Study the Effect of Ceramic Coating on the Performance and Emissions of Diesel Engine

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Abstract

In this study, the effect of ceramic coating on the performance and gases emission on diesel engine was investigated. A four-stroke, direct injected, single cylinder, diesel engine was tested at constant speed and at different load conditions without coating. Then, the inlet and exhaust valves faces were coated by about 500µm with ceramic materials. Ceramic layers were made of Yttria-Stabilized Zirconia (YSZ), and NiCrAl as a bond coat. The coating technique adapted in this work is the flame spray method. The engine with valves ceramic-coated research was tested for the same operation conditions of the engine (without coating). The results indicate a reduction in both fuel consumption by about 7.6% and particulate emissions by about (13% for HC and 14.5% for CO) with increasing in exhaust gases temperature after coating.

Keywords: Diesel engine, Ceramic coating, Engine performance, Exhaust emissions.

دراسة تأثير الطلاء السيراميكي على أداء وانبعاثات محرك ديزل

الخلاصة

في هذا البحث، تم دراسة تأثير الطلاء الخزفي على أداء وانبعاث الغازات لمحرك ديزل رباعي الأشواط ذو حقن مباشر وأحادي الاسطوانة. تم دراسة الأداء لهذا المحرك بسرعة ثابتـة وحمل متغير قبل الطلاء. تم طلاء وجه صمامي العادم والدخول بسمك (500) مايكرون بمواد خزفية. حيث تم استخدام الزركونيا المثبتة بالياتيريا كماده طلاء بالاضافه الى مـسحوق طـلاء رابط من نيكل—كروم- الألمنيوم. في هذا العمل، اعتمدت تكنولوجيا الطلاء الحـراري بتقنيـه الرش باللهب. اختبر المحرك تحت نفس ظروف التشغيل قبل وبعد الطلاء وقد أعطـت النتـائج تحسين في اداء المحرك من ناحية النقصان في معدل استهلاك الوقود وبنسبة 7.6% والنقـصان في الملوثات وبنسب (13% للهيدروكربونات الغير محترقـة و4.5% لغـاز احـادي اوكـسيد الكاربون وزيادة في درجة حرارة غازات العادم بعد الطلاء.

مفاتيح الكلمات: محركات الديزل، الطلاء السيراميكي، أداء المحرك، غازات العادم.

Nomenclature:

BSFC- Brake specific fuel consumption (*kg/ kW.h*)
CO_2- Carbon dioxide
CO- Carbon monoxide
HC- Hydrocarbon (*ppm*)
K- Thermal conductivity (*W/m K*)
LHR- Low heat rejection
N- Rotational speed (*rpm*)
NOx- Nitrogen Oxides
PSC- Plasma spray coating
PSZ- Partially stabilized zirconia
SN- Silicon Nitride
SFC- Specific fuel consumption
T- Exhaust gas temperature (°C)
T_b- Torque of engine (*N.m*)
TBC- Thermal barrier coating
W_b- Brake power (*kW*)
YSZ- Yttria-stabilized zirconia

1. Introduction and background

The automobile industry is facing a serious challenge to improve vehicle fuel efficiency. Global demand for cars is soaring - one forecast has the number of worldwide cars increasing five-fold by 2050 to 2.9 billion (Special report, 2008). In the scenario of increase of vehicle population at an alarming rate due to advancement of civilization, use of diesel fuel in not only transport sector but also in agriculture sector is leading to fast depletion of diesel fuels and increase of pollution levels with these fuels, efficient fuel utilization has become pertinent for the engine manufacturers, users and researchers involved in the combustion research. While search for alternate fuels is continuing, researchers are also attempting to find different techniques of efficient fuel utilized in diesel engines (Murthy, 2010).

Reductions in fuel consumption can be achieved by a variety of measures, including improved aerodynamics, weight reductions and hybrid power trains. Significant improvements must also be made to the efficiency of the internal combustion (IC) engine that powers nearly all the world's vehicles. One promising technology for improving IC engine efficiency, as well as performance and durability, is the Thermal Barrier Coating (TBC) (Murthy, 2010). TBC 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 (İlker, 2010). A thermal barrier application is shown in fig. 1.

