Alternative Thermal Barrier Coatings for CI Engines - A Research Review

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Abstract- The depletion of supply of fossil fuels and their increased cost has driven the attention towards energy security. The energy security can be partially achieved by improving the efficiency of energy producing equipment's. Diesel fuels can be used more efficiently in low heat rejection engines (LHR), in which the temperature of combustion chamber is increased by creating thin layer of ceramics, a thermal barrier. Also the use of thermal barrier coatings (TBCs) to increase the combustion temperature in diesel engines has been pursued for over 20 years. Increased combustion temperature can increase the efficiency of the engine, decrease the CO and unburnt Hydrocarbons (UBHC). TBCs have not yet met with wide success in diesel engine applications. To reach the desirable temperature of 850-900°C in the combustion chamber from the current temperature of 350-400°C, a coating with a thickness of order 1mm is required. This paper gives a complete review on the TBCs on CI engines.

Index Terms- Thermal barrier coating, Diesel engine, Low heat rejection engine.

1. INTRODUCTION

To meet tough automotive competition and stringent government regulations, more efficient engine components, improved engine oils, and high performance coating materials have been developed within the automotive industry.

The efficiency of most commercially available diesel engine ranges from 38% to 42%. Therefore, between 58% and 62% of the fuel energy content is lost in the form of waste heat. More than 55% of the energy which is produced during the combustion process is removed by cooling water and through the exhaust gas. [1]

The quantity of the energy acquired from the fuel is not an intended level because of the factors in the combustion chamber of the engine. Some of the factors are, design of the combustion chamber, lack of adequate turbulence in the combustion chamber, poor oxygen at the medium, lower combustion temperature, compression ratio and advance of injection timing. It is thought that combustion temperature is one of the most important factors among the above mentioned factors. All of the hydrocarbons cannot be reacted with oxygen chemically during combustion time. With this aim, coating the combustion chamber components with low thermal conductivity materials becomes a more important subject at these days. For this reason, combustion chamber components of the internal combustion engines are coated with ceramic materials using various methods.

Low Heat Rejection (LHR) engines aim to utilize the maximum energy or we can save the energy by reducing the heat lost to the coolant. This will reduce the heat transfer through the engine walls, and a greater part of the produced energy can be utilized, involving an increased efficiency [2]. The diesel engine with its combustion chamber walls insulated by ceramics is referred to as LHR engine. Thermal barrier coatings (TBC) are used to improve reliability and durability of hot section metal components and enhance engine performance and thermal efficiency and elimination of the cooling system in diesel engines. Because the combustion chamber temperatures of ceramic-coated engines are higher than those of uncoated (base engine) engines, it may be possible to use a fuel with a large distillation range and lower quality fuels. Thermal barrier coatings are duplex systems, consisting of a ceramic topcoat and a metallic intermediate bond coat. The topcoat consists of ceramic material whose function is to reduce the temperature of the underlying, less heat resistant metal part. The bond coat is designed to protect the metallic substrate from oxidation and corrosion and promote the ceramic topcoat adherence [3]. A thermal barrier application is shown in figure 1.

1.1. *Properties of Coating Materials:*

The coating material should have the following properties [4].

- **Low thermal conductivity**: The coated material should resist almost or Complete heat transfer to the substrate.

- **High thermal stability**: The coated material should be able sustain very high temperature having very high melting point. There by base or substrate material is protected from high temperature corrosion.
- **High wear resistance**: The coated material should have oxidation and corrosion resistant property. This can be obtained by properly heat treatment the coated material.
- **Hardness**: The coated material should possess optimum range of both micro and macro hardness.
- **Good adhesive property**: The coated material should be well adhered to the substrate. So that bonding strength will be excellent.

