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EXPERIMENTAL ANALYSIS OF THE COMBUSTION CHAMBER COATED WITH Mo AND Al_2O_3-TiO_2 IN A DIESEL ENGINE

EKSPERIMENTALNA ANALIZA ZGOREVALNE KOMORE DIZELSKEGA MOTORJA PREVLEČENE Z Mo IN Al_2O_3-TIO_2

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The effect of thermal-barrier coatings (TBCs) reduces fuel consumption, effectively improving the engine efficiency. This research focused on a TBC with a thickness of 300 µm insulating the combustion chamber of a direct ignition (DI) engine. The piston crown, inlet and exhaust-valve head were coated using air-plasma-spray coating. Ceramic powder materials such as molybdenum (Mo) and aluminum oxide titanium dioxide (Al_2O_3-TiO_2) were used. A performance test of the engine with the coated combustion chamber was carried out to investigate the brake power, brake thermal efficiency, volumetric efficiency, brake specific fuel consumption and air-fuel ratio. Also, an emission-characteristic test was carried out to investigate the emissions of unburned hydrocarbon (HC), carbon monoxide (CO), nitrogen oxides (NO, NO_2, NO_3) and smoke opacity (SO). The results reveal that the brake thermal efficiency and brake specific fuel consumption show significant increases because of these coating materials. The effect of the Al_2O_3-TiO_2 coating significantly reduces the HC and CO engine emissions.

Keywords: thermal barrier coatings, molybdenum, aluminum oxide titanium dioxide, hydrocarbon, carbon monoxide

Termične zaščitne prevleke (TBC; Thermal Barrier Coatings) učinkovito zmanjšajo porabo goriva in izboljšujejo izkoristek dizelskih motorjev. V pričujoči raziskavi so se avtorji osredotočili na TBC debeline 300 µm, ki je bila nanešena kot izolacijska prevleka na delih zgorevalne komore dizelskega motorja. Prevleke na obročih ventilov ter notranjih in zunanjih delov izpušnih glav ventilov so bile narejene s postopkom tehnike plazemskega naprševanja v zraku. Za izdelavo prevlek so uporabili keramične prahove na osnovi Mo in Al-Ti oksida (Al_2O_3-TiO_2). Na motorju z zgorevalno komoro, ki je imela izdelane prevleke so ugotavljali njegove lastnosti. Testirali so moč motorja, termični izkoristek, volumetrični izkoristek, specifično porabo goriva in razmerje zrak-gorivo. Prav tako so bile izvedene meritve emisij zgorevalnih plinov tako, da so določili vsebnost nezgorelih ogljikovodikov (HC), vsebnost ogljikovega monoksida (CO), dušikove okside NO_x (NO, NO_2, NO_3) in količino delcev v izpušnih plinih (SO; angl.: smoke opacity). Rezultati testov so pokazali, da je izdelana termična zaščitna prevleka pomembno vplivala na povečanje termični izkoristek in specifično porabo goriva. Prevleka na osnovi Al_2O_3-TiO_2 močno zmanjša emisije HC in CO v izpušnih plinih motorja.

Ključne besede: prevleka kot termična zaščita, molibden, aluminijev oksid, titanov dioksid, ogljikovodiki, ogljikov monoksid

I INTRODUCTION

The engine combustion chamber surface, piston crown, head of the cylinder, inlet and exhaust valves were coated with the base coating of NiCrAl and top coating of $CaZrO_3$ and $MgZrO_3$ with plasma spraying.[1] A thermal-barrier coating can eliminate visible smoke, NOx emissions.[2] The injection delay and EGR rate in a diesel engine were investigated in the optimum EGR rate range of 15–20 % for 550 cm^3 and 1100 cm^3. The thermal fatigue resistance of the two TBC layers was investigated and it was found that the degradation mechanism increased the spallation of the coated diesel and petrol engine.[4] The TBC-coated engine compared with the engine without a coating exhibited a 6 % reduction in the heat loss through the piston and cylinder wall coating. To assess an aluminium-alloy piston, cast iron with a thickness of 100-µm and a 200-µm oxide-based coating were used.[5]

