Fabrication, Performance and Emission Analysis of a LHR Diesel Engine

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***Abstract*-For over a century internal combustion engines have been and still is one of the most successful compact portable autonomous power sources being used in the transport of people and goods over relatively long distances in a quicker manner. Therefore, reciprocating engines have been the choice of the automotive and allied industries for many years. However converting reciprocating motion into rotary motion is not as mechanically efficient as pure rotary motion. Thus, energy conservation and efficiency have been the quest of engineers concerned with internal combustion engine. Theoretically, if the heat rejected could be reduced, then the thermal efficiency would be improved, at least up to the limit set by the second law of thermodynamics. Low Heat Rejection (LHR) engines aim to do this by reducing the heat lost to the coolant.**

In this study performance and emission characteristics of a partially insulated Compression Ignition engine is investigated. To create partial insulation in the combustion chamber the cylinder head, valves and piston crown was coated with 0.225mm thick alumina (Al_2O_3). The results of this study indicate that the Brake Thermal Efficiency (BTE) has increased by 2% compared to conventional engine and Specific Fuel Consumption (SFC) of the engine is reduced.

Keywords: Low Heat rejection, CI engine, Brake Thermal Efficiency (BTE),Specific Fuel Consumption (SFC)

I. INTRODUCTION

Low Heat Rejection Engine

The diesel engine with its combustion chamber walls insulated by ceramics is referred to as LHR engine. The LHR engine has been conceived to improve fuel economy by eliminating the conventional cooling system and converting part of the increased exhaust energy into shaft work using the turbocharged system. Most have concluded that insulation reduces heat transfer, improves thermal efficiency, and increases energy availability in the exhaust.

However, contrary to the above expectations some experimental studies by Cheng and Wong [3], D.W.Dickey[4] have indicated almost no improvement in thermal efficiency and claim that exhaust emissions deteriorated as compared to those of the conventional water-cooled engines.

Thermodynamics of LHR engine

By applying the first law of thermodynamics to the diesel engine, all of the fuel energy injected in to the cylinder must appear either as brake output work, as energy in the exhaust stream or as heat rejected to the coolants (water, oil, and air). The first law suggests that the heat rejection to the coolant was eliminated by perfectly insulating the cylinder and deleting the cooling system, the coolant energy could be converted into brake power.

Unfortunately, the second law of thermodynamics does not allow that transformation to occur. A simple explanation for this is that by blocking the heat loss from the cylinder gases when the piston is at Bottom Dead Centre (BDC), the expansion stroke cannot improve the cycle efficiency because the piston has already completed its work extraction process.

Thus it is clear that most can be gained by blocking heat loss at Top Dead Center (TDC). This gain will decrease as the piston approaches the BDC. Thus the amount of heat which is prevented from flowing to the coolant and which does not appear in the brake output will appear in the exhaust stream as increased temperature.

II. THERMAL BARRIER COATING

In this study Alumina (Al_2O_3) was chosen as a thermal barrier coat material and its properties are tabulated in table.1.

TABLE 1. Properties of Alumina

Composition	Al_2O_3
Purity	Alumina 99.9%
Density	3.9 gm/cc
Melting point	2015^o C
Specific Heat at 100^{o}C	930 J/kg K
Thermal conductivity	40 W/mK at 20^{o}C
Thermal shock index	0.2
Thermal cycle index	0.8
Flexural strength	380 MPa
Hardness HV	1500 kgf/mm^2
Tensile Strength	262 MPa
Poison ratio	0.26
Young’s modulus	370 GPa
Co-efficient of thermal expansion	8 μm/m ^{o}C

The most useful criterion for comparing materials for operation under thermal conditions is the Eichelberg quality factor [18]:

$$Quality\ Factor = \frac{Z\ \times\ Ultimate\ Tensile\ Stress}{\propto \times E}$$

Where,

Z – Thermal Conductivity of the material in W/mK

α - Co-efficient of Thermal Expansion in K^{-1}

E – Young's Modulus of Elasticity in N/m^2

$$Quality\ Factor = \frac{40 \times\ 262\ \times 10^{6}}{8\ \times 10^{-6} \times 370 \times 10^{9}}$$

Quality Factor= 3.54 kW/m

Thus the quality factor for alumina is 3.54 kW/m, which is very much less than the safe limit of 200 kW/m thereby concluding that our material will withstand the thermal stresses.