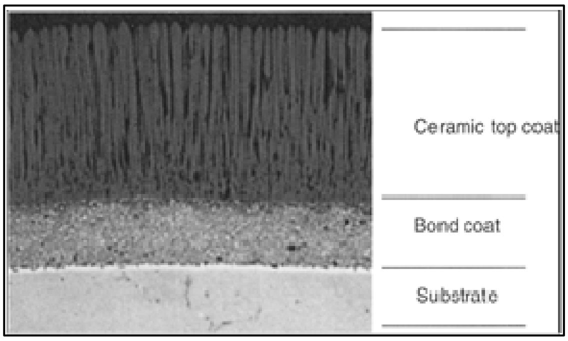

Fig. 1. Thermal barrier coating consisting of metallic bond coat on the substrate and ceramic top coat on the bond coat.

1.2. *Advantages of Thermal Barrier Coatings for Diesel Engines:*

Some advantages of thermal barrier coatings on diesel engines are below.

- Low cetane fuels can be burnt.
- Improvements occurs at emissions except NO_x
- Increased effective efficiency and thermal efficiency,
- Using lower-quality fuels within a wider distillation range,
- The ignition delay of the fuel is considerably reduced,
- The faster vaporization and the better mixing of the fuel,
- Reduced specific fuel consumption,
- Multi-Fuel capability,
- Improved reliability,
- Increased life time of engine parts and combustion temperature,
- Reduces the transient stress and thermal stress in the parts,
- High surface emissivity,
- Decreased the heat removed by the cooling system,
- Decreasing knocking and noise caused by combustion [1, 5-17].

2. ALTERNATIVE MATERIALS FOR THERMAL BARRIER COATING

The selection of thermal barrier coating materials is restricted by some basic requirements. They are high melting point, no phase transformation between room temperature and operation temperature, low thermal conductivity, chemical inertness, thermal expansion match with the metallic substrate, good adherence to the metallic substrate and low sintering rate of the porous microstructure. So far, only a few materials have been found to basically satisfy these requirements. There is a great thermal expansion coefficient match between YSZ, bond coat and substrate (10.7x10-6 k-1 vs. 17.5x10-6 k-1 for NiCoCrAlY and 16x10-6 K-1 for IN737) [18]. Good thermo-mechanical performance and fair oxidation resistance are other properties of YSZ as a TBC.

2.1. *Zirconates:*

Zirconates materials with a pyrochlore structure have a fair thermal expansion co-efficient in the range of 9E-6 k-1 to 10E-6 k-1. 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 [19]. Some materials in this category; e.g. BaO·ZrO2, SrO·ZrO2, and La2O3·2ZrO2, undergo phase transformation or become non-stoichiometric during heating.

2.2. *Garnets:*

Polycrystalline garnet ceramics are used in different applications due to their unique properties. Particularly YAG (Y3Al5O12) is a good choice for many high-temperature applications, due to its excellent high temperature properties and phase stability up to its melting point (1970°C) [14]. Other advantages which make YAG a candidate as a TBC are their low thermal conductivity and its low oxygen diffusivity [5]. Although the thermal conductivity value is almost the same as zirconia, the thermal expansion coefficient is lower.

2.3. *Yittria Stabilized Zirconia:*

7-8% yittria stabilized zirconia has high thermal expansion coefficient, low thermal conductivity and high thermal shock resistance. Disadvantages of yttria stabilized zirconia are sintering above 1473 K, phase transformation at 1443 K, corrosion and oxygen transparent [22].

2.4. ***Al2O3.SiO2.MgO system:***

Most traditional, high temperature refractory ceramic materials are found in the Al2O3.SiO2.MgO phase diagram. (Figure 2). Among these oxides, some have been considered as alternatives to YSZ in TBCs.