The effects of ceramic coatings on a diesel engine provide for a much better thermal efficiency, lower levels of CO, unburned HC, NO_x concentration and also a reduced smoke emission into the coated engine. Some researchers examined the performance and emission of a coated engine.[6] Engine efficiency improved due to the increased thickness of the yttria-stabilized zirconia (YSZ) coating, decreased temperature and heat flux and a redesign of the piston crown using a finite-element analysis.[7] Another study was focused on various types of coatings used in different structural engineering materials, examining the thermal insulation, corrosion, erosion, wear and lubrication.[8] The efficiency and ecological characteristics of a VCR diesel engine were improved due to the changes in the compression ratio. A conventional engine has a different speed and load at ambient conditions.[9]

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The study the wear characteristics, an air-plasma-sprayed CoNiCrAlY inner metallic coating on an aluminium-alloy substrate was examined. The available literature concentrates on the wear characteristics and microstructure properties of an CoNiCrAlY coating applied with the air-plasma-spray technique used to increase the sliding distance and reduce the wear rate.[10] Some researchers found the crack number density theory relating to an air-plasma-sprayed thermal barrier coating. They examined a crack-number-density model, conducting a quasi-isothermal/cyclic oxidation test to assess an air-plasma-sprayed coating. This CND model can be described as a thermal-barrier-coating failure.[11] Thermal barrier coatings with an Al_2O_3–Pt composite bond coat and $La_2Zr_2O_7$–Pt top coat are prepared with cathode plasma electrolytic deposition. The thermal barrier coating can prevent a low oxygen-diffusion rate, low thermal conductivity and increase the mechanical property because of the cathode plasma electrolytic deposition. The coating consisted of an Al_2O_3 bond coat with a thickness of 6–8 μm and a $La_2Zr_2O_7$ top coat with a thickness of 120 μm.[12] The use of a biodiesel/diesel blended fuel by a common-rail DI diesel engine showed that a higher biodiesel content causes a low engine power output. This effect of a biodiesel blend is found up to B50.[13] In the TBC on a diesel engine, a rich mixture region leads to its better performance due to a higher temperature and a higher surface-to-volume ratio. Improvement in the thermal efficiency leads to reduced heat-transfer losses during engine emission and combustion.[14] The thermal behavior of the electrolytic jet plasma oxidation (EJPO) coating of an IC engine was analyzed using a finite-element-analysis model, and the wear resistance was evaluated.[15]

The emission reduction occurs when a thermal-barrier-coated engine uses a blend of various non-edible oils, cashew-nut-shell oil, orange oil and neem oil obtained via a transesterification process, which can also modify the biodiesel used for an engine coated with partially stabilized zirconia material with a thermal barrier coating. The study analyzing the above focused on finding an alternative fuel with better BTE, BSFC, reduced engine emissions of HC, CO and NO_x in comparison with conventional diesel.[16] Performance parameters of the engines using biodiesel-diesel blends were investigated by applying the Taguchi method and grey relational analysis. The result showed the maximum performance and minimum emission. A compression ratio of 14, a nozzle pressure of 250 bar and injection timing of 20° allowed the maximum performance of a diesel engine.[17] The benefits of the thermal barrier coating are a greater level of thermal fatigue and heat release rate within a yttria-stabilized zirconia-insulated engine component using diesel and biodiesel. The piston was insulated with plasma-spray coating.[18] This study focuses on a 300-μm-thick thermal barrier coating (TBC) for the combustion chamber of a single-cylinder four-stroke diesel engine. The piston crown as well as the inlet and exhaust valve heads are coated with an air-plasma-spray coating technique. According to the available literature, the use of aluminium oxide titanium dioxide (Al_2O_3-TiO_2) ceramic-powder coating and punnagam oil methyl ester (POME) is the preferred method for improving emission levels.[19] By acting as a thermal barrier, the coating protects the coated part wherever it may be in the engine. Aluminum oxide (Al_2O_3) + molybdenum (Mo) + titanium oxide (TiO_2) (40 % + 30 % + 30 %) alloys constitute the top coat of the piston. The best performance can be obtained by combining the selected materials and their respective properties.[20] According to this research paper, engine performance is improved due to a 15 % decrease in the oil consumption, and the operation of the component that is the heart of the internal combustion engine, is 10 % higher than that of the traditional engine, whose overall fuel consumption decreases by 11 %.[21] The effects of the methyl ester produced from corn oil via transesterification are beneficial. The performance of D2 fuels and the rate of exhaust emissions were investigated using identically coated and uncoated engines. The tests were first carried out on the uncoated engine, then on the coated engine, and the results were compared. All the test fuels used for the coated engine showed a decrease in the engine power and specific fuel consumption, as well as significant improvements in exhaust-gas emissions (except for NO_x) when compared to the uncoated engine.[22] The objective of this research is to evaluate the thermal barrier coating (TBC) that can withstand the temperature of the combustion chamber using ceramic powder materials of molybdenum (Mo) and aluminium oxide titanium dioxide (Al_2O_3-TiO_2).