Thermal Barrier Coating Technology

Before applying the Thermal Barrier Coating (TBC), 300 µm of the material is machined off from the cylinder head and piston crown. The surface was sand blasted and then it is coated with 75 µm NiAl bond coat and then225 µm thickness alumina was coated using Plasma spray coating technique. The specifications of the plasma spray are given in the Table.2

TABLE 2.Plasma spray specifications

Particle Velocity	500 – 550 m/s
Oxide content	1 – 2 %
Porosity	1 – 8 %
Deposition rate	1 – 5 kg/hr
Current	530 A
Voltage	72 V
Spray Distance	100mm
Torch Nozzle Diameter	6 mm

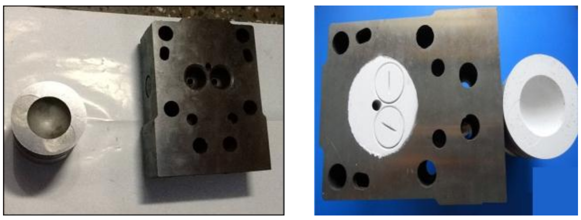


Fig 1. Picture of stock and Alumina coated Piston and Cylinder Head

III. EXPERIMENTAL SETUP

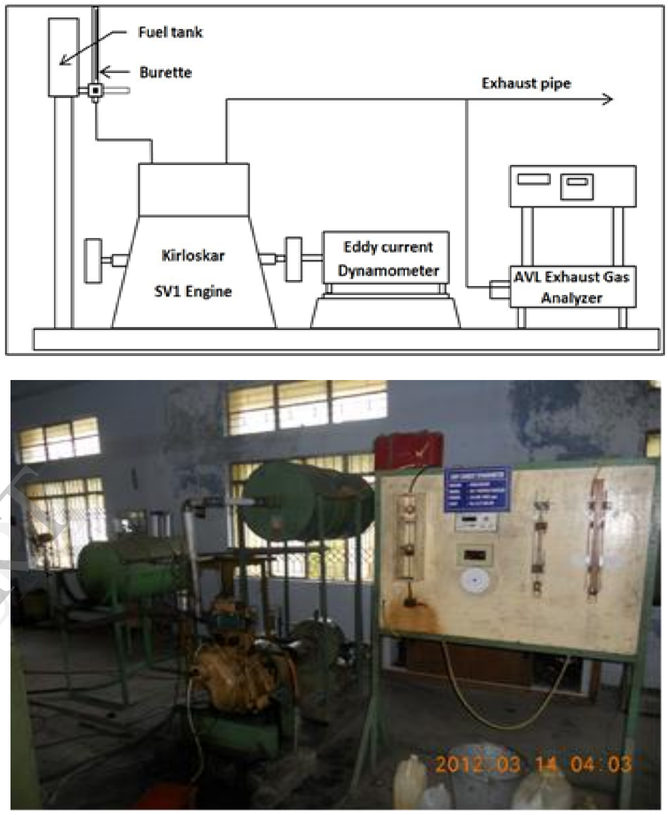
The experimental set-up is designed to suit the requirements of the present investigations.The specifications of the engine are given in the table 3. The schematic sketch of the experimental setup and the actual experimental setup on which the experiment is conducted is given in figure 2.

The measured ambient air temperature, pressure and humidity are 35 °C, 1.008 bar and 63%. Same piston, piston rings and injector were used in both configurations (metallic and ceramic coated components).

TABLE 3. Specifications of the test engine

Make	Kirloskar
Engine type	Single cylinder, Four stroke, Water cooled
Bore x Stroke	87.5 x 110 mm
Compression Ratio	17.5 : 1
Rated output	5.9 kW (8 hp)
Rated Speed	1800 RPM
Dynamometer	Eddy Current Dynamometer

Fig 2. Schematic sketch and actual experimental setup



The engine was coupled to an eddy current dynamometer. Calibrated high precision weighing scale was used to measure the fuel consumption rate. The air flow rate was measured using a hot film anemometer type air mass flow sensor. AVL 437 smoke meter gas analyzer was used to measure HC, CO, CO_2, No_xconcentration in the exhaust.

Fig 3. Eddy Current Dynamometer

Fig 4. AVL Exhaust gas analyzer

The engine is operated under no load for the first 20 minutes and for each load the engine is operated long enough to stabilize the condition. The load on the dynamometer, air flow rate, fuel flow rate, exhaust temperature, cooling water flow rate, are noted and recorded after allowing sufficient time for the engine to stabilize. From the observed readings, the parameters of brake power, brake thermal efficiency, brake specific consumption and heat loss to cooling water are evaluated.

IV. RESULTS AND DISCUSSIONS

PERFORMANCE CHARACTERISTICS

Specific Fuel Consumption

Fig 5. shows the comparison of SFC between the conventional and LHR engine. It can be seen from the graph that ceramic coated engine operate at slightly lower Brake Specific Fuel Consumption (BSFC) than conventional engine. Maximum of 6.6% reduction in BSFC is achieved with LHR engine.

