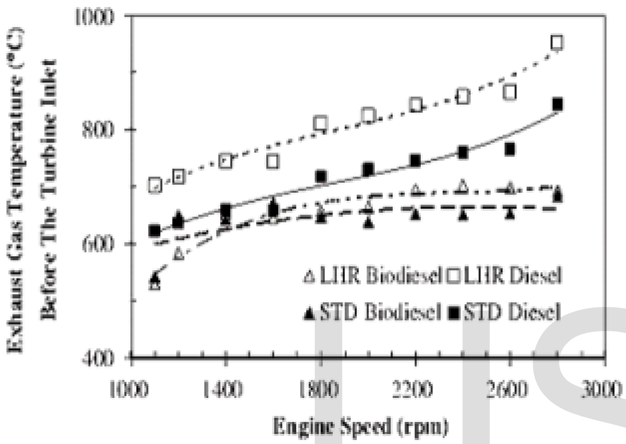

Fig.6 Changes of exhaust gas temperatures according to engine speed

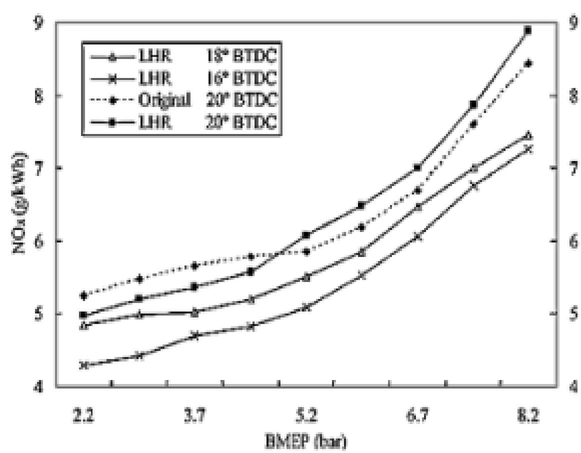

Fig.7. Variation of Nox at different injection timings

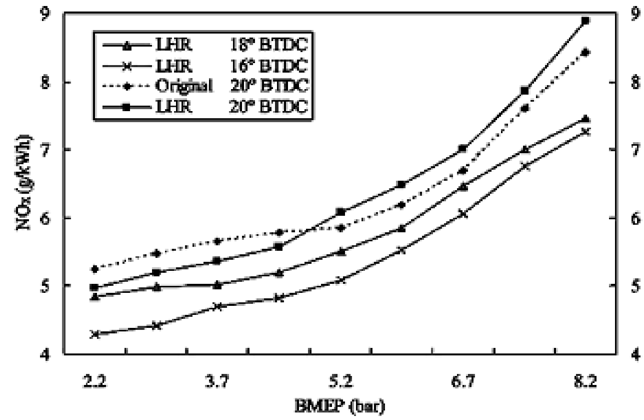

Fig. 8. Variation of NOx emissions with brake mean effective pressure for original engine with 20◦ BTDC and LHR engine with 20˚BTDC,18˚BTDC, 16˚BTDC at 1500 rpm

12. Conclusion

1. The applications of thermal barrier coatings to various components of combustion zone of an engine such as piston and cylinder liner has produced significant improvements in thermal and mechanical efficiency and other performance parameters of the engine like specific fuel consumption and reduces exhaust emission. Thus this paper explores various aspects, effect and application of thermal barrier coating in piston, cylinder liner, SI engine and Diesel engine. So this paper serves as a complete reference guide for the researches who work on coatings for engine applications.

3. The major advantages of thermal barrier coatings for diesel engines are low cetane fuels can be burnt and the valves lifetime increases by 300 percent and the overall cost decreases by 20 percent. The decrease in oil consumption is around 15 percent. The engine which is the heart of internal combustion engine can be operated 10 percent more than the traditional engine. There will be an increase engine life time by 20 percent the overall fuel consumption decreases by 11 percent.

2. The pollutants emitting out from the exhaust of the automotive vehicles is also increasing due to the increase in the number of vehicles. The main causes of these emissions are: non-stoichiometric combustion, dissociation of nitrogen, solid carbon particulates. So, the engineers and scientists have todevelop engines and fuels of developing very few emissions or no emissions.

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