Energy Conversion and Management 85 (2014) 173–189

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Combustion, performance, and emission characteristics of low heat rejection engine operating on various biodiesels and vegetable oils

M.J. Abedin *, H.H. Masjuki, M.A. Kalam, A. Sanjid, A.M. Ashraful

Centre for Energy Sciences, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 15 February 2014
Accepted 16 May 2014

Keywords:
Low heat rejection engine
Thermal barrier coating
Thermal spraying technique
Engine performance
Exhaust emission
Biodiesel

ABSTRACT

Internal combustion engine with its combustion chamber walls insulated by thermal barrier coating materials is referred to as low heat rejection engine or LHR engine. The main purpose of this concept is to reduce engine coolant heat losses, hence improve engine performance. Most of the researchers have reported that the thermal coating increases thermal efficiency, and reduces exhaust emissions. In contrast to the above expectations, a few researchers reported that almost there was no improvement in thermal efficiency. This manuscript investigates the contradictory results in order to find out the exact scenario. A wide range of coating materials has been studied in order to justify their feasibility of implementation in engine. The influence of coating material, thickness, and technique on engine performance and emissions has been studied critically to accelerate the LHR engine evolution. The objectives of higher thermal efficiency, improved fuel economy, and lower emissions are accomplishable but much more investigations with improved engine modification, and design are required to explore full potentiality of LHR engine.

1. Introduction

The increased impact of global warming on Earth, limited efficiency of automotive engines, and stringent anti-pollution laws imposed in certain countries have created a stimulus to explore more efficient engine with acceptable emission level. The fast depletion of fossil fuels and rapid increase in fuel price also increased interest in alternative fuels for automotive engines, in recent years. In this context, low heat rejection engine operation on biodiesels and vegetable oils can be an important subject matter to explore [1–4].

Internal combustion (IC) engine with its cylinder head, walls, valves, pistons etc. insulated by thermal barrier coating (TBC) materials is referred to as LHR engine [5]. TBC materials have been successfully applied to IC engines, in particular to the combustion chamber walls. In an IC engine, approximately one third of the total supplied fuel energy is converted to the useful work. Since the working gas in a practical engine cycle is not exhausted at ambient temperature, a major part of the energy is lost as engine exhaust heat. In addition, another major part of the fuel energy is lost via cooling medium [1,6,7]. Theoretically, if the rejected heat could be reduced, then the thermal efficiency would be improved, at least up to the limit set by the 2nd law of thermodynamics. But practically, this may not happen due to the complex nature of IC engine and complexity involved in coating process. In addition, thermal and mechanical limitations are present in TBC materials. However, higher thermal efficiency, lower emissions, lower fuel consumption, and elimination of the cooling system from engine are the major promises of LHR engine [8].

Several ceramic coatings such as TiO_2, Al_2O_3, mullite, CaO/MgO–ZrO_2, YSZ have been used in engine application [9–11]. Partially stabilized zirconia (PSZ), mostly 6–9% yttria stabilized zirconia (i.e. YSZ) is the most widely used TBC material and it showed good performance in high temperature applications like diesel engines, gas turbines etc. [12–14]. But TBCs like mullite, Ca/Mg-PSZ, Al_2O_3 and TiO_2 can be good alternatives to YSZ due to their suitable properties for engine application. A table has been provided showing the properties, advantages, and disadvantages of TBC materials in Section 2.1. This table can be a useful tool for the selection of a new TBC material. The TBC coatings affect the combustion process, and hence the performance, and emission characteristics of the engine [15–19]. Because, TBC changes ignition characteristics of the fuel–air mixture, and its subsequent reaction mechanisms, which are directly related to the exhaust emission characteristics. In addition, thermo-physical properties of TBCs, porosity, and

* Corresponding author. Address: Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. Tel.: +60 149901927; fax: +60 3 79675317.

E-mail addresses: joynul06me@yahoo.com, joynul06me@siswa.um.edu.my (M.J. Abedin).

http://dx.doi.org/10.1016/j.enconman.2014.05.065
0196-8904/

Nomenclature

Abbreviation

LHR	low heat rejection
TBC	thermal barrier coating
PSZ	partially stabilized zirconia
YSZ	yttria stabilized zirconia
CTE	coefficient of thermal expansion
IC	internal combustion
CI	compression ignition
TDC	top dead centre

surface roughness have a direct influence on unburned, and partially burnt hydrocarbons due to surface quenching, and retention residual in the pores [20]. The durability of TBC materials is limited by two basic failure mechanisms: one is oxidation of the bond coat, and other one is thermal expansion mismatch between top coat and bond coat [21,22]. The influence of these TBC materials and bond coating materials on engine performance and emissions has been investigated thoroughly in this paper.