2 SELECTION OF TBC MATERIALS

An internal combustion engine combusts fuel producing a high temperature inside the combustion chamber. With the increasing temperature, atmospheric oxygen and nitrogen react to produce NO_x (NO, NO_2, NO_3) pollutants of the atmosphere. This is because the engine temperature is maintained at a certain level due to the insulated combustion chamber.

The physical and chemical properties of the Al_2O_3-TiO_2 ceramic powder combined with the property that can withstand the wear and tear, a low coefficient of friction, higher ionic conductivity, high hardness and low thermal conductivity can create better engineering materials. The chemical composition of Al_2O_3-TiO_2 includes 87 % of Al_2O_3, 9.5–13.5 % of TiO_2, 0.5 % of SiO_2 and 3 % of MgO. Molybdenum exhibits of a high melting point, higher thermal conductivity and low coefficient of thermal expansion used in many industrial applications. The physical and chemical properties of Al_2O_3-TiO_2 and Mo, respectively, are presented in **Table 1**.

Table 1: Properties of Al_2O_3-TiO_2 and Mo

Properties	Al_2O_3-TiO_2	Mo
Molecular weight (g/mol)	181.86	95.94
Density (kg/m^3)	3500	1020
Melting point T_m (°C)	2000	2620
Thermal conductivity λ W/(m·K) at 20 °C	2–4	142
Coefficient of thermal expansion K^{-1} at 20 °C	2×10^{-6}	5.2×10^{-6}
Poisson's ratio ν at 20 °C	0.21	0.31
Hardness (VHN)	–	160–180
Young's modulus E (GPa)	20	320
Nominal particle size (µm)	45-50	–
Coating weight (mg/cm^2)	0.18	–
Service temperature (°C)	540	700
Refractive index	1.7	3.7362

3 EXPERIMENTAL SET-UP

Figure 1 shows the experimental set-up of a TVI Kirlosker direct-ignition engine, operating at a power of 4.86 kW and 1500 min^{-1}. A water-cooled engine is connected to eddy-current dynamometer link PV angle encoder sensors and engine exhaust manifold with attached AVL DiGas analyzer and AVL 437C smoke meter. The experimental set-up was prepared to reduce the thickness of the piston crown, inlet and exhaust-valve heat surface to a 300-µm thickness with a CNC horizontal milling machine. After that the machined component was insulated with Al_2O_3-TiO_2 to coat the piston crown, inlet and exhaust valve head surface with a thickness of 300 µm using the plasma spray coating technique.

This component replaced the Kirloskar TV1 engine, which was dismantled; the engine piston, inlet and exhaust valve were then assembled. Again the test was carried out on the engine using the Mo ceramic material coating the piston crown, inlet valve and exhaust valve head.

The results revealed that the engine performance and emissions, when compared with the conventional diesel engine, were improved with the Mo-insulated engine and Al_2O_3–TiO_2 coated engine. In the experimental test, Mo and Al_2O_3–TiO_2 were plotted at a constant engine revolutions of 1500 min^{-1}, for the no-load conditions of 25 %, 50 %, 75 %, and 100 %. The experimental test was carried out to assess the engine performance intended for the brake power, brake thermal efficiency, volumetric efficiency, specific fuel consumption and air-fuel ratio. In the next stage, the engine emissions intended for unburned HC, CO, NO_x and SO were tested, also with respect to the λ level.