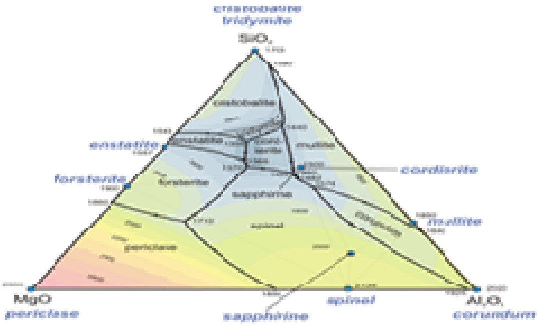

Fig. 1. Al2O3.SiO2.MgO phase diagram

2.5. ***Cordierite:***

Cordierite (2MgO.2Al2O3.5SiO2) has a very low TEC (1.67x10 -6 k-1 [15]) but, for certain applications, could be an alternative for TBCs. However, after plasma spraying, the cordierite deposition is amorphous. While heating, two phase transformation occur, at 830°C and 1000°C, which produce a volume change and cause cracking [16]. To deposit crystalline cordierite, the addition of 6 wt% TiO2 has been reported to be effective [17].

2.6. ***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 [19].

2.7. ***Spinel:***

Although spinel has very good high temperature and chemical properties, its thermal expansion coefficient prevents its usage as a reliable choice for thermal barrier coatings [19].

2.8. ***Mullite:***

Mullite is applied on SiC as an oxidation resistant layer to form an environmental barrier coating (EBC). Its low oxygen diffusivity, low creep rate at high temperatures, high thermo-mechanical fatigue resistance and close TEC match with SiC (4-5x10-6 K-1 vs. 5- 6x10-6 K-1 [20]) makes it the ideal choice for this application. In thin coatings (up to some hundred microns) on top of a metallic substrate, the durability of mullite has been reported to be better than that of zirconia [21].

2.9. ***Alumina:***

It has very high hardness and chemical inertness. Alumina has relatively high thermal conductivity and low thermal expansion coefficient compared with yttria stabilized zirconia. Even though alumina alone is not a good thermal barrier coating candidate, its addition to yttria stabilized zirconia can increase the hardness of the coating and improve the oxidation resis-tance of the substrate. The disadvantages of alumina are phase transformation at 1273K, high thermal conductivity and very low thermal expansion coefficient [18].

3. FUEL CONSUMPTION

Numerous investigators have modeled and analyzed the effects of in-cylinder thermal insulation on fuel consumption. The level of improvement that has been predicted ranged from 2 to 12 %. Kamo et al. [22] Test results indicate that coatings on the cylinder liner bore produced a reduction in fuel consumption while coatings on the piston and cylinder head-face surface were more effective in reducing heat rejection. Uzan et al. [8] reported 2% decrease in the engine specific fuel consumption with TBCs. Murthy et al. [23] indicate that LHR engine showed deteriorated performance at recommended injection timing and pressure and improved performance at advanced injection timing and higher injection pressure, when compared with conventional engine (CE). At peak load operation, brake specific fuel consumption (BSFC) decreased by 12%.

Thring [24] stated that comparison of SFC between baseline and LHR engine should be done carefully, because reducing the heat rejection affects other engine operating parameters such as volumetric efficiency, air-fuel mixing and etc., which in turn affect fuel consumption. Hence it is felt that, comparison between the two engines should be made at same engine operating conditions and same engine operating parameters. In general, it has been reported that fuel consumption of, naturally aspirated LHR engine is in the range of 0 to 10% higher, turbocharged LHR engine in the order of 0 to 10% lower and turbo-compounded LHR engine in the order of 0 to 15% lower, when compared with the conventional cooled engine.

Buyukkaya et al. [11] showed that 1-8% reduction in brake specific fuel consumption could be achieved by the combined effect of the thermal barrier coating (TBC) and injection timing. The investigation of Alkidas [25] has shown that the fuel economy of the LHR engine is of the same level as that of water cooled engine at the medium load, but deteriorated significantly at the high load condition. He attributed this to increased temperature of the combustion chamber walls, thus also increasing the temperature of the fuel issuing from the heated nozzle orifice resulting in the reduced fuel viscosity. This caused a heavy leakage fuel inside the nozzle and extended injection duration as well. Admitting the need for tuning of the fuel injection system for LHR engine operation, he optimized an injector tip configuration and achieved equal or superior fuel consumption. Assanis et al. [26] have shown that with proper adjustment of the injection timing it is possible to partially offset the adverse effect of insulation release rate. Their data have shown that reducing heat rejection from the cylinder, shift the combustion from pre-mixed towards diffusion. They have shown that by advancing the timing, the LHR engine achieves the same pre-mixed heat release rate and rate can also offset the adverse effect of insulation. Sun et al. [27] have shown that decrease in pre-mixed combustion by about 75% in an insulated engine increases the BSFC by about 9%.

