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# EXPERIMENTAL ANALYSIS OF THE THERMAL-BARRIER COATING FOR AN $Al_2O_3$-$TiO_2$ CERAMIC COATED CI ENGINE OPERATING ON CALOPHYLLUM INOPHYLLUM OIL

# EKSPERIMENTALNA ANALIZA KERAMIČNE PREVLEKE NA OSNOVI $Al_2O_3$-$TiO_2$, KI DELUJE KOT TERMIČNA BARIERA V ZGOREVALNI KOMORI BIODIZELSKEGA MOTORJA

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This work focuses on the thermal barrier coating (TBC) with a thickness of 300 μm for the combustion chamber of a single-cylinder four-stroke diesel engine. The piston crown, and inlet and exhaust-valve head are coated using the air-plasma-spray coating technique. Records found in the available literature revealed that the use of aluminum oxide titanium dioxide ($Al_2O_3$-$TiO_2$) ceramic-powder coating and punnagam oil methyl ester (POME) is the most preferred method for improving emission levels. Punnagam oil methyl ester (POME) was prepared with transesterification in order to blend the same substances with biodiesel proportions of B25, B50, B75, B100 and conventional diesel. The proposed test report relies on a single-cylinder four-stroke diesel engine without any modification. This research is aimed at reducing the emission levels and attaining a greener and cleaner system by using a renewable fuel. The test was carried out to assess the engine performance, viz., the brake power, brake thermal efficiency, volumetric efficiency, brake specific fuel consumption and air-fuel ratio, assess the emission levels when combining POME and the $Al_2O_3$-$TiO_2$ coated engine and compare them with those of conventional diesel. The amounts of pollutants such as unburned hydrocarbon (HC), carbon monoxide (CO), oxide of nitrogen (NOx) and the emitted smoke opacity were compared to those produced by conventional diesel. The result revealed that POME and the $Al_2O_3$-$TiO_2$ ceramic improved the performance of the engine so that the pollution levels are much better than those produced by conventional diesel.

Keywords: punnagam oil methyl ester, thermal-barrier coating, air-plasma-spray coating technique, aluminum oxide titanium dioxide, ceramic powder material, performance, engine emission

V članku sta se avtorja osredotočila na opis zaščitne plasti, ki deluje kot termična bariera debeline 300 μm v eno-valjnem štiri-taktnem motorju. Površine oz. krona bata, glav sesalnega in izpušnega ventila, so bile prevlečene s postopkom zračno-plazmskega naprševanja. V literaturi obstajajo dokazi, da je uporaba keramičnega prahu na osnovi $Al_2O_3$-$TiO_2$ za izdelavo prevlek vitalnih delov dizelskega motorja, ki deluje na bio-olje metilnega estra (POME; angl.: Punnagam oil methyl ester) najboljša metoda za preverjanje emisije izpušnih plinov. POME so pripravili s procesom trans-esterifikacije, da bi dobili mešanico, ki odgovarjajo razmerjem B25, B50, B75, B100, med bio- in konvencionalnim dizlom. Predlagani testi so se nanašali na eno-cilindrični štiri-taktni dizelski motor brez kakršnihkoli modifikacij. Ta postopek so izvedli z namenom zmanjšanja nivojev emisij z uporabo čistejšega motorja na obnovljivo gorivo. Preizkuse so izvedli, da bi ugotovili lastnosti motorja glede na moč zaviranja, termično učinkovitost zavor, volumetrično učinkovitost, specifično porabo med zaviranjem, razmerje gorivo-zrak in oceno nivoja emisij kombinacije POME- in $Al_2O_3$-$TiO_2$-prevlek v primerjavi s konvencionalnim dizelskim motorjem. Izvedli so primerjavo emisij onesnaževalcev okolja, kot so: nezgoreli ogljikovodiki (HC), ogljikov monoksid (CO), dušikovi oksidi (NOx) in trdni delci (saje). Rezultati testov so pokazali, da kombinacija POME in $Al_2O_3$-$TiO_2$ keramična prevleka vitalnih delov motorja izboljša lastnosti delovanja izbranega motorja in tudi ugotovljeni nivo emisij onesnaževalcev okolja je bil mnogo manjši kot jih je imel uporabljeni konvencionalni dizelski motor.

