



The Effect of Ceramic Coating on Performance and Emission of Diesel Engine Operated on Diesel Fuel and Biodiesel Blends

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ABSTRACT

In this work, the effect of ceramic coating on performance, exhaust gas temperature and gases emissions of diesel engine operated on diesel fuel and biodiesel blends was investigated. A conventional four stroke, direct injected, single cylinder, diesel engine was tested at constant speed and at different load conditions using diesel fuel and biodiesel blends. The inlet and exhaust valves, the head of piston and cylinder head of the engine were coated by ceramic materials. Ceramic layers were made of (210-240) μm of Al_2O_3 and (30-60) μm of $4\text{NiCr}_5\text{Al}$ as a bond coat for inlet and exhaust valves and (350-400) μm of YSZ and (50-100) μm of $4\text{NiCr}_5\text{Al}$ as a bond coat for head of piston and (280-320) μm of Sic and (40-80) μm of $4\text{NiCr}_5\text{Al}$ as a bond coat for cylinder head. The coating technique adapted in this work is the flame spray method. The engine with valves, piston and cylinder head ceramic coated research was tested for the same operation conditions of the engine (without coating). The results showed that a reduction in brake specific fuel consumption of 19.29%, 15.91%, 14.65% and 7.06%, an increase in brake thermal efficiency of 23.68%, 19.77%, 16.51% and 6.32%, the increase in exhaust gas temperature of 9.01%, 7.22%, 15.7% and 11.42%, the reduction of CO emission of 18.57%, 20%, 20.5% and 27.77%, the reduction of HC emission of 28.97%, 43.9%, 38.88% and 36.41% for diesel, B5, B10 and B100 respectively.

Key words: ceramic coating, diesel engine, engine performance, emission, biodiesel.

تأثير الطلاء الخزفي على أداء وأنبعاث محرك ديزل يعمل بوقود الديزل وخليط ووقود الديزل الحيوي

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الخلاصة

في هذا البحث، تم دراسة تأثير الطلاء الخزفي على أداء ودرجة حرارة غاز العادم وأنبعاث الغازات لمحرك ديزل رباعي الاشواط وحقق مباشر وأحادي الاسطوانة. تم دراسة الاداء لهذا المحرك بسرعة ثابتة وحمل متغير باستخدام وقود الديزل الحيوي. تم طلاء وجه صمامي الدخول والعادم ووجه البستن ووجه الاسطوانة بمواد خزفية. حيث تم استخدام طبقة مكونة من (210-240) ميكرون من الألومينا كمادة طلاء و (30-60) ميكرون من نيكل-كروم-الألومينيوم كمسحوق طلاء رابط لطلاء صمامي الدخول والعادم وتم استخدام طبقة مكونة من (350-400) ميكرون من الزركونيا المثبتة بالياتيريا كمادة طلاء و (50-100) ميكرون من نيكل-كروم-الألومينيوم كمسحوق طلاء رابط لطلاء وجه لبستن وتم استخدام طبقة مكونة (280-320) ميكرون من سليكون

الكاريبيد كمادة طلاء و (40-80) ميكرون من نيكل-كروم-الالومنيوم كمسحوق طلاء رابط لطلاء وجه الاسطوانة. في هذا العمل، اعتمدت تكنولوجيا الطلاء الحرارية بتقنية الرش باللهب. اختبر المحرك تحت نفس ظروف التشغيل قبل الطلاء وقد اعطت النتائج العملية انخفاض في معدل استهلاك الوقود المكبح بمقدار (19.29%، 15.91%، 14.65%، 7.06%) وزيادة في كفاءة الكبح الحرارية بمقدار (23.68%، 19.77%، 16.51%، 6.32%) وزيادة في درجة حرارة غاز العادم بمقدار (9.01%، 7.22%، 15.7%، 11.42%) وانخفاض في غاز اول اوكسيد الكربون بمقدار (18.75%، 20%، 20.5%، 27.77%) وانخفاض في انبعاث الهيدروكربونات غير المحترقة بمقدار (28.97%، 43.9%، 38.88%، 36.41%) لوقود الديزل ووقود الديزل الحيوي بنسبة خلط (5:95) و (10:90) ووقود الديزل الحيوي (100%) على التوالي.

مفاتيح الكلمات: طلاء السيراميك، ماكينة الديزل، اداء الماكينة، الانبعاث، الديزل الحيوي.

1. INTRODUCTION

The effect of ceramic coating on performance, exhaust gas temperature and gases emissions of diesel engine operated on diesel fuel and biodiesel blends was investigated using a conventional four stroke, direct injected, single cylinder, diesel engine. The standard engine (without coating) was fully instrumented and connected to the dynamometer. The tests were performed at different engine loads and constant speed. The experiments were conducted at six load levels, viz. 1, 2, 3, 4 and 5 (N.m) and constant speed (3000 rpm). The required engine load percentage was adjusted by using the hydraulic dynamometer. These procedures were repeated to cover the engine load range at the specified speed. This work is adopted with an investigation of ceramic coating when the inlet and exhaust valves, head of piston and cylinder head insulation were applied. The valves were coated with (30-60) μm bond coating ($4\text{NiCr}_5\text{Al}$) then coated with a (210-240) μm coating of Al_2O_3 , the head of piston was coated with (50-100) μm bond coating ($4\text{NiCr}_5\text{Al}$) then coated with a (350-400) μm coating of 8% Y_2O_3 - ZrO_2 and the cylinder head was coated with (40-80) μm bond coating ($4\text{NiCr}_5\text{Al}$) then coated with a (280-320) μm coating of Sic by the flame spray technique. To ensure the repeatability of experimental results, every test was repeated another one time. The average value of the repeated testes was adopted in the analysis. Points of large discrepancy were neglected. There were some differences between the tests of the same conditions. The reasons behind that are the instruments error, the change in the ambient conditions, and the human error.