4 RESULTS AND DISCUSSION

4.1 Performance analysis

4.1.1 Comparison of the brake-power values under varying brake thermal efficiency

The comparison of the conventional, Al_2O_3–TiO_2 coated engine and Mo insulated engine is shown in **Figure 2**. The insulated engine has a low thermal conductivity, resulting in a high operating temperature and ignition delay caused by the physical and chemical reaction in the combustion chamber. The increase in the thermal efficiency of the engine's full-load condition for the Al_2O_3-TiO_2 insulated piston is 29.67 %; the report gives lower values of 27.95 % and 28.33 % for the Mo-insulated and uncoated piston, respectively. The brake thermal efficiency of the Al_2O_3-TiO_2 coated engine was much better due to a reduction in the level of heat in the combustion chamber.[23]

4.1.2 Comparison of the brake-power values under varying brake specific fuel consumption

BSFC is also known as the brake specific fuel consumption; it is independent of the conventional and coated engine, as illustrated in **Figure 3**. For all the cases, the energy consumption is compared between the Al_2O_3-TiO_2 coated engine, which is 0.29 kg/kWh, being

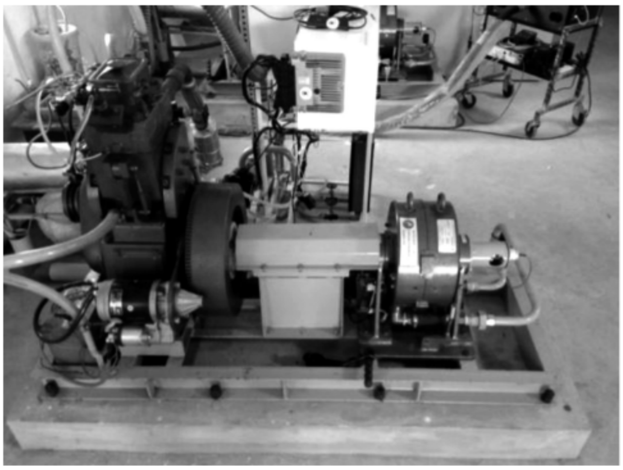

Figure 1: Photograph of the experimental set-up

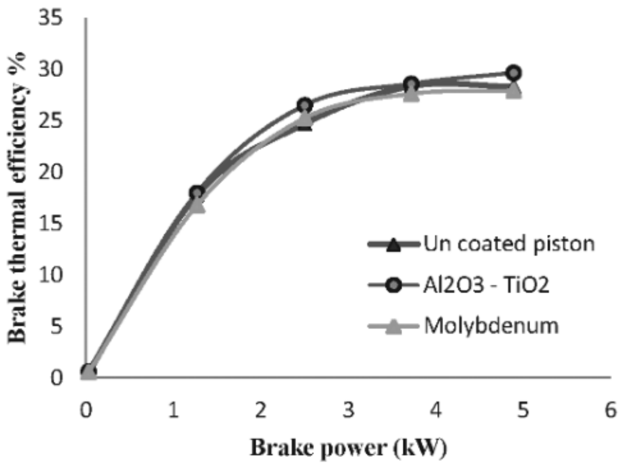

Figure 2: Variation in the brake power with the brake thermal efficiency

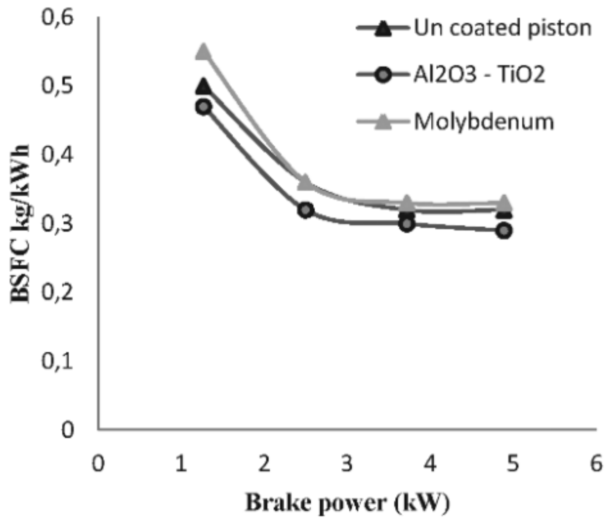

Figure 3: Variation in the brake power with the BSFC

the most economic (BSFC), the Mo-coated engine (0.33 kg/kWh) and conventional diesel engine (0.32 kg/kWh).

4.1.3 Comparison of the brake-power values under varying volumetric efficiency

Volumetric efficiency is the breathing capability of an engine based on the atmospheric condition, used to improve the air breathing inside the cylinder. **Figure 4** illustrates that the variation in the volumetric efficiency is lower for the coated and insulated piston than that of the conventional diesel at the maximum load; the initial condition of the breathing differs from the low-load condition. The Al_2O_3–TiO_2 insulated engine exhibits a better atomization, thereby improving the complete combustion. The result reveals that the Al_2O_3–TiO_2 insulated engine exhibits 83.25 % of the engine peak load condition, the Mo-insulated engine exhibits 82.72 % and the uncoated engine exhibits 83.13 %.