This is due to additional heat gained due to reduced heat transfer through the cylinder head which also increases the mean gas pressure in combustion chamber during combustion. Researchers such as R.kamo et al [11], T.Morel et al [13] have reported improvement in reduction of fuel consumption in LHR engine and investigation of Miyairi [12] and J.A.Gatowski [6] shows increase in fuel consumption up to 25% in LHR engines than conventional engines.

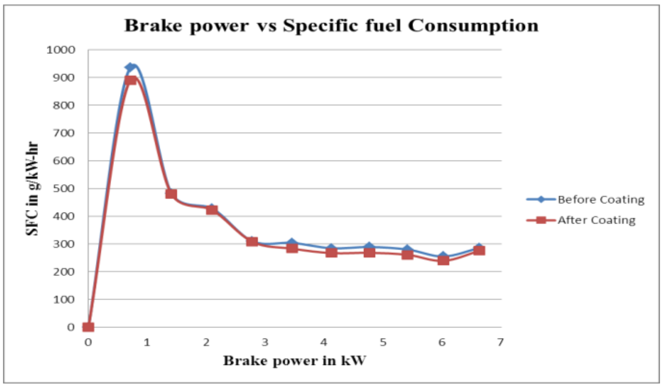


Fig 5. Effect of Brake power on Specific Fuel Consumption

Thermal efficiency

Thermal efficiency rightly called as fuel conversion efficiency is the measure with which the chemical energy of the fuel is converted into useful work. Thermal efficiency is the ratio of brake or shaft work obtained to the energy supplied by the fuel. Researchers such as Y.Miyari [12], T.Morel [13], reported improvement in thermal efficiency with LHR engine. However investigations of others such as Cheng and Wong [3], D.W.Dickey [4] reported deterioration in Thermal efficiency with higher smoke, particulate, CO, NOx levels with insulation. The variation of Brake Thermal efficiency (BTE) with respect to brake loads for conventional and LHR engine is shown in fig 6. Improvement in efficiency is mainly due to reduction in heat transfer, improved power output and reduced fuel energy input.

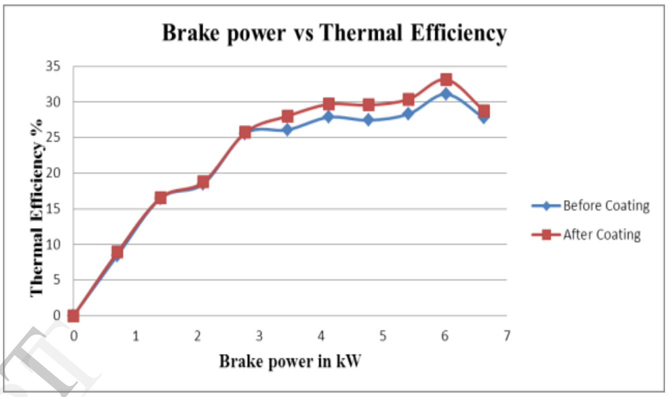


Fig 6. Effect of Brake power on Thermal efficiency

Volumetric Efficiency

Fig 7. Shows comparison of volumetric efficiency between ceramic coated and base engine with various brake loads. Volumetric efficiency primarily depends on the operating conditions of the engine. Reduction in heat transfer to the coolant with ceramic insulation causes an increase in temperature of the combustion chamber walls of an LHR engine. Due to the heat transfer to the inflowing air charge the density of the inflowing air fuel mixture reduces thereby volumetric efficiency decreases in ceramic coated engine. It is evident from the graph that maximum drop of 3.7% in volumetric efficiency is observed in LHR engine than the base engine.

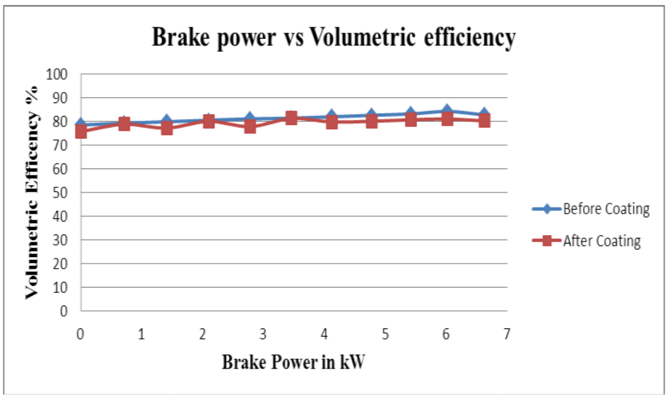


Fig 7. Effect of brake power on Volumetric Efficiency

Mechanical Efficiency

Mechanical efficiency is defined as the ratio of brake power to the indicated power. Fig 8. Shows the variation of mechanical efficiency of LHR engine and base engine with various brake loads. It is observed that at all loads the mechanical efficiency of LHR engine is slightly higher than the base engine. This is due to the reduction in frictional power in LHR engine than the base engine. On an average 2.27% increase in mechanical efficiency is observed at all loads of LHR engine than the base engine.