2. BACKGROUND

Until the middle of the 20th century the number of IC engines in the world was small enough that the pollution they emitted was tolerable, and the environment, with the help of sunlight, stayed relatively clean. As world population grew, power plants, factories, and an ever-increasing number of automobiles began to pollute the air to the extent that it was no longer acceptable, **Willard W. P, 1997**.

Engine efficiency improvement efforts via constructional modifications are increased today; for instance, parallel to development of advanced technology ceramics, ceramic coating applications in internal combustion engines grow rapidly, **Murat et al, 2012**.

A TBC system, usually, consists of two layers - a metallic bond coat and top ceramic coat. The function of the bond coat is to protect the substrate from oxidation and provide sufficient bonding of the top ceramic coat to the substrate. The insulating ceramic layer provides a reduction of the temperature of the metallic substrate, which leads to improved component durability, **Satrughna Das, 2007**.

Thermal barrier coatings (TBC) provide the potential for higher thermal efficiencies of the engine, improved combustion and reduced emissions. In addition, ceramics show better wear



characteristics than conventional materials. Lower heat rejection from the combustion chamber through thermally insulated components causes an increase in available energy that would increase the cylinder work and the amount of energy carried by the exhaust gases, which could be also utilized. Thermal barrier coatings are becoming increasingly important in providing thermal insulation for LHR engine components, **Sivakumar et al, 2012**.

Dennis Assanis and Kevin Wiese, 1991 studied the effects of ceramic coatings on diesel engine performance and exhaust emissions. Tests were carried out over a range of engine speeds at full load for a standard metal piston and two pistons insulated with 0.5 mm and 1.0 mm thick ceramic coatings. The 0.5mm ceramic coated piston produced 10% higher thermal efficiency than the metal piston and exhaust CO levels were between 30% and 60% lower than baseline levels. Similarly, unburned HC levels were 35% to 40% lower for the insulated pistons.

Holloman L. and Levy A.V., 1992, discussed the use of ceramic coatings on the combustion zone surfaces of large, natural gas-fueled, internal combustion engines was. The performance was measured in the field before and after coating. It was determined that the durability, power output, fuel consumption, exhaust emissions, and other operating characteristics all improved due to ceramic coating of the flame side surfaces of cylinder heads, power pistons, and valves.

Hejwowski T. and Weronki A., 2002, evaluated the effects of thin thermal barrier coatings on the performance of a diesel engine. Results obtained from the engine with thermally insulated pistons were compared with the baseline engine data. The performance of the modified engine-driven car was found satisfactory. The ceramic coating did not produce observable knock in the engine, no significant wear of piston skirts or cylinder liners was found.

Shrirao P. N. and Pawar A. N., 2011, studied the effect of mullitecoating (Al₂O₃= 60%, SiO₂= 40%) on a single cylinder, four stroke, direct injection, diesel engine. Tests were carried out on standard engine (uncoated) and low heat rejection (LHR) engine with and without turbocharger. The results showed that there was 2.18% decreasing in specific fuel consumption, 12% increasing in exhaust gas temperature, 22.05% decreasing in CO emission and 28.20% decreasing in HC emission of LHR engine with turbocharger compared to standard engine at full load.

The aim of this paper is to study the effect of ceramic coating inlet and exhaust valve, head of piston and cylinder head of diesel engine on the performance of diesel engine operated on diesel fuel and biodiesel blends and emissions like (CO, CO₂, and HC). The results of the two cases are compared.

3.EXPERIMENTAL WORK

3.1 Coatings Technique

The coating technique adopted in this work is the flame spray method type (rototec 800) as shown in **Fig.1**. 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.

3.2 Coating Procedure

The following procedure was adopted during coating process:

1. The substrates were cleaned and roughened using emery paper (p220) and grit-blasted using sand blast system with pressure (4-6) bar by sand blast device.
2. The grit-blasted substrates were cleaned using anhydrous ethanol alcohol and dried at 200 °C by a furnace for 30 min.

3. The ceramic powder type Al₂O₃ (400 mesh) and 4NiCr5Al metal powder (bond coat) with particle sizes ranging from 50 to 90 μm for inlet and exhaust valves coating – **Fig. 2**, 8% Y₂O₃-ZrO₂ (325 mesh) and (4NiCr5Al) metal powder (bond coat) with particle sizes ranging from 50 to 90 μm for piston coating – **Fig. 3** and Sic (200 mesh) and (4NiCr5Al) metal powder (bond coat) with particle sizes ranging from 50 to 90 μm for cylinder head coating – **Fig. 4**, were used.
4. The substrate is fixed on the flange normal to the flame and powder flow.
5. The cooling system (air compressor) is switched on to cool the substrates and protect it from melting during spraying process.
6. The system is switched on and the flame is ignited. The flame holder is controlled manually.
7. The bond powder required for the first layer is loaded into the holder.
8. The substrate is heated to a suitable temperature around (300 °C) by the flame.
9. The coating process is started by moving a lever on the hopper to allow all the powder to flow through the holder with the flame. A distance of about (20 cm) between the flame and the specimen is maintained.
10. Step 8 is repeated until 30-60 μm as a thickness of bond layer is obtained for valves, 50-100 μm for piston and 40-80 μm for cylinder head.
11. The ceramic powder (required for the top coat) is then loaded and step 7 is repeated until 210-240 μm thickness for valves is obtained, 350-400 μm for piston and 280-320 μm for cylinder head.
12. 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.
13. For adhesion process, the topcoat is preheated to about 1500°C directly after completing the spray process.
14. The flame is then withdrawn gradually away from the valve to minimize thermal shock.
15. After the thermal coating process is completed, the excess parts of coating material are removed by grinding process to avoid crankshaft breakdown.