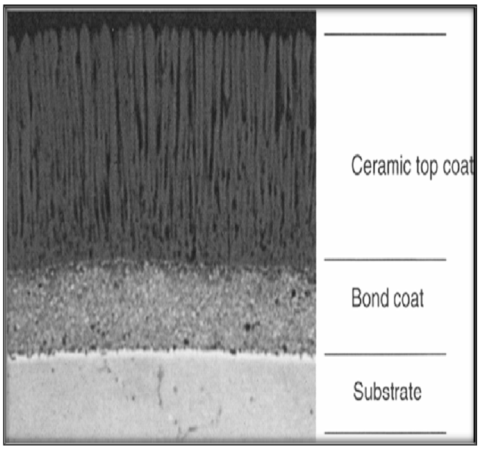

Fig. 1: Thermal barrier coating consisting of metallic bond coat on the substrate and ceramic top coat on the bond coat (İlker, 2010)

The selection of thermal barrier coating materials is restricted by some basic requirements. They have 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 (İlker, 2010).

Thermal barrier coatings are most commonly stabilized zirconias such as Yttria-Stabilized Zirconia (YSZ), but other ceramics like Silicon Nitride (SN) have been used. Thermal conductivities (k) have ranged from less than 0.5 W/m K to 10 W/m K, and thicknesses have ranged from 0.1 mm to 4.5 mm. Ceramic coatings can be applied by a variety of methods, such as thermal spraying techniques (Michael, 2009).

Imdat (2005) studied the effect of insulated surfaces (piston, cylinder head and valves) on diesel engine energy balance system by plasma spray. The results indicate a reduction in fuel consumption and heat losses to engine cooling system of the ceramic-coated engine. Adnan (2005) showed the effects of injection timing on NOx emissions by coating the combustion chamber components with plasma spray. It was observed a decrease on the NOx emissions with about 40% and the brake specific fuel consumption (BSFC) with about 6% compared to that of the standard case. Pawar **(**2005) made a model (Annand.s heat transfer model) , and it has been developed for comprehensive predictions and assessments of varying temperature and heat transfer through cylinder head and valves of diesel engine. Thermal insulation materials like (PSZ) and (SN) are used. In case of without insulated valves the heat transfer rate is higher by about 54.62% and 37.57% than the 1 mm and 0.5 mm PSZ thermal insulated valves, respectively and 12.62% higher than 1 mm SN thermal insulated valves. Srivathsan (2010) studied the effect of (YSZ) on the cylinder head, piston top surface and the valve seats. It is concluded that a thermally insulated engine reduces the fuel consumption, improves the fuel efficiency. Also the emissions of HC and CO are reduced to a great extent while the emissions of NOx are increased due to higher combustion temperature.

The aim of this paper is to study the effect of ceramic coating on the performance of diesel engine and emissions like (CO, CO_2, and HC) by coating the head of inlet and exhaust valve of diesel engine. Then, compare the results before and after coating process.

2. Experimental Work

2.1 Coatings Technique and Procedure:

The coating technique in this work is the flame spray method type (rototec 800). This apparatus consists of a chamber containing a flange to hold the specimen and an Oxy-Acetylene flame. The powder particles flow with the flame and is deposited on the specimen. The powder was supplied through a special tube in the flame gun.

