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ORIGINAL ARTICLE

Investigation on effect of Yttria Stabilized Zirconia coated piston crown on performance and emission characteristics of a diesel engine

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Abstract Experimental investigation is carried out under different loading conditions in a three cylinder diesel engine with its piston crown coated with Yttria Stabilized Zirconia (YSZ) to understand the influence of the thermal barrier coating (TBC) on performance and emission characteristics in comparison with baseline engine characteristics. YSZ is chosen as the candidate material for coating the piston crown because of its desirable physical properties such as high coefficient of thermal expansion, low thermal conductivity, high Poisson's ratio, and stable phase structure at higher temperature conditions. For the measurement of emission characteristics, ISO 8178-4 "C1" 8 Mode testing cycle procedure is followed. Experimental results revealed that the heat loss to the cooling water is reduced up to 5–10% and the thermal efficiency is increased by 3–5% with reduction of brake specific fuel consumption by up to 28.29%. Experimental results also revealed that Hydro carbon (HC) emission is reduced up to 35.17%, carbon monoxide (CO) by up to 2.72% and Carbon di-oxide (CO_2) emission is increased by up to 5.6%.

1. Introduction

Diesel engines play a major role in the automotive industry. It has assumed a dominating role in both transport and agricultural industry due to its higher fuel economy and low running cost. However the heat carried away by the coolant and exhaust gases carry considerable amount of fuel energy from the combustion chamber even in diesel engines leaving only 30–40% of the total energy for conversion into useful work. The engine cooling system absorbs combustion and friction-generated heat energy and dissipates it to the surroundings to ensure engine temperature always remain below the safe level. The lubrication system and exhaust gases are the other sources which carry away the heat from the combustion chamber.

Researchers are continuously striving to improve the performance and emission characteristics of the Internal Combustion engines due to the continuous demand from the industry for some technological and environmental requirements besides rapid increase in the cost of the fuel. On the other hand the improvements in engine materials become increasingly

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important by the introduction of new alternative fuels. Thermal barrier coating is predominantly used by many researchers to increase the heat resistance inside the combustion chamber and thereby improving the thermal efficiency of the existing engines. Ceramic coatings not only act as heat resisting medium, but also prevent the thermal fatigue and shocks in protecting the substrates. Ceramic coating also helps in reducing the emission levels of Hydrocarbon and Carbon Monoxide. The application of TBC reduces the heat transfer through the cooling water [5] and hence assists the engine for better combustion inside the combustion chamber. Due to the increased after combustion temperature, the exhaust gas temperature also raises proportionately. While there have been numerous research papers in the recent years describing the theoretical benefits obtained from the use of ceramic components in reciprocating engines, the amount of the literature that describes practical results is very limited.

Generally in LHR engines, the thermal barrier coating is done on Cylinder head, cylinder liners, piston crowns and valves. Most of the researchers have concluded that the thermal efficiency of TBC coated Low Heat Rejection (LHR) engines is higher with better brake specific fuel consumption [3].

According to second law of thermodynamics, insulating the combustion chamber of an internal combustion engine will theoretically result in improved thermal efficiency. Kamo et al. [3] by experimental determination predicted that thin thermal barrier coated engine could improve its thermal efficiency by 5–6% in comparison with the standard engine. Bruns et al. [1] predicted that fuel economy could be improved in the range of 16–37%. The results of Wallace et al. [2] indicated a gain of 14% in the indicated thermal efficiency for fully adiabatic condition and 7% for semiadiabatic condition. The investigation of Havstad et al. [10] has shown improvements ranging from 5% to 9% in ISFC of an insulated engine over a baseline engine. The investigation of Kamo [7] has shown that TBC engine with its piston and cylinder head coated with 0.1 mm thickness of YSZ and the cylinder liner coated with 0.5 mm thickness of YSZ improved the fuel efficiency by 5–6% at all loads and speeds. Investigation of Miyairi et al. [11] reported higher fuel consumption by the LHR engine coated with Mg–ZrO_2.

The efficiency of most commercially available engines can be improved by coating the piston crown with an insulating material such as stabilized zirconia. The main requirements of the thermal barrier coating materials include low thermal conductivity, resistance to corrosive and erosive environments, co-efficient of thermal expansion high enough to be compatible with metal and thermal shock resistance. Various TBC materials and its characteristics are given in Table 1. The plasma sprayed stabilized zirconia was used extensively in aero engines as an ideal thermal barrier coating material. Morel et al. [9] determined that Yttria was the preferred stabilizing agent for zirconia. The stabilized zirconia has been successfully tried by several investigators as thermal barrier coating agent for piston crown.

Based on the open literature review, it is found that Low Heat Rejection engines with thin TBC on combustion chamber components coated with YSZ are the most effective one in terms of improving the Thermal efficiency and fuel consumption [5] of Internal Combustion engines. However significant number of literatures revealed that NO_x emission levels were increased due to the application of Thermal Barrier Coating inside the combustion chamber. In the present work, the piston crown is coated with 100 micron thickness of YSZ by plasma spray coating method and engine is tested for its performance and emission characteristics at various loads and speeds as per **ISO 8178-4 "C1" 8 Mode test cycle** for off road vehicles [17].

2. Plasma spray technique

Thermal Spraying technique consists of different types such as Chemical deposition method (CVD), plasma arc method, Physical vapor deposition method (PVD), Plasma spray method. From the above four methods, plasma spray method is adopted in our experimental study. The main objective in plasma spraying was to constitute a thin layer that has high protection value over other exposed surfaces. Yttria Stabilized Zirconia (YSZ) is sprayed in powder form molten in ionized gas rapidly on the piston crown surface to form a 100 μm thin TBC coating. A typical Plasma spray coating system is shown in Fig. 1. The Snapshots of uncoated baseline engine piston (left) and YSZ coated piston (right) are shown in Fig. 2. The system primarily consists of power unit, powder supply unit, gas supply unit, cooling system, spraying gun and control unit. The coating material is made up of 8 mol% of Yttria (Y_2O_3) and remaining mole% of fully stabilized Zirconia (ZrO_2). The plasma spray specifications are mentioned in Table 2.

3. Experimental test setup

A four stroke, direct injected, water-cooled, Three cylinder, naturally aspirated diesel engine is used for investigation. The base engine specifications are presented in Table 3.

The Schematic of experimental setup is shown in Fig. 3. The experiments were conducted at four load levels, viz. 25%, 50%, 75% of full load and full load using Eddy current dynamometer at five different speeds viz. 1200, 1400, 1600, 1800 and 2000 rpm. The mass flow rate of air is measured using a manometer setup by Air Box method. Fuel flow rate is measured by a gravimetric type Fuel consumption meter. Pressure and temperature sensors are mounted at important locations in engine exhaust, water inlet, water outlet, air intake, lube oil for online recording of pressure and temperature values using a Digital Dyno Controller unit and Data Acquisition System. Emission characteristics such as Carbon monoxide (CO), Hydro carbon (HC) and carbon dioxide (CO_2) were measured by using AVL Di-gas 444 Gas analyzer as per **ISO 8178-4 "C1" 8 Mode testing cycle** for off road vehicles [17]. All the readings were carried out using ARAI–EDACS controller setup and the readings were stored in a personal computer automatically.

4. Results and discussion

Experimental result shows that reduction in heat rejection to cooling medium had resulted in an increase in exhaust energy at all load levels. In case of Thermal Barrier Coated engine, there is a increase in the volumetric efficiency of the engine at different loadings and speed conditions.