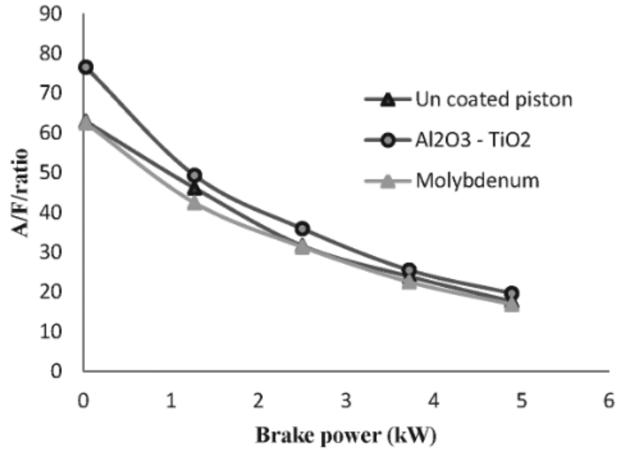

Figure 5: Variation in the brake power with the A/F ratio

4.1.4 Comparison of the brake-power values under a varying air-fuel ratio

Air-fuel ratio reflects the mixture of fuel with air, having an important effect on the engine with regard to whether the fuel burns completely and chemically correctly, with no excess air shown in **Figure 5**. The comparison shows that the air-fuel ratio is better for the Al_2O_3–TiO_2 insulated engine at all load conditions than for the uncoated engine and Mo conventional diesel engine. The result for the Al_2O_3–TiO_2 insulated engine is 19.65 %, the Mo engine shows a very low value, 16.85 %, and the uncoated engine shows 17.67 %; so the most suitable one is that for the Al_2O_3–TiO_2 insulated engine.

4.2 Engine emissions

4.2.1 Comparison of the brake-power values under varying carbon monoxide emissions

Carbon monoxide emissions were assessed while keeping the engines at constant revolutions of 1500 min^{-1} and no-load conditions of 25 %, 50 %, 75 % and 100 %; the CO emissions were plotted for the Al_2O_3-TiO_2 and

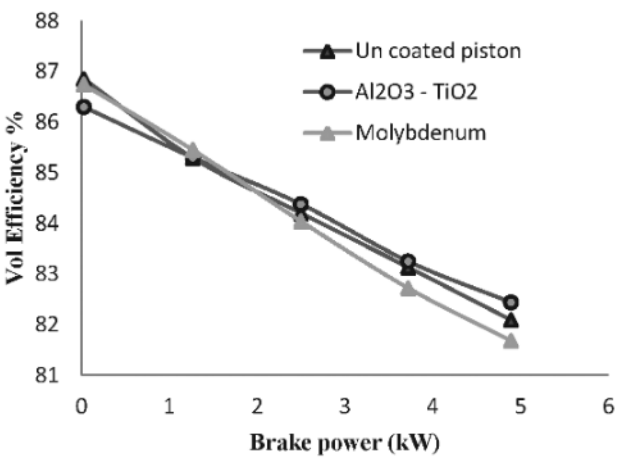

Figure 4: Variation in the brake power with the vol. efficiency

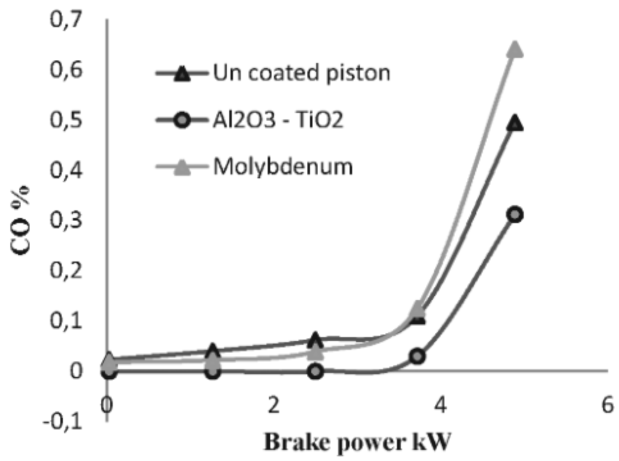

Figure 6: Variation in the brake power with CO emissions

Mo-insulated engine. A higher oxygen content of the engine eliminated its rich fuel incomplete combustion. **Figure 6** shows that the CO emission is higher for the conventional diesel engine than for the coated engine at all load conditions. The result for the engine emission of the Al_2O_3-TiO_2 insulated engine is 0.851 %; for the Mo engine, it is low, 0.641 %, and the uncoated engine shows a much lower level, 0.495 %.