The surfaces of intake and exhaust valves were cleaned and roughened using emery paper (p220) and grit-blasted using sand blast system with pressure (4-6) bar. Then, the grit-blasted substrates were cleaned using anhydrous ethanol alcohol and dried to 200 °C by a furnace for 30 min. The ceramic powder type 8%Y2O3- ZrO2 with particle sizes 10-45 µm and NiCrAl metal powder (bond coat) with particle sizes ranging from 50 to 90 μm were used. The valve is fixed on the flange to make 90° with the powder flame flow. Then, the system is switched on and the flame is ignited. The flame holder is controlled manually. The bond powder required for the first layer is loaded into the holder, and the inlet valve is heated to a suitable temperature around (300 °C) by the flame. The coating process is started by moving a lever on the holder to allow all the powder to flow through the holder with the flame with a distance of about (20 cm) between the flame and the specimen. The previous step is repeated until 50 to 100 µm thickness of bond layer has been reached. The ceramic powder (required for the top coat) is then loaded and the same procedure of bond was also repeated until 350 to 400 µm thickness has been reached. The coating is heated to about 1500 °C for a suitable time to permit the adhesion for layers. The temperature for bond coat and top coat is controlled by adjusting the distance between the flame and the specimen and the pressure of Oxy-Acetylene (about 1500 °C for bond layers and 2800 °C for the ceramic layers). The flame is withdrawn gradually away from the valve to minimize thermal shock. For exhaust valve, the same procedure was repeated. To measure the thickness of coating layer after spraying process, Coating thickness gauge type (QuaNix1500 Germany) was used. Also, Infrared thermometer was used to know the temperature of surface before spraying process and the temperature of the fusion after spraying process.

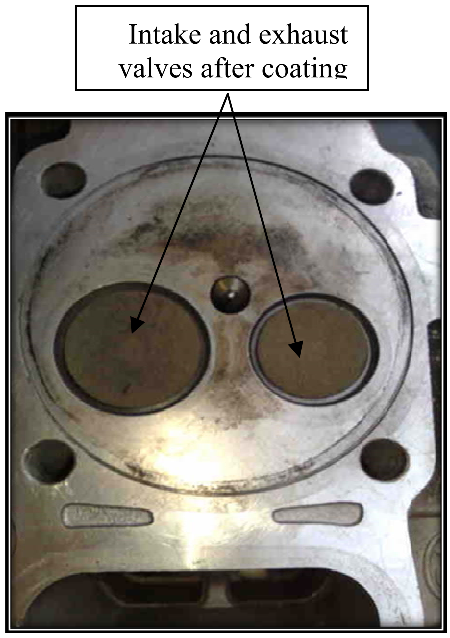

Fig. 2: Photographic view of valves (After Ceramic Coating)

2.2 Engine test setup and procedure:

The engine tests were conducted in a single cylinder, direct injection (F 170) type diesel engine. The engine specifications are listed in Table 1. This engine was coupled to a calibrated hydraulic dynamometer for speed and torque measurements. They were fixed on the stainless steel base type (TD 114) which was designed for this purpose. The water is used as a friction fluid for dynamometer. The system of fuel measurement consumption consists of a tank with capacity (4.5L) and a glass tube of known volume was used. In addition, measurement of air consumption that consists of an air box which is used to reduce the vibration that occurs when the engine is working with a water manometer. The temperature of exhaust gas was measured by a calibrated thermocouple (type K) that is fixed at the entrance of exhaust gas pipe (the beginning of the exhaust gas exit). The exhaust gas analyzer type (mod 488) was used to analyze gases the emissions of exhaust gases. It detects the CO-CO_2-HC contents. The gases are picked up from the engine exhaust pipe by means of the probe. They are separated from the water they contain through the condensate filter and then they are conveyed to the measuring cell. A ray of infrared light, which is generated by transmitter, is sent through the optical filters on to the measured elements. The gases which contain the measuring cell absorb the ray of light at different wavelength, according to their concentration.

The engine was allowed to run with neat diesel fuel at a constant speed for nearly 10 min to attain the steady-state condition at the lowest possible load. The performance of engine was observed at a constant speed of 3000 rpm and varying load.

Table 1: Main technical specification of engine

Item		**Technical Specification**
Model		170F
Type		Single-cylinder, vertical,4-stroke, air-cooled, direct-injection
Bore×Stroke (mm)		70 × 55
Displacement (L)		0.211
Fuel tank capacity (L)		2.5
Lubrication oil capacity (L)	Full	0.75
	Effective	0.25
Cooling type		Forced air cooled system
Lubrication type		Pressure, splash
Starting type		Recoil manual start and optional electric start

3. Mathematical Relationships Used to Calculate Engine Performance: (Ganesan, 2008; Mohanty, 2007)

1. Fuel consumption:

$$\dot{m}_f = \frac{V_f}{time} * \rho_{fuel} \qquad (1)$$

Where:
V_f - Volume of fuel consumption
ρ_{fuel} = 850 kg/m³ (As the specification of diesel oil from ALDORA refinery).