Ključne besede: olje metilnega estra Punnagam, keramična prevleka, termična bariera, tehnika zračno-plazemskega naprševanja, keramična $Al_2O_3$-$TiO_2$ prevleka, lastnosti in emisija dizelskega motorja

## 1 INTRODUCTION

R. Prasad et al.[1] compared the performance of a TBC-coated engine and an engine without any coatings. It was observed that the TBC-coated engine reduced heat losses by 6 % due to the coating of the piston and cylinder walls. D. Assanis et al.[2] implemented the effects of ceramic coatings on a diesel engine, providing a much better thermal efficiency, lower levels of CO, unburned HC and the NOx concentration and also reduced smoke emissions into the coated engine. B. Kamanna et al.[3] used a finite-element analysis to redesign the piston crown, therefore improving the mechanical efficiency of a diesel engine. T. Hejwowski et al.[4] studied the effect of thermal-barrier coatings, reducing the fuel consumption and improving the engine efficiency effectively. The engine-combustion chamber surface, piston crown, head of the cylinder, inlet and exhaust valves were coated with a base coating of NiCrAl and top coating of $CaZrO_3$ and $MgZrO_3$ using plasma-spray coating. The coated engine was evaluated with respect to the reduction of particulate emissions from the engine, such as CO, HC. A. Uzun et

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al.[5] described that the thermal-barrier coating is able to eliminate visible smoke and reduce the NOx emission. The thermal-fatigue resistance of two TBC layers was investigated by T. Hejwowski et al.[6] and it was concluded that this mechanism improves the spallation from coated diesel and petrol engines. Kumara and Pandey[7] examined the wear characteristics for the air-plasma spray deposited on the CoNiCrAlY inner metallic coating on an aluminum-alloy substrate. The wear characteristics and microstructure properties obtained with the air-plasma-spray technique used for the CoNiCrAlY coating increase the sliding distance and reduce the wear rate of the CoNiCrAlY coating. The thermal-barrier coating can prevent a low oxygen-diffusion rate, low thermal conductivity and improve mechanical properties. S. Deng et al.[8] prepared coatings with a bond-coat thickness of 6-8 μm, an $Al_2O_3$ composite, and a top-coat thickness of 120 μm, $La_2Zr_2O_7$. In the TBC on a diesel engine, a rich-mixture region leads to good performance of the thermal-barrier coating due to a higher temperature to surface volume ratio. M. Yao et al.[9] concluded that there would be improvement in the thermal efficiency because of the TBC. The heat-transfer losses of the thermal-barrier-coating engine emissions and combustion are also discussed. The thermal behavior of an electrolytic jet plasma oxidation (EJPO) coating was analyzed with a finite-element analysis, confirming that it provides improved thermal behavior of IC engines coated with electronic jet plasma oxidation. X. Shen et al.[10] concluded that the thermal conductivity improves because of the coating thickness and that this also improves the wear resistance. The emission reduction of a thermal-barrier-coated engine using a single blend ratio of various non-edible oils, cashew-nut shell, orange and neem oil via a transesterification process can change the performance of biodiesel. An engine coated with partially stabilized zirconia acting as the thermal barrier coating is used. V. Karthickeyan et al.[11] focused on the alternative BTE fuel battery, BSFC, engine emissions HC, CO and NOx, as compared to the conventional diesel. In his study, H. K. Suh et al.[12] investigated the nozzle geometry and cavitation characteristics of diesel and biodiesel fuel. It was found that the biodiesel rate of flow velocity is constant and that diesel fuel increases with the flow rate. The performance parameters of engines using thumba biodiesel/diesel blends were analyzed by applying the Taguchi method and gray relational analysis. A. Karnwal et al.[12] concluded that the maximum performance and minimum emission were found with a CR of 14, nozzle pressure of 250 bar and injection timing of 20°. The usage of biodiesel/diesel blended fuel in a common-rail DI-diesel engine proved that a higher biodiesel content causes a low engine power output. G. R. Kanna et al.[14] predicted the fuel-injection pressure and fuel-injection time for the conversion of palm oil into biodiesel with an artificial neural network. The benefits of the thermal-barrier coating were discussed by Selvam et al.[15]. It was found that when the TBC amount is large, it provides for a high level of thermal fatigue and heat-release rate within a yattria-stabilized zirconia-insulated engine.