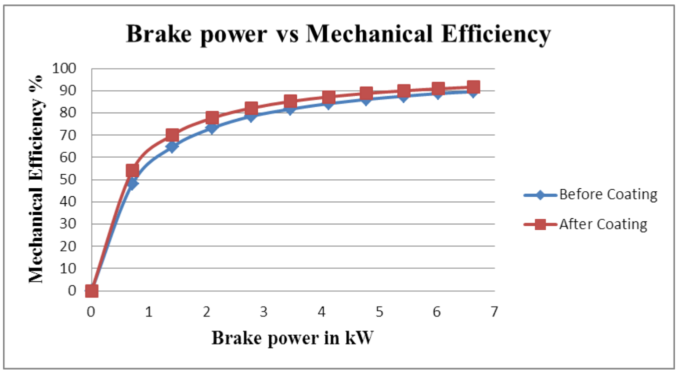


Fig 8. Effect of brake power on Mechanical efficiency

Exhaust gas temperature

Fig 9. Shows variation of exhaust gas temperature depending on the brake load of the engine. As seen in fig 9. exhaust gas temperature increases as the engine load increases in both the conventional and LHR engines. This is due to the amount of fuel per unit time increases as the engine load increases and consequently more heat energy is produced, as a result exhaust gas temperature increases.

The increase in exhaust gas temperature in LHR engine compared with base engine is 6.75%. The increase in exhaust gas temperature in LHR engine than the base engine can be explained by the decrease in heat losses going into the cooling system and outside due to the coating and the transfer of this heat to the exhaust gas.

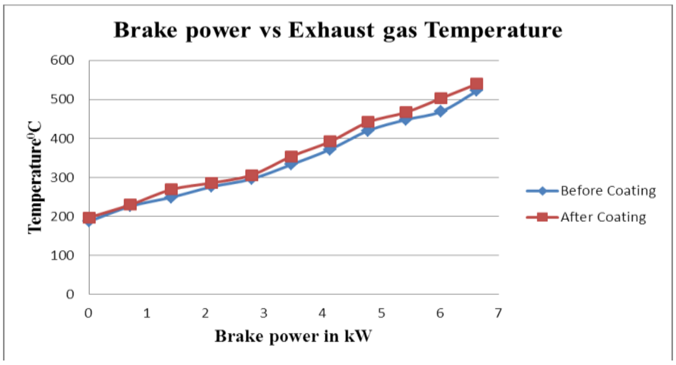


Fig 9. Effect of brake power on Exhaust gas temperature

Cooling Water Outlet Temperature

Fig 10. Shows the variation of cooling water outlet temperature of LHR engine and base engine with various brake loads. Due to steady increase in loads the outlet temperature of the cooling water shows increasing trends in both LHR and base engine. But the outlet temperature recorded in LHR engine is considerably lower than the outlet temperature recorded in base engine. This is due to the fact that ceramic coating provided in the LHR engine serves as an insulating layer for the heat transfer from the combustion chamber to the coolant water. Maximum of 5.8% decrease in outlet temperature of cooling water is recorded in LHR engine than the base engine.

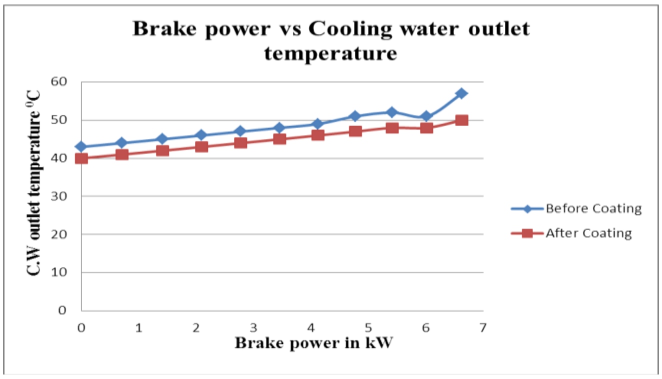


Fig 10. Effect of brake power on Cooling water outlet temperature

EMISSION CHARACTERISTICS

Unburnt Hydrocarbons Emission

Fig 11 . Shows the variation of unburnt hydrocarbon emissions with various brake loads. It is observed from the graph that HC emissions show a decent increase in both LHR and base engines with increase in brake power. About 17.64% deterioration in HC emissions is observed in LHR engine than the base engine. This deterioration in HC emissions is due to decreased quenching distance and increase lean flammability limit. The high 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 the completion. However certain studies by Wade et al [16] records increased level of HC emissions. The deterioration in combustion is the main reason for increased HC emissions.