The most popular thermal spraying method to deposit TBC in the engine cylinder walls is plasma spraying method due to its ability to melt the substrate at high temperature. Besides, high bond strength (15–25 MPa), lower porosity (1–7%), and wide range of coating thickness (300–1500 μm) is attainable in this process [23]. A brief description of this method has been provided in Section 2.2. The influence of thermal spraying methods on engine performance and emissions has been studied in this manuscript.

LHR engine combustion is significantly different from uncoated engine combustion. The four major deviations in Combustion characteristics of LHR-diesel operation from uncoated-diesel operation are: [24]

a. Ignition delay period shortens.
b. Pre-mixed burning phase decreases and diffusion burning phase increases.
c. Total combustion duration increases.
d. Heat release rate during the diffusion burning phase decreases.

A lot of studies have been carried out since 1978 on LHR engine development, performance, emissions and durability [25]. Although the use of LHR engine concept is found to be promising, the reported studies showed contradictory results. Most of the researchers [6,14,26–30] have reported that the thermal coating reduces coolant heat loss, increases thermal efficiency, reduces emissions (except NO_x), and increases exhaust energy availability. In contrast to the above expectations, a few researchers reported that almost there was no improvement in thermal efficiency [31,32]. Since the temperature in the combustion chamber is higher in the LHR engines than that of uncoated engines, it is possible to use lower cetane number fuels in LHR engine [24,33–35].

The objectives of this review article are: to study the conversion process of diesel engines into LHR engines; to find out the feasibility of using new alternative TBC materials for engines; to investigate the LHR engine combustion, performance, heat losses, and emission characteristics using diesel, biodiesels, and vegetable oils; to study the reasons behind the contradictory results.

2. LHR engine preparation

2.1. Suitable bond coating and TBC materials for IC engines

The TBC system consists of a TBC, a bond-coat, and a substrate. The bond-coat relaxes the thermal stresses due to the mismatch of the coefficient of thermal expansion (CTE) between the TBC and the substrate. The bond-coat has been also employed for the protective coating from oxidation and corrosion of the substrate [22]. There is a wide range of metallic alloys used as bond coat, normally consisting of a MCrAlY alloy, where M stands for Ni, Fe, Co or combination of them. Some alloys also include other materials such as Ta or Re. Some types of bond coats are made of electroplated Ni and Pt aluminides followed by diffusion aluminizing [11,36–38].

What are the required key properties to be a good TBC? Definitely, there is no single material which fulfils all requirements. Therefore, we need to find out suitable TBC and Bond coating materials which are able to withstand severe conditions like IC engine combustion chamber.

The basic requirements of a good TBC are: [9,39,40]

a. Low thermal conductivity.
b. No phase transformation in the range of room temperature to in-cylinder temperature.
c. High melting point.
d. Chemical inertness.
e. Same thermal expansion coefficient with metallic substrate.
f. Good adherence capability with metallic substrate.
g. Low sintering rate of porous microstructure.

Investigation shows that inelastic behavior of thick TBC ceramic material and its unique micro-structure determines the failure mechanism [41]. During the heating of a thick TBC, a compressive stress develops which becomes tensile after cooling and initiates cracks [42]. Mismatch in thermo-mechanical properties between bond coating and top coating initiates cracks in the interface [43].

Although several ceramic materials have been used as TBC in engines, only a few of them like 7–8% YSZ have received good attraction due to their physical properties like thermal conductivity, strength, chemical stability, thermal expansion coefficient etc. In Table 1, physical properties, advantages, and disadvantages of some suitable TBC and bond coating materials for IC engine are provided. From this table, one can predict which coating material is more suitable for IC engine application.

2.2. How to convert standard engine into LHR engine?

After the selection of a suitable TBC material, the next job is, it needs to be deposited on combustion chamber walls. TBC can be deposited by using various techniques. These techniques are known as thermal spraying processes. Thermal spraying is a group of coating processes wherein a feedstock material is heated and propelled as individual particles or droplets onto a surface (Fig. 1). The thermal spray gun generates the necessary heat by using combustible gases or an electric arc. As the materials are heated, they are changed to a plastic or molten state which are confined and accelerated by a compressed gas stream to the substrate. The particles strike the substrate, flatten, and form thin platelets (splats) that conform and adhere to the irregularities of the prepared substrate and to each other. As the sprayed particles impinge upon the surface, they cool and build up splat by splat into a laminar structure forming the thermal spray coating. Coating