## 2 SELECTION OF THE THERMAL-BARRIER-COATING MATERIAL

The objective of the study is to demonstrate that applying a thin layer of a thermal-barrier coating on a piston head and valve heads can improve the heat energy. A thick coating can withstand high heat energy, changing it into low heat energy. A thermal barrier coated with the ($Al_2O_3$-$TiO_2$) ceramic material with a thickness of 300 μm is used by employing the air-plasma-spray coating technique. The thermal-barrier coating is successfully used for the piston-head inlet and exhaust-valve head when it has a thickness of 300 μm. The most universal TBC is used for yattria-stabilized zirconium ($ZrO_2/Y_2O_3$), which is widely believed to improve the performance of a turbine blade at a temperature of 1100 °C. The plasma-spray technique is used in various industrial applications where high wear resistance and corrosion resistance with a thermal insulation are necessary to generate sustainable heat energy. The findings from the literature reveal that various types of $Al_2O_3$–$TiO_2$ plasma-sprayed coatings with different compositions ($Al_2O_3$–13 *w*/% $TiO_2$, $Al_2O_3$–40 *w*/% $TiO_2$ and $Al_2O_3$–50 *w*/% $TiO_2$) can be prepared for AISI 304L austenitic stainless-steel substrate materials.

The physical and chemical properties of an aluminum oxide titanium dioxide ceramic material ($Al_2O_3$-$TiO_2$) has the potential to withstand the wear and tear, exhibiting high hardness, low coefficient of friction, high ionic conductivity, high melting point and low thermal conductivity, which make it into a superior engineering material. **Figure 1** illustrates the air-plasma-spray coating used to coat the piston head and inlet and exhaust valve heads using an aluminum oxide titanium dioxide ceramic material ($Al_2O_3$-$TiO_2$) for a modified TVI kirloskar engine. A CNC horizontal milling machine is used for machining the piston crown and valve heads and after the machining, the components are coated with an air-plasma-spray coating (APS) with a thickness of 300 μm. The coating material consists of a highly reactive ceramic powder with low thermal expansion, low thermal conductivity, high thermal-shock resistance and high toughness; the chemical composition of the coating is $Al_2O_3$ = 87 %, $TiO_2$ = 9.5–13.5 %, $SiO_2$ = 0.5 % and MgO = 3 %.

## 3 SELECTION OF ALTERNATIVE FUEL

This study was carried out in four phases. In the first phase, punnagam oil methyl ester (POME) was prepared using transesterification. In the second phase, blended biodiesel prepared from a mixture of different categories

**Figure 1:** Plasma-spray coating

including B25, B50, B75, B100 and normal diesel was used. In the third phase, the thermal-barrier coating was applied to obtain good heat energy and withstand the heat during a test of the ($Al_2O_3$-$TiO_2$) ceramic material, using the air-plasma-spray coating technique. The final phase included an experiment carried out on a single-cylinder four-stroke direct-injection ($Al_2O_3$-$TiO_2$) material-coated engine. The test was carried out to assess the engine performance and emission characteristics. Vehicles like trucks, buses, cars, trains and airplanes release an enormous amount of pollution, irreversibly affecting the air quality. Hence, finding and developing an alternative fuel have become inevitable. An alternative fuel can overcome this problem. It can be made of non-edible vegetable oil and animal fat. Vegetable oil can cause an injection problem because of its high viscosity and poor volatility leading to engine deposits, filter gumming and piston-ring jamming. However, an alternative fuel helps surmount these problems. Hence, the objective of the study is to create an alternative fuel that will control the increasingly high emission levels of the pollutants that affect the air quality.

**Figure 2:** Punnagam tree and seeds

The calophyllum inophyllum seed oil (known widely in Tamil as the punnagam oil) is used in this experiment. The punnagam-seed oil is non-edible and cultivated in the vast expanse of East Africa, Malaysia, Australia and southern Coastal India. The tree is grown extensively in Maharashtra, the coastal area of Tamil Nadu and Andamans. It has low hanging branches and takes a long time to grow. Its height is normally 8–20 m, its leaf is of an elliptical shape. The fruit is a round green drupe. The seeds are obtained twice per year, April to June and October to December and an annual yield of these seeds is 20–100 kg/tree. Punnagam seeds, as shown in **Figure 2**, can be extracted by removing the outer shell. They have to be dried in the sun and crushed; later, oil is extracted from crushed punnagam seed. This process leads to a hitherto unknown alternative, a non-conventional fuel involving punnagam seeds. These are first dehusked and converted into punnagam oil methyl ester (POME) through a transesterification process. It exhibits superior diesel properties and can be used in a diesel engine.