3.3 Evaluation of Coating (Bond Strength and Hardness)

The bond strength of coatings is the most important property which determines the field of use of coatings especially for thermal barrier coatings. The Adhesion strength value between the substrate and the coating layers was measured using the apparatus type (Microcomputer Controlled Electronic Universal Testing Machine (WDW-50E)). The strength found equals to (26.8) MPa for 8% YSZ, (31.6) MPa for alumina coating and (39.64) MPa for silicon carbide coating. The Adhesion strength depends on the type of bonding layer and, spraying distance. The hardness value of (8% YSZ) coating was measured using a Vickers-hardness and found equal to (710) Hv and (788) Hv for alumina coating and (855) Hv for silicon carbide coating.

3.4 Test Engine Setup and Procedure

The engine tests were conducted in a single cylinder, direct injection (F 170) type diesel engine. Table 1 presents the main technical specifications of the engine used and **Fig. 5** shows it. 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 (4.5 l) and a glass tube of known volume was used. The measurement of air consumption consists of an air box which is used to reduce the vibration



presented when the engine is working with a water manometer. The schematic diagram of the experimental set up is shown in **Fig. 5**. The temperature of exhaust gases was measured by temperature digital indicator (code 952416) that is fixed at the entrance of exhaust gas pipe (the beginning of the exhaust gas exit). The exhaust gases analyzer type (FLUX 2000-4) was used to analyze exhaust gases. 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 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 and biodiesel blends 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. To avoid interface between valves and the piston head due to valves coating, a gasket with 0.3 mm thickness (thickness of valve coating) was inserted between valves and piston head which works to withdraw valves from the piston head and thus maintain the overlap time and the standard piston was machined to remove material equal to the desired coating thickness and to keep the compression ratio unchanged.

3.5 Fuels Used

In this study the commercial diesel fuel employed in the tests was obtained locally and alternative used fuel substitute for diesel fuel was biodiesel with the mixing ratio of 5:95, 10:90 of biodiesel to diesel fuel and 100% biodiesel. The marketing specifications of fuel used as provided from chemical engineering department in technology of university are shown in table 2. To avoid isolation when biodiesel mixed with diesel fuel, solenoid driven dosing pump type (AQUA) was used as a fuels mixer. Where each type of fuel enters the pump through two different tubes and go out of one tube, thus both types of fuel are mixed well. Laboratory samples of Biodiesel was prepared by mixing alcohol (methanol) with KOH as a catalyst in a tank and then added sunflower oil heated to 55°C to the tank and then the resulting solution was mixed well for about 30 minutes and stored for 24 hour. Then be observed biodiesel layer to the top and glycerol layer to the bottom. Then biodiesel layer was separated from the lower layer and mixed well with water for 10 minutes as well as the resulting solution was left for 24 hour. Then the upper biodiesel layer was separated from water layer and heated to 100°C to eliminate water moisture. The biodiesel production is shown in **Fig. 6**.

Mathematical relationships used to calculate engine performance is, Ganesan, 2008, Mohanty, 2007.

1. Fuel consumption:(Kg/s)

$$m_f = \frac{V_f}{time} * \rho_{fuel} \quad (1)$$

where:

V_f - volume of fuel consumption (m^3)

2. Brake power :(kW)

$$W_b = \frac{2\pi NT_b}{60000} \quad (2)$$

Where:



Tb - torque of engine ($N.m$)

N - rotational speed (rpm)

3. Brake Specific Fuel Consumption: $\left(\frac{kg}{kW.hr}\right)$

$$BSFC = \frac{m_f}{W_b} * 3600 \quad (3)$$

4. Brake thermal efficiency:

$$\eta_{tb} = \frac{W_b}{m_f * L.C.V * \eta_c} \quad (4)$$

$$= \frac{3600}{BSFC * L.C.V * \eta_c} \quad (5)$$

Where:

$L.C.V$ - lower calorific value of kilogram fuel (kJ/kg)

η_c -combustion efficiency (assuming=97%)

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.

4. RESULTS AND DISCUSSION:

4.1 Brake Specific Fuel Consumption:

Figs. 7, 8, 9 and 10 indicate the variations of the BSFC for diesel fuel and biodiesel blends before and after ceramic coating under various engine torques. The BSFC of LHR engine at all torques is lower than the standard engine with diesel fuel and biodiesel blends. The main reason is that the ceramic materials 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 as per 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.