4.2.2 Comparison of the brake-power values under varying hydrocarbon emissions

Unburned hydrocarbon (HC) emissions were assessed while keeping the engines at a constant speed of 1500 min^{-1} and no-load conditions of 25 %, 50 %, 75 % and 100 % of the brake power; the HC emissions were plotted for the Al_2O_3-TiO_2 and Mo-insulated engine. The Mo and Al_2O_3-TiO_2 had a high latent heat of vaporization, which was to reduce the combustion chamber temperature and ignition delay with high flame quenching. Unburned hydrocarbon emissions can be formed, reducing the fuel injection entrancement at a lower loading condition. HC emissions are shown in **Figure 7**. The emission of the Al_2O_3-TiO_2 insulated engine is lower than those of the Mo-coated engine and conventional-diesel engine at all load conditions.[24]

4.2.3 Comparison of the brake-power values under varying NO_x emissions

The cause for a NO_x formation in an IC engine was a high temperature, above 800 °C at the full-load condition. The test carried out on the Al_2O_3-TiO_2 coated engine showed good atomization; the complete combustion raised the engine temperature minimum and the NO_x emission was increased. This can be observed on **Figure 8**. Another test revealed a reduced NO_x level at the top speed. For the Al_2O_3-TiO_2 coated engine, it was 1610 ng/kg, a little higher than for the Mo-insulated engine, which was 1533 ng/kg, and for the conventional-diesel engine, it was 1587 ng/kg.[25]

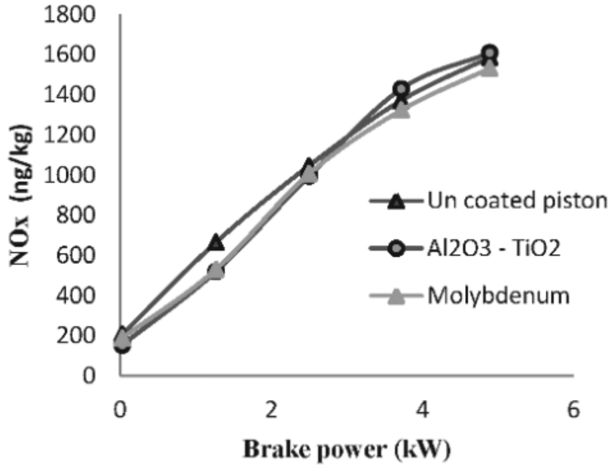

Figure 8: Variation in the brake power with NO_x emissions

4.2.4 Comparison of the brake-power values under varying smoke opacity

An engine eliminates the exhaust gas with smoke opacity when the engine starting period is too high for its exit. The exiting smoke opacity was better for Al_2O_3-TiO_2 than for the Mo-insulated engine and conventional-diesel engine. The smoke opacity measured as a percentage indicates that the smoke-opacity level for the Al_2O_3-TiO insulated engine is low, 95 %, the Mo-insulated engine smoke level is 99.1 % and the conventional diesel-engine smoke level is 98.7 % at all load conditions.

4.2.5 Comparison of the brake-power values at a varying λ level

The experimental test was carried out in the engine at constant revolutions of 1500 min^{-1} and the no-load conditions of 25 %, 50 %, 75 % and 100 % of the brake power at a varying exhaust mixture in oxygen or the λ level. Due to the engine's initial task to supply the excess fuel, the engine does not supply sufficient air. As the engine eliminates the amount of air escaping from the exhaust, it is better to use the Al_2O_3-TiO_2 and Mo-insulated