## 4 EXPERIMENTAL SET-UP

**Figure 3** represents the experimental set-up, which uses a kirloskar engine. The engine is a single-cylinder diesel-engine with a bore of 87.5 mm, a stroke of 110

**Figure 3:** Schematic layout of the experimental set-up

mm and a compression ratio of 17.5:1. The rated power is 5.2 kw @ 1500 $min^{-1}$. Tests were carried out at 1500 $min^{-1}$ at full load. The diesel engine was connected to the eddy-current dynamometer for loading. The set-up consists of a fuel tank, stand-alone panel box consisting of an air box, fuel measuring unit, manometer, transmitters for air and fuel-flow measurements, process indicator and engine indicator. Rota-meters are provided for water cooling and a calorimeter is used for water-flow measurements. AVL DiGas 444 is used to measure the emission parameters like CO, HC, $CO_2$, $O_2$ and NOx while an AVL 437C smoke meter is used to measure the exhaust-smoke opacity.

## 5. RESULTS AND DISCUSSION

The results depicted below reveal the engine performance and emission levels. The current result is an outcome of a comparison of a conventional engine with a diesel and transesterified biodiesel (POME) engine coated with the ($Al_2O_3$-$TiO_2$) ceramic. The engine was tested at a constant speed of 1500 min-1 under a no-load condition and for 25, 50, 75, 100 biodiesel percentage. The test was carried out to assess the engine performance regarding the brake power, brake thermal efficiency, volumetric efficiency, air-fuel ratio and specific fuel consumption. In the next phase engine-emission characteristics regarding unburned hydro carbon, carbon monoxide, nitrous oxide, and engine-smoke opacity were tested.

### *5.1 Engine performance parameters*

#### *5.1.1 Brake power versus brake thermal efficiency*

**Figure 4** presents the brake power and brake thermal efficiency. The brake thermal efficiency is compared against the $Al_2O_3$-$TiO_2$ coated conventional-diesel engine and $Al_2O_3$-$TiO_2$ coated POME engine. The engine exhibits low thermal conductivity, thereby improving the operation at a high temperature and reducing the ignition delay caused by physical and chemical reactions in the

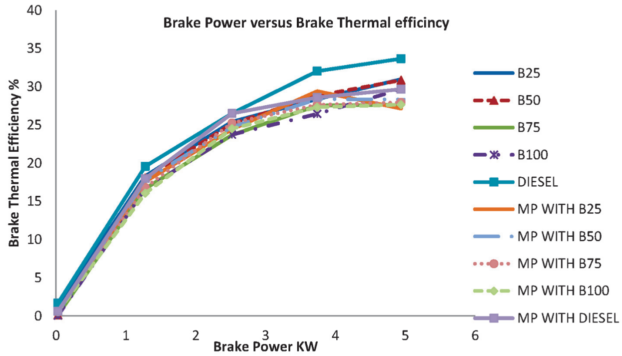


**Figure 4:** Brake power versus brake thermal efficiency

combustion chamber. A careful scrutiny of the brake thermal efficiency shows that the blend (POME) ($Al_2O_3$-$TiO_2$) coated engine performed much better. The break thermal efficiency of the coated, blend (POME) engine (MP with B75) exhibits an improved performance compared with the diesel engine.

#### *5.1.2 Brake power versus volumetric efficiency*

The experimental result for the volumetric efficiency depends upon the operating conditions and atmospheric condition of the operating engine. **Figure 5** presents a comparison of the levels of the volumetric efficiency against several conditions. It is observed that the use of the blend (POME) leads to a good atomization, thereby improving the complete combustion of exhaust gases. Also, the conventional diesel and the blend (POME) are better for the modified piston engine operating under full operating conditions.

#### *5.1.3 Brake power versus brake specific fuel consumption*

The increase in the brake specific fuel consumption (BSFC) shown in **Figure 6** illustrates the variation in the brake power versus the BSFC for biodiesel, also known as the brake specific energy consumption (BSEC). The mean effective pressure of the ($Al_2O_3$-$TiO_2$) coated engine is high for the modified piston using B75 when comparing the blended (POME) and conventional diesel. The BSFC, also known as the brake specific energy consumption (BSEC), is independent of the blend (POME), ($Al_2O_3$-$TiO_2$) insulated engine.