4.2 Brake Thermal Efficiency:

The variation of BTE with engine torque is shown in **Figs.11, 12, 13 and 14** for base engine and TBC engine for different fuels under various engine torques. The TBC engine reports better performance than the base engine. Improved brake thermal efficiency was observed in TBC engine at all torques. The thermal barrier coating in combustion chamber improves the BTE when compared with base engine. Since the thermal barrier coating prevents the heat loss from the walls to the surroundings. The BTE was increased due to the reduction in heat transfer from the gases to the walls during the combustion or expansion because of the higher wall temperatures. Thin thermal barrier coating shifts the combustion from premixed to diffusion stage.

4.3 Exhaust Gas Temperature:

Figs. 15, 16, 17 and 18 show the variations of EGT for base engine and TBC engine for different fuels. It is concluded that the EGT is higher for the engine with ceramic coated components



than the engine under normal conditions and with different fuels. This is due to the raise in the temperature of the mixture inside the combustion chamber and decrease in heat losses going into the cooling system and outside due to the coating and due to increase in amount of fuel burnt per unit time.

4.4 Emissions:

Figs. 19, 20, 21 and 22 show CO variations for base engine and TBC engine for different fuels under various engine torques. It is clear that CO is decreased after the coating due to the complete combustion. CO emission from diesel engine is related to the fuel properties as well as combustion characteristics. It is well known that better fuel combustion usually resulted in lower CO emission. The carbon monoxide, which arises mainly due to incomplete combustion, is a measure of combustion efficiency. Generally, oxygen availability in diesel fuel and biodiesel blends is high so at high temperatures carbon easily combines with oxygen and reduces the CO emission.

Figs. 23, 24 and 25 show variations of HC emissions with torque of the engine before and after ceramic coating. In general, it is clear that the unburned hydrocarbon emissions are reduced when the engine works with coating. HC emission is low in the LHR engine with compared with the standard engine. 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.

5. CONCLUSION

In this study, the effect of ceramic coating on the performance, exhaust gas temperature and gases emissions characteristics of a diesel engine operated on diesel fuel and biodiesel blends were experimentally investigated. Based on the experimental results of this study, the following conclusions were drawn.

- The BSFC of LHR engine were found to be lowered than BSFC of SE due to the effect of ceramic insulation which act as a barrier for the heat transfer to the surrounding and reduces the heat loss from the engine. These reductions were up to 19.29%, 15.91%, 14.65% and 7.06% for diesel fuel, B5, B10 and B100 respectively.
- The BTE of LHR engine were found to be higher than BTE of SE due to the reduction in heat transfer from the gas to the walls during the combustion or expansion because of the higher wall temperatures. These increasing were up to 23.68%, 19.77%, 16.51% and 6.32% for diesel fuel, B5, B10 and B100 respectively.
- The EGT of LHR engine were found to be higher than EGT of SE due to the raise in temperature of mixture inside the combustion chamber and decrease in heat losses going into the cooling system. These increasing were up to 9.01%, 7.22%, 15.7% and 11.42% for diesel fuel, B5, B10 and B100 respectively.
- Particulate emissions decreased clearly in LHR engine compared with SE engine due to the more complete combustion in the insulated configurations. These reductions were up to 18.57%, 20%, 20.5% and 27.77% for CO of diesel, B5, B10 and B100 respectively and 28.97%, 43.9%, 38.88% and 36.41% for HC of diesel, B5, B10 and B100 respectively.

NOMENCLATURE

CO-carbon monoxide

HC- hydrocarbons (ppm)

CO₂-carbon dioxide

B5-5:95 of biodiesel to diesel fuel mixing ratio

B10-10:90 of biodiesel to diesel fuel mixing ratio

B100-100% biodiesel

BSFC-brake specific fuel consumption

YSZ- yttria-stabilized zirconia

LHR- low heat rejection

SE-standard engine

KOH- potassium hydroxide

EGT-exhaust gas temperature

BTE-brake thermal efficiency



Figure 1. The flame spray gun type (rototec 800).



Figure 2. Photographic view of valves (before and after ceramic coating).



Figure 3. Photographic view of piston (before and after ceramic coating).

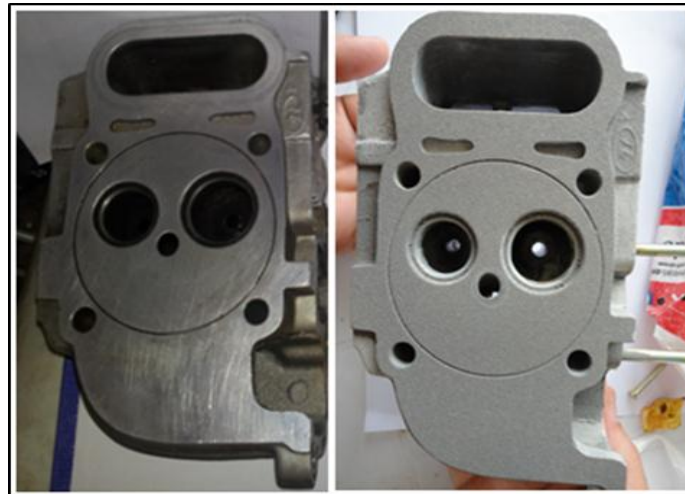


Figure 4. Photographic view of cylinder head (before and after ceramic coating).

Table1. Main technical specifications of engine.

Item	Technical specification
Model	170F China
Type	Single-cylinder, vertical, 4-stroke, air-cooled, direct-injection
Bore×Stroke (mm)	70×50
Displacement (l)	0.211
Compression ratio	20:1
Fuel tank capacity (l)	4.5
Max. speed (rpm)	3600
Max. power (kW)	3.4



Figure 5. Diesel engine (the board and engine).