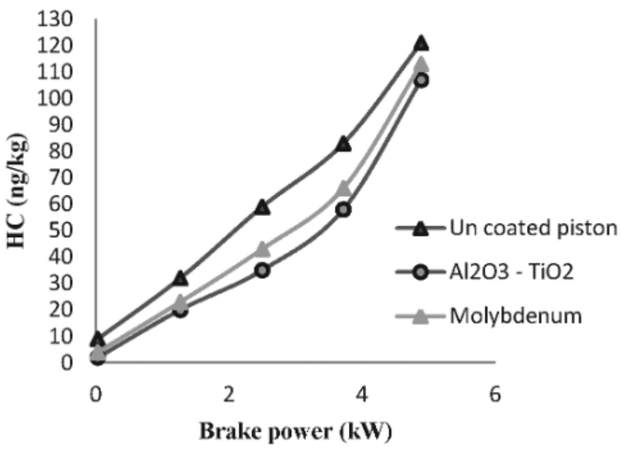

Figure 7: Variation in the brake power with hydrocarbon emissions

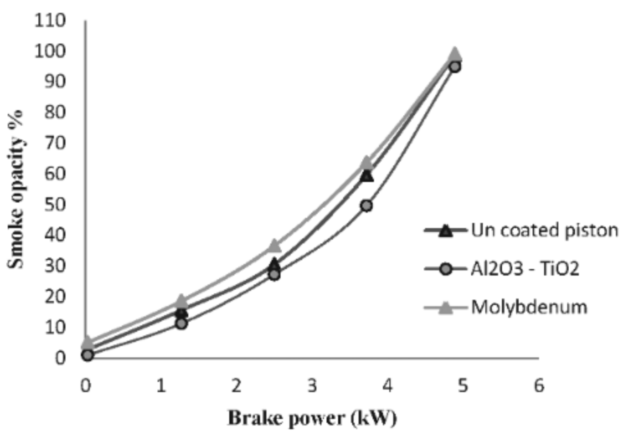

Figure 9: Variation in the brake power with smoke opacity

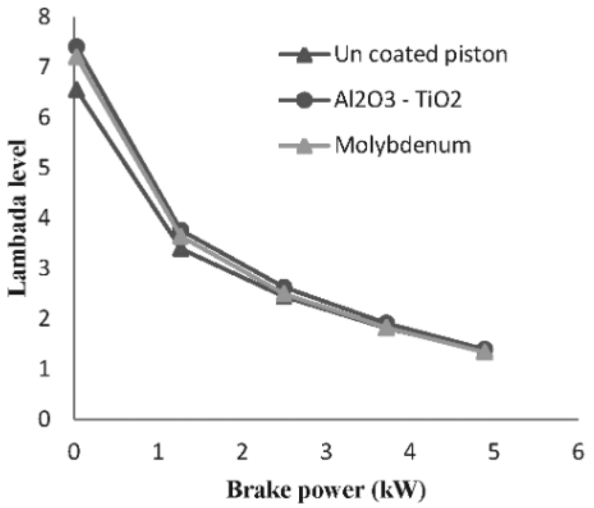

Figure 10: Variation in the brake-power values with the λ level

engines. The variation in the Al_2O_3-TiO_2 insulated engine's λ goes from 7.4 under the initial condition to a low value of 1.35 under the full load condition.

5 CONCLUSIONS

This experimental work was carried out on Al_2O_3-TiO_2 and Mo ceramic powder coated DI engines. Important conclusions were drawn as the thermal efficiency increases due to the decrease in the engine component temperature, leading to expansion work, thereby increasing the brake thermal efficiency of the engine at the maximum load condition. The loss in the engine power is improved with the use of the Al_2O_3-TiO_2 and Mo-insulated engines when compared with the conventional diesel engine. The Al_2O_3-TiO_2 coated engine enhances combustion; a cooling medium can reduce the heat energy, improving the brake specific fuel consumption. The result reveals that breathing atmospheric air is better for the insulated engine, making the engine to operate smoothly; the results for the volumetric efficiency and A/F ratio of the engine are also better. As the ceramic-insulated engine operates at a high operating temperature, the engine eliminates additional 1.01 % of NO_x. A lower HC emission rate for the Al_2O_3-TiO_2 insulated engine is 84 ng/kg, the rate for the Mo-insulated engine is 113 ng/kg and that of the uncoated engine is 121 ng/kg. The CO emission for the Al_2O_3-TiO_2 insulated engine is better compared to the ceramic-coated and uncoated engines. Thus, the Al_2O_3-TiO_2 coated engine is better for economic improvement and preservation of human health.

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