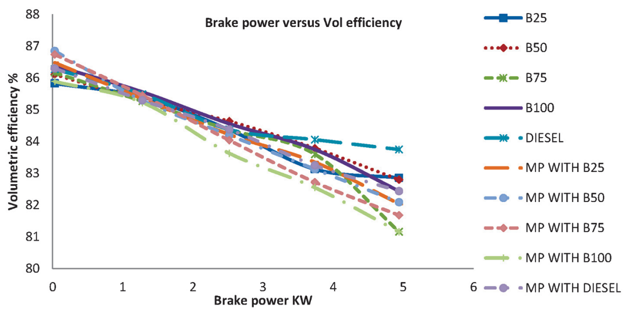


**Figure 5:** Brake power versus volumetric efficiency

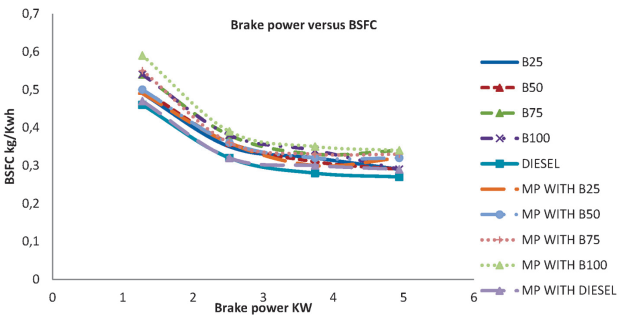


Figure 6: Brake power versus brake specific fuel consumption

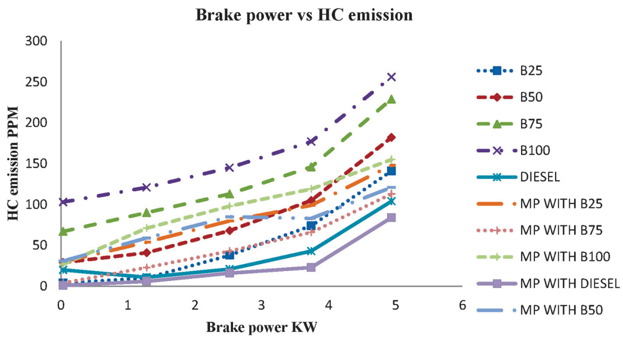


Figure 9: Brake power versus hydrocarbon emissions

### *5.1.4 Brake power versus air-fuel ratio*

**Figure 7** shows the variation in the brake power versus the air-fuel ratio. The air-fuel ratio is the most important parameter of an IC engine as it is gradually reduced at all loads when compared to the blend (POME) ($Al_2O_3$-$TiO_2$) insulated engine. The result reveals that POME is minimum when used with an ($Al_2O_3$-$TiO_2$) insulated engine. So, the use of the ($Al_2O_3$-$TiO_2$) insulation together with blend POME is suitable for the given engine.

## *5.2 Engine exhaust emissions*

### *5.2.1 Brake power versus carbon monoxide emissions*

The variation in the brake power versus carbon monoxide (CO) emissions is shown in **Figure 8**. The objective of comparing (POME) B25, B50, B75, B100 and conventional diesel, and the ($Al_2O_3$-$TiO_2$) coated engine leads to reduced carbon monoxide emissions. The results reveal that the conventional engine causes a high level of emissions due to an inadequate level of the oxygen content when tested in the POME ($Al_2O_3$-$TiO_2$) coated engine, while the carbon monoxide emissions decrease considerably.

### *5.2.2 Brake power vs hydrocarbon emissions*

Hydrocarbon emissions are reduced substantially when the right blend of POME and oxygen (air-fuel mixture) is released into the combustion chamber. When the conventional diesel and oxygen are let into the combustion chamber, hydrocarbon emissions are very high since the conventional diesel and oxygen do not mix easily. The intention is to find out which of the three variables (various blends of POME including B25, B50, B75, B100 or the conventional diesel or the ($Al_2O_3$-$TiO_2$) coated engine) results in lower hydrocarbon-emission levels. **Figure 9** reveals that POME together with the ($Al_2O_3$-$TiO_2$) coated engine results in a lower amount of hydrocarbon emissions, whereas the conventional engine releases large amounts of hydrocarbon emissions.

### *5.2.3 Brake power vs NOx emissions*

The variation in the brake power versus NOx engine emissions is shown in **Figure 10**. The conventional diesel leads to high NOx-emission levels and when the conventional diesel is released into the combustion chamber, the temperature soars and produces NOx emissions. To surmount the problem of unacceptably high levels of NOx emission, the ($Al_2O_3$-$TiO_2$) coated engine is inserted into the modified TV1 Kirlosker diesel engine. It is revealed that the coated engine is able to absorb a cer-