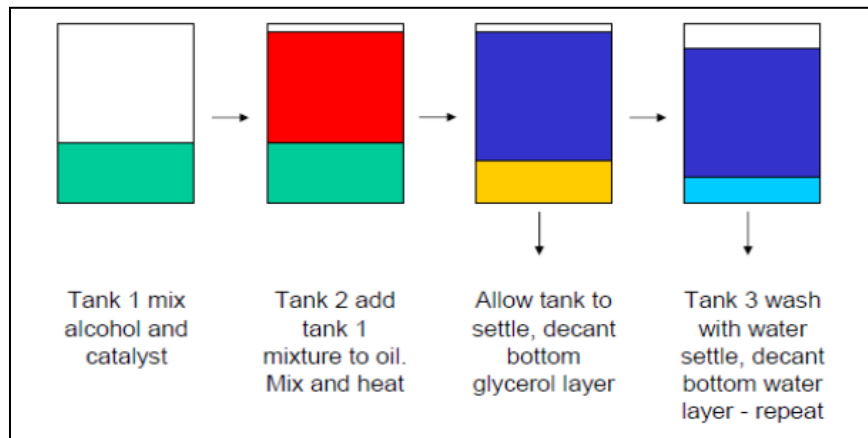


Figure 6. Biodiesel production (Daniel Geller).

Table 2. The marketing specifications of fuel used as provided from chemical engineering department in technology of university.

Property of fuel	Cetane number at 23°C	Pour point(°C)	Specific Gravity at 15 °C	Kinematic Viscosity at 40 °C	Flash Point(°C)	Carbon Residue (Wt. %)	Lower calorific value (kJ/kg)
Diesel	46.8	-25	0.826	3.5	77	2	45208.8
5% Biodiesel + Diesel	49.6	Less than -10	0.828	3.420	89	2.63	41678
10% Biodiesel + Diesel	51.5	Less than -10	0.831	3.7	92	3.1	41422
100% Biodiesel	69.5	Less than -10	0.884	5.486	178	6.25	40834

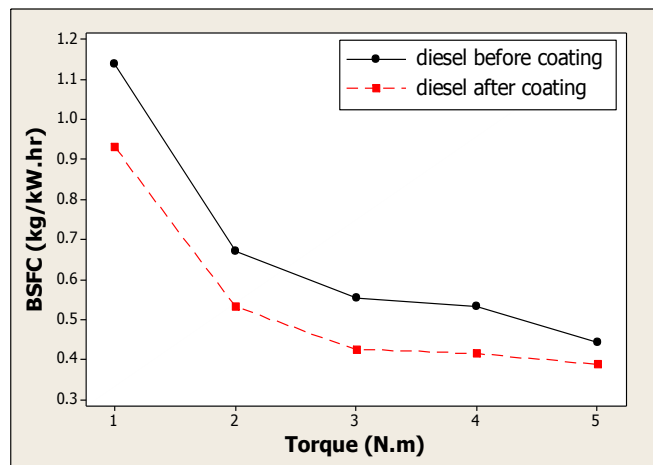


Figure 7. BSFC versus torque before and after ceramic coating for diesel fuel.

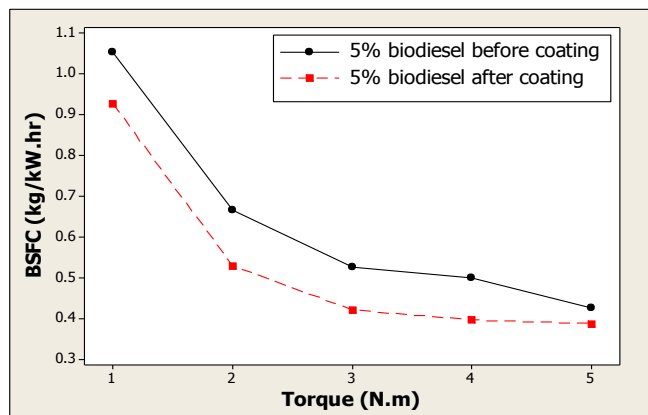


Figure 8. BSFC versus torque before and after ceramic coating for 5% biodiesel.

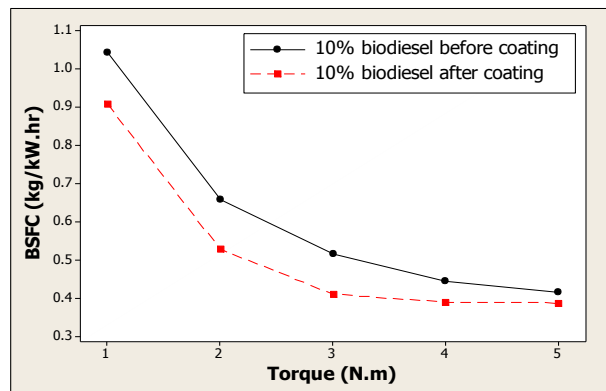


Figure 9. BSFC versus torque before and after ceramic coating for 10% biodiesel.