4. ENGINE EFFICIENCY

4.1. *Volumetric Efficiency:*

The volumetric efficiency is an indication of breathing ability of the engine. It depends on the ambient and operating conditions of the engine. Reducing heat rejection with the addition of ceramic insulation causes an increase in the temperature of the combustion chamber walls of an LHR engine. The volumetric efficiency should drop, as the hotter walls and residual gas decrease the density of the inducted air. As expected all the investigations such as Thring [24], Assanis et al. [26], Gatowski [28], Miyairi et al. [29], and Suzuki et al. [30], on LHR engine show decreased volumetric efficiency. The deterioration in volumetric efficiency of the LHR engine can be prevented by turbo-charging and that there can be more effective utilization of the exhaust gas energy.

4.2. *Thermal Efficiency:*

The improvement in engine thermal efficiency by reduction of in-cylinder heat transfer is the key objective of LHR engine research. Much work has been done at many research institutes to examine the potential of LHR engines for reducing heat rejection and achieving high thermal efficiency. Researchers such as Thring [24], Alkidas [25], Havstad et al. [31], Moore et al. [32], and many others have reported improvement in thermal efficiency with LHR engine. They attribute this to in transfer reduction and lower heat flux. However investigations of others such as Cheng et al. [33], Woschni et al. [34]. Dickey [35] and some others report that thermal efficiency reduces with insulation. They all attribute this to an increase in the convective heat transfer coefficient, higher heat flux (increase in-cylinder heat transfer) and deteriorated combustion. The in cylinder heat transfer characteristics of LHR engine are still not clearly understood. Thus the effect of combustion chamber insulation on reducing heat rejection and hence on thermal efficiency is not clearly understood as on date. Hoag et al. [36], Sudhakar [37], Yoshimitsu et al. [38], and Yonushonis [39] have reported improvement in the reduction of fuel consumption and in the thermal efficiency of LHR engine.

The effects of ceramic coating on the performance of the diesel engine were investigated by Taymaz [40, 41]. The combustion chamber surfaces, cylinder head, valves and piston crown faces were coated with ceramic materials. The layers were made of CaZrO3 and MgZrO3 and plasma coated onto the base of the NiCrAl bond coat. The ceramic-coated research engine was tested at the same operation conditions as the standard (without coating) engine. The results showed that the increase of the combustion temperature causes the effective efficiency to rise from 32% to 34% at medium load and from 37% to 39% at full load and medium engine speeds for ceramic-coated engine while it increases only from 26% to 27% at low load. The values of the effective efficiency are slightly higher for the ceramic-coated case as compared to the standard case (without coating).

5. CONCLUSION

By insulating combustion chamber components, it is available to keep combustion temperatures high. Due to high combustion temperatures thermal efficiency can be increased, exhaust emissions can be improved and fuel consumption can be decreased on diesel engines. Ceramic materials which have low thermal conductivity and high thermal expansion coefficient are used for making combustion chamber components thermal insulated.

In this paper, the advantages and disadvantages of several materials for use as thick thermal barrier coatings in diesel engines were reviewed.

For a successful coating thermal coating, ceramic material has a high melting point, high oxygen resistance, high thermal expansion coefficient, high corrosion resistance, high strain tolerance, and low thermal conductivity and phase stability.

The objectives of improved thermal efficiency, improved fuel economy and reduced emissions are attainable, but much more investigations under proper operating constraints with improved engine design are required to explore the full potential of Low Heat Rejection engines.

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