2. Brake Power:

$$\dot{W}_b = \frac{2\pi N T_b}{60,000} \left(kW\right) \qquad (2)$$

Where:
T_b - torque of engine (*N.m*)
N- rotational speed (*rpm*)

3. Brake Specific Fuel Consumption:

$$BSFC = \frac{\dot{m}_f}{\dot{W}_b} * 3600 \left(\frac{kg}{kW.hr}\right) \qquad (3)$$

4. Results and discussion :

Fuel consumption and exhaust temperature:

A comparison of the BSFC for the standard engine (SE) and the ceramic coated engine (CE) under constant speed and varying load is shown in Fig. (3). Because of the higher surface temperatures of valves, the BSFC values of the LHR engine were lower than those of the standard engine. The relative reduction in the BSFC is seen to be within the range of 7.6%. Zirconia has a low thermal conductivity material. It will act as barrier for the heat transfer to the surroundings from the components engine's combustion chamber and reduces the heat loss from the engine. Also, according to the first law of thermodynamics, the heat reduction in heat loss will ultimately increase the power output and thermal efficiency of the engine and this lead to reduce the BSFC.

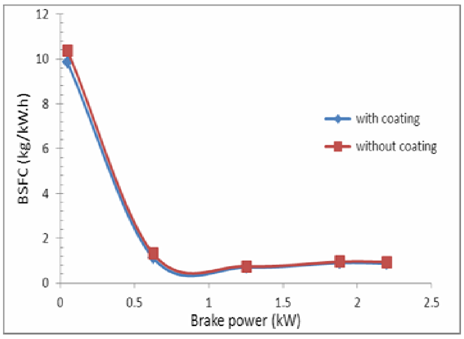

Fig. 3: BSFC versus brake power, before and after ceramic coating, at constant speed engine (3000 rpm)

In Fig. 4, the exhaust gas temperatures from the two engine configurations are plotted as a function of load. It can be seen from the graph the temperature of the exhaust gas is higher for the engine works under zirconia coated conditions than the engine works under normal conditions. This is due to the more amount of heat generated inside the combustion chamber, where all amount of heat cannot be converted into useful work. Exhaust gas temperature increase under this condition because of this heat that is mixed with the exhaust gas. The exhaust gas temperatures were seen to increase by 34.5 °C (on average) with the addition of insulation.

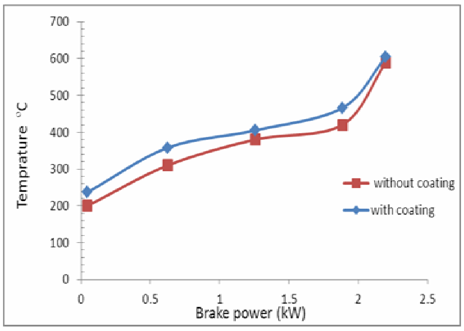

Fig.4: Exhaust gas temperature versus brake power, before and after ceramic coating, at constant speed engine (3000 rpm)

***Emissions*:**

From the fig. 5, it is clear that the CO emission is less in LHR engine this may be due to the complete combustion. The carbon monoxide, which arises mainly due to incomplete combustion, is a measure of combustion in efficiency. Generally, oxygen availability in diesel is high so at high temperatures carbon easily combines with oxygen and reduces the CO emission. It is observed that at part load (up to 0.62 kW) the CO emissions are roughly same for the engine with and without coating. And there is an increase of CO at full load condition when it runs without coating conditions because of the specific fuel consumption increase.