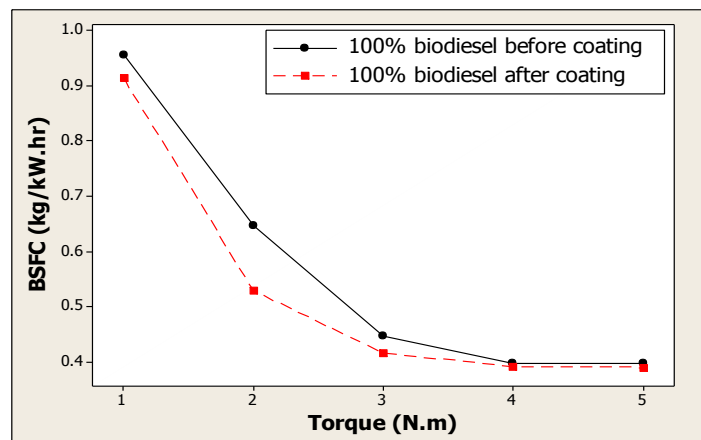


Figure 10. BSFC versus torque before and after ceramic coating for 100% biodiesel.

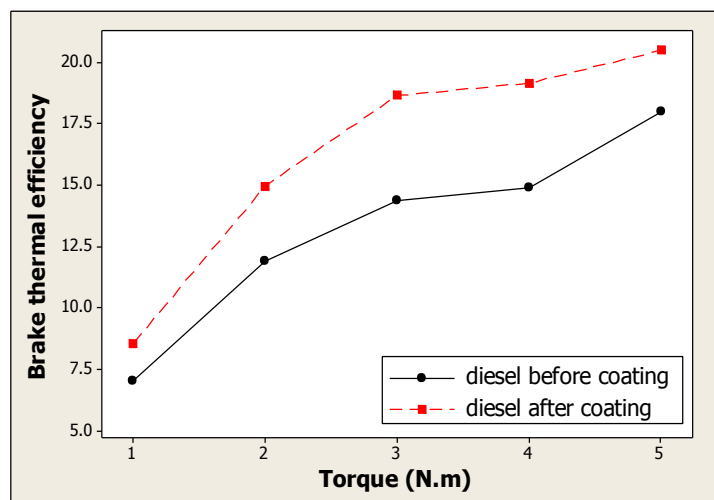


Figure 11. BTE versus torque before and after ceramic coating for diesel fuel.

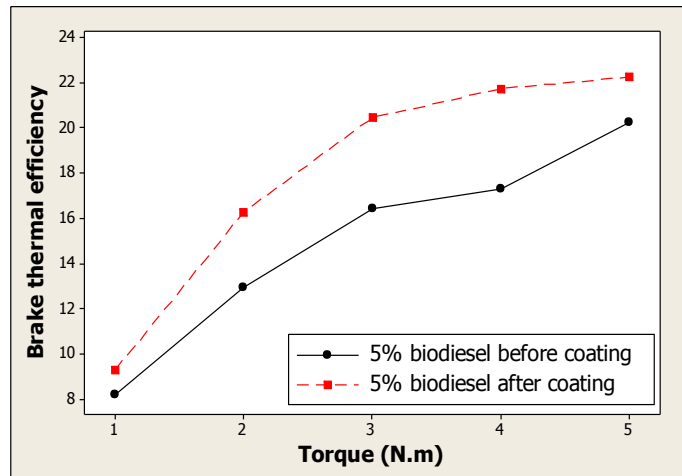


Figure 12. BTE versus torque before and after ceramic coating for 5% biodiesel.

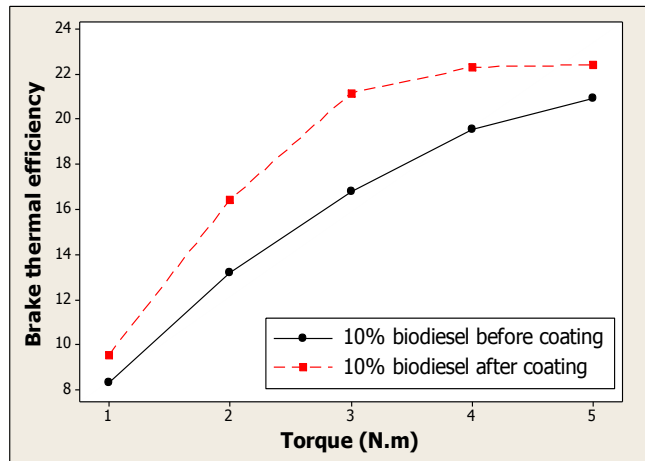


Figure 13. BTE versus torque before and after ceramic coating for 10 % biodiesel.

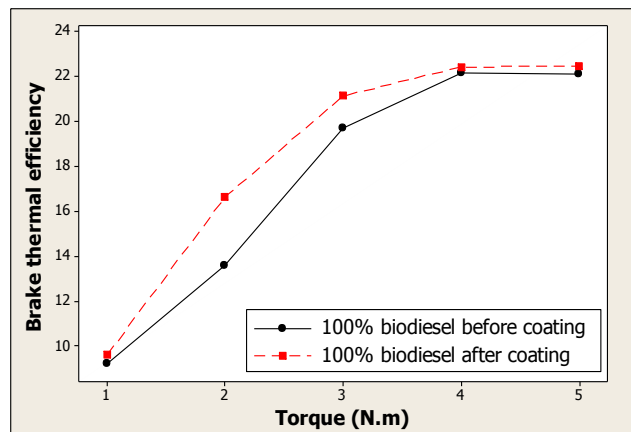


Figure 14. BTE versus torque before and after ceramic coating for 100 % biodiesel.