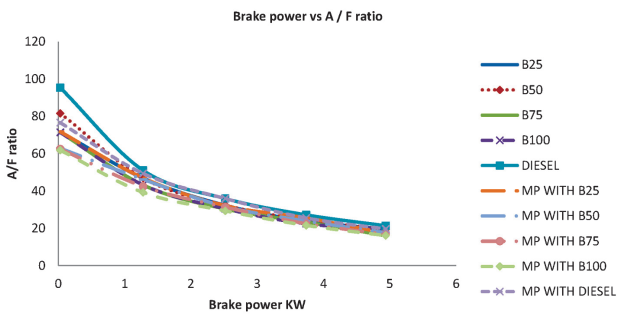


Figure 7: Brake power versus air-fuel ratio

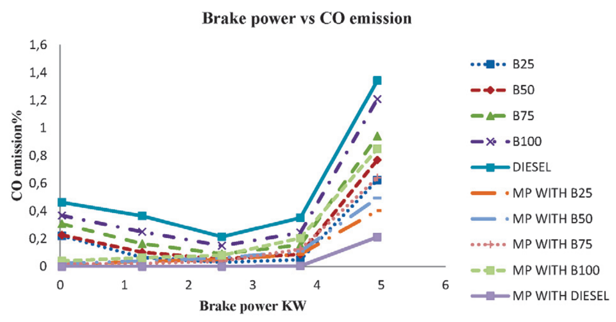


Figure 8: Brake power versus CO emission

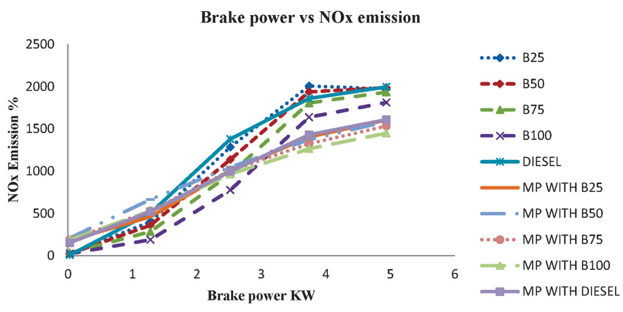


Figure 10: Brake power versus NOx emissions

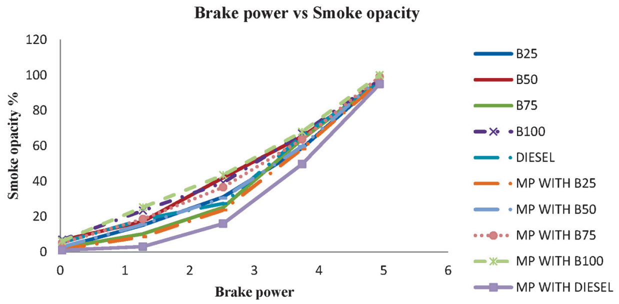


**Figure 11:** Brake power versus smoke opacity

tain level of heat. Hence, the temperature comes down and results in lower NOx emissions. The objective is to find out which of the two variables including the conventional diesel and ($Al_2O_3$-$TiO_2$) coated engine leads to lower levels of NOx emissions. The blend (POME) and coated engine lead to lower emissions, whereas the conventional diesel leads to higher NOx emissions.

*5.2.4 Brake power versus smoke opacity*

**Figure 11** predicts the variation in the brake power versus the smoke opacity. The conventional-diesel engine demonstrated higher smoke opacity, which can be ascribed to the high amount of the fuel content in the conventional engine. The result revealed that POME and the ($Al_2O_3$-$TiO_2$) ceramic powder insulating the engine lead to lower smoke opacity. On the other hand, the conventional-diesel engine demonstrated higher smoke opacity. This can be ascribed to the high amount of fuel content in the conventional engine.

## 6 CONCLUSION

The coated-engine temperature leads to a work expansion by increasing the brake thermal efficiency for the suitable engine at the maximum load. The ($Al_2O_3$-$TiO_2$) coated, blend (POME) engine enhances combustion, reduces heat energy and decreases the brake specific fuel consumption. The results emphasize the efficiency of the POME ($Al_2O_3$-$TiO_2$) coated engine with a modified piston using the 75 % blend and exposed to a full load. The results also reveal that the CO-emission level and NOx emissions are significantly reduced when the blend (POME) ($Al_2O_3$-$TiO_2$) coated engine is used. In addition, the HC emissions are gradually increased. The study also highlights the fact that the smoke opacity came down as compared with the conventional-diesel engine. Thus, the $Al_2O_3$-$TiO_2$ coated engine using blend POME can reduce the discrepancy between economic development and preservation of human health.

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