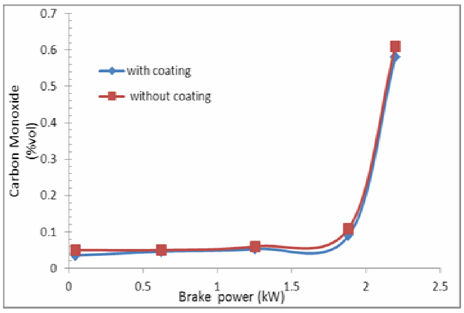

Fig. 5: CO emission versus brake power, before and after ceramic coating, at constant speed engine (3000 rpm)

The unburned HC emissions are higher when the engine works without the zirconia coating. The emission of unburned hydrocarbon from the LHR engines is more likely to be reduced because of the decreased quenching distance and the increased lean flammability limit. The higher temperatures both in the gases and at the combustion chamber walls of the LHR engine assist in permitting the oxidation reactions to proceed close to completion. In case of LHR engine with valves coating, HC is lower by about 13% than standard engine as shown in fig. 6.

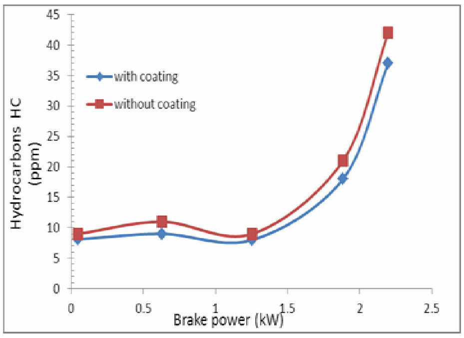

Fig. 6: HC emission versus brake power, before and after ceramic coating, at constant speed engine (3000 rpm)

5. Conclusion

From the observations and test results reported herein, applying thin ceramic coatings of (0.5) µm to the intake and exhaust valves of diesel fuel combustion engine may result in a significant reduction in fuel consumption, and it causes the cylinder walls to become hotter and increases exhaust gas energy. Almost an average of 34.5 °C increase in the combustion gas temperature has been observed for the LHR engine compared to the standard engine. The brake specific fuel consumption (BSFC) values of the LHR engine were found to be lowered by about 7.6% than those of the standard engine because some of the additional heat energy in the cylinder is converted into useful work due to the insulation of the ceramic coating. The emission characteristics of the insulated engine at moderate and full loads appeared to be attractive. Particulate emissions decreased clearly in the LHR engine. These reductions were up to 13.2% for HC and 14.5% for CO.

References

Adnan P., Halit Y. , Can H. ,and Ahmet K."The effects of injection timing on NOx emissions of a low heat rejection indirect diesel injection engine " Applied Thermal Engineering, Elsevier, pp.3042 – 3052, 2005 .

Ganesan, V., "Internal Combustion Engines", 3rd Edition, 2008.

Imdat T., "An experimental study of energy balance in low heat rejection diesel engine", Faculty of Engineering, University of Sakarya, Published by Elsevier Ltd, 2005.

İlker T. Y., Metin G., and Mehmet A**.,** "Thermal barrier coating for diesel engines ", International scientific conference, Gabrovo, November, 2010.

Michael A. M., "An investigation of metal and ceramic thermal barrier coatings in a spark-ignition engine", Graduate Department of Mechanical and Industrial Engineering, Msc. thesis, University of Toronto., 2009.

Mohanty R. K., "Internal Combustion Engines", McGraw-Hill, 2007.

Murthy P.V. K, Murali K. M. V. S., Sitarama R. A. , Vara P. C. M ., and Srinivasulu N.V., "Performance Evaluation of Low Heat Rejection Diesel Engine with Pure diesel ", international journal of applied engineering research, dindigul Volume1, No 3, 2010.

Pawar A. N. , and Jajoo B. N. "Analysis of Heat Transfer in Ceramic Coated Cylinder Head and Valves of Diesel Engines", IE (I) Journal.MC, Vol 86, April 2005.

Special Report: The art of the possible. Economist, http://www. economist.com/node/12544947, 2008.

Srivathsan, P.R. Babu, P.T. Banugopan, V.N. Prabhakar, S. Annamalai, K. “Experimental Investigation on a Low Heat Rejection Engine", published by IEEE, 2010