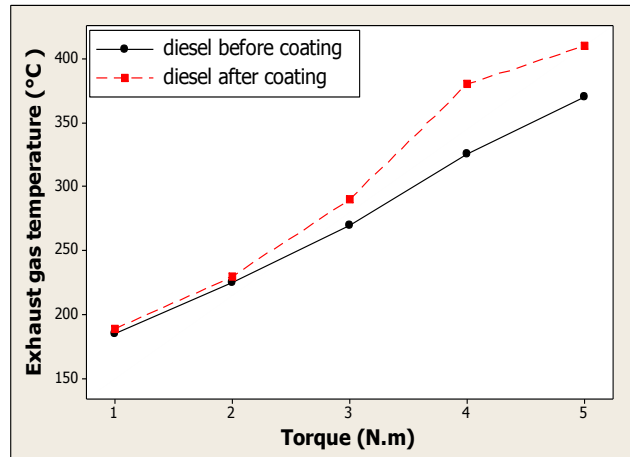


Figure 15. EGT versus torque before and after ceramic coating for diesel fuel.

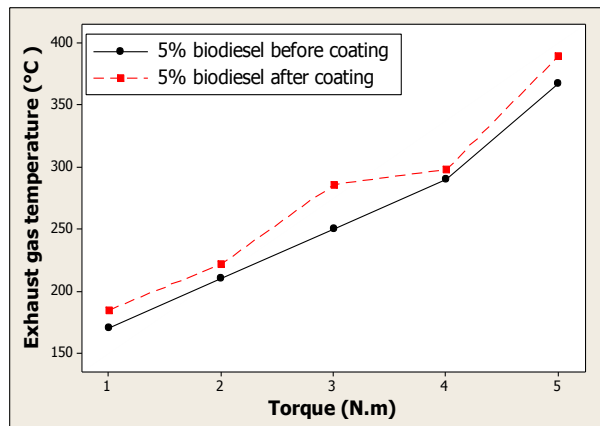


Figure 16. EGT versus torque before and after ceramic coating for 5% biodiesel.

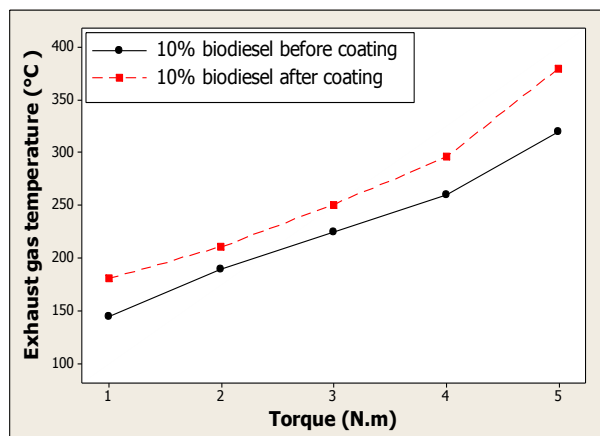


Figure 17. EGT versus torque before and after ceramic coating for 10% biodiesel.

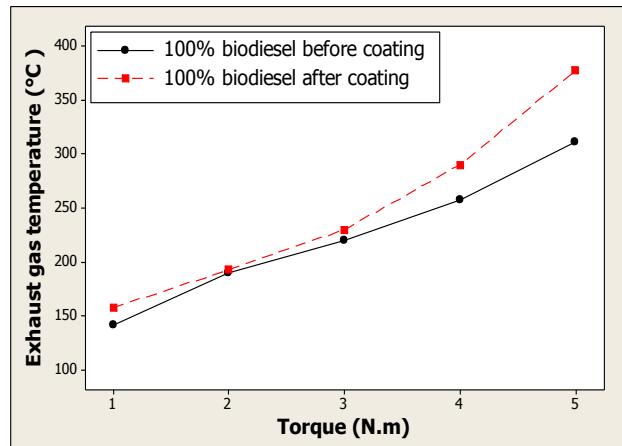


Figure 18. EGT versus torque before and after ceramic coating for 100% biodiesel.

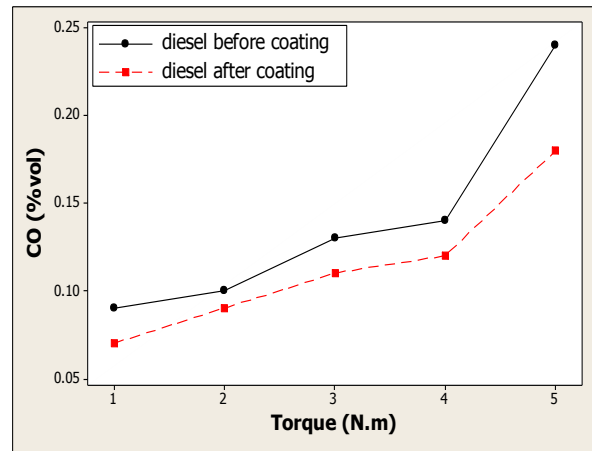


Figure 19. CO emission versus torque before and after ceramic coating for diesel fuel.

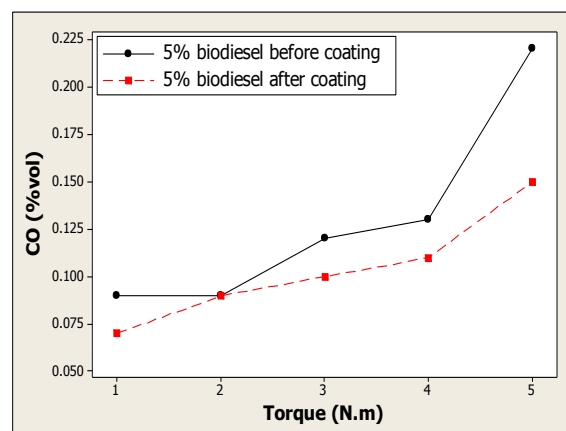


Figure 20. CO emission versus torque before and after ceramic coating for 5% biodiesel.

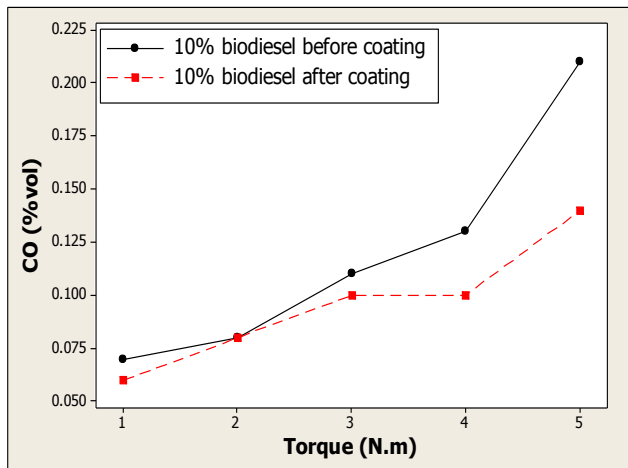


Figure 21. CO emission versus torque before and after ceramic coating for 10% biodiesel.

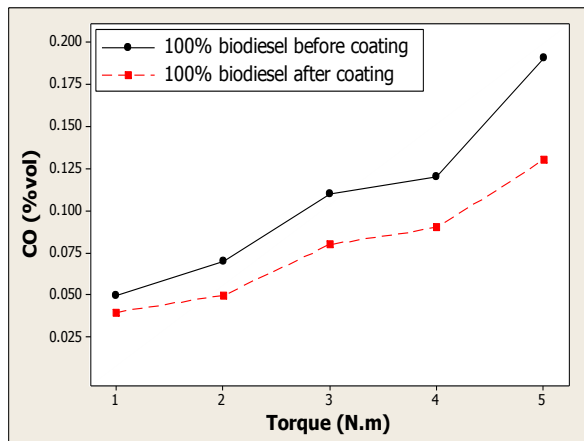


Figure 22. CO emission versus torque before and after ceramic coating for 100% biodiesel.

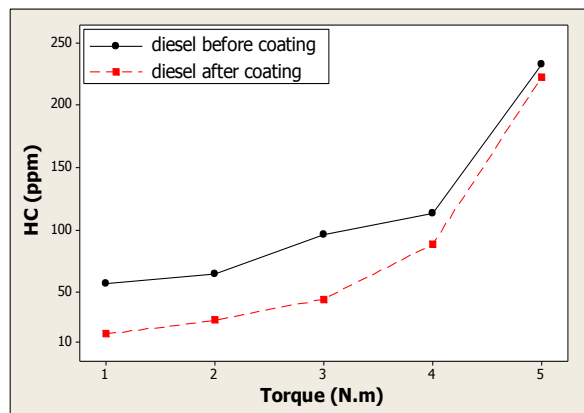


Figure 23. HC emission versus torque before and after ceramic coating for diesel fuel.

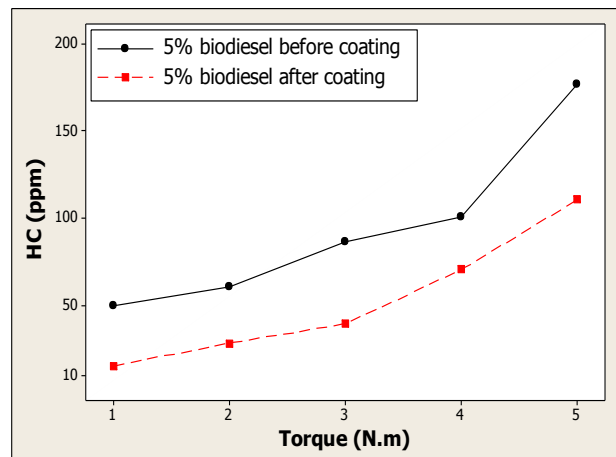


Figure 24. HC emission versus torque before and after ceramic coating for 5% biodiesel.

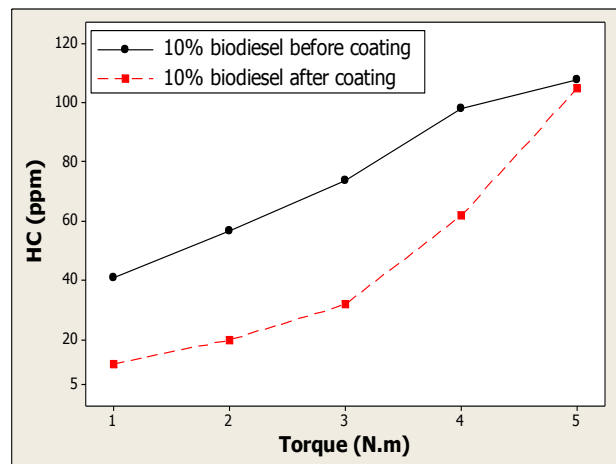


Figure 25. HC emission versus torque before and after ceramic coating for 10% biodiesel.

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