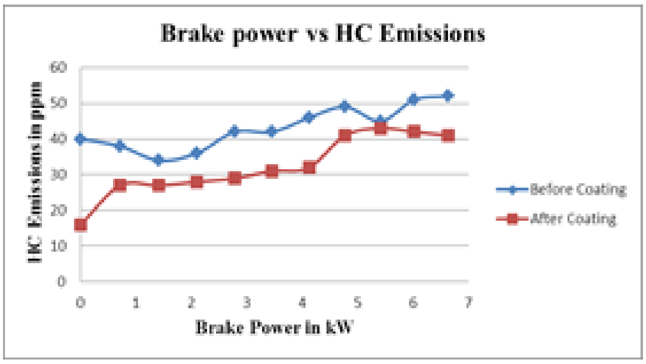


Fig 11. Effect of brake power on HC emissions

Carbonmonoxide Emissions

CO is found decreased (Fig 12.) after coating due to complete combustion. Generally oxygen availability in diesel is high, so at all temperatures, C easily combines with O_2 and reduces CO emission. At part load conditions upto 4kW, CO emissions are almost very closer for LHR engine and the base engine. But at full load conditions the emissions of CO deteriorates to 3.06% in LHR engine than the conventional uncoated engine. But the research by D.W.Dickey [4] records increase in CO emissions in LHR engine than base engine due to poor combustion.

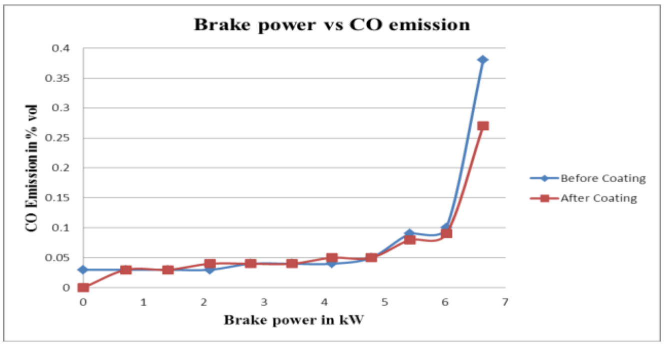


Fig 12. Effect of brake power on CO emissions

No_x Emissions

The behavior of oxides of nitrogen in exhaust gas follows the predicted trends as shown in fig 13. NO_x is formed by chain reactions involving nitrogen and oxygen in the air. The reactions are highly temperature dependent. Since diesel engines always operate with excess air, NO_x emissions are mainly a function of gas temperature and residence time. Most of the earlier investigations show that NOx emission from LHR engine is generally higher than that in conventional engines. Fig 13. shows increase in NO_x emissions with increase in brake loads. Maximum of 5.16% increase in NO_x emissions is observed in LHR engine.

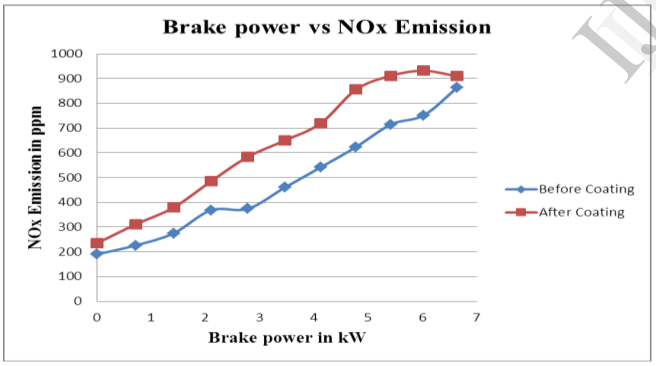


Fig 13. Effect of brake power on NO_x emissions

Smoke

Fig 14. Shows the variation of smoke produced in LHR engine and the base engine with the various brake loads. From the graph it is evident that maximum of 8.8% deterioration of smoke in LHR engine is observed. This is due to enhanced soot oxidation which was made possible by both the high combustion temperature and the intense turbulence created by the reversed squish. However short ignition delay, poor air-fuel mixing is responsible for increased smoke formation in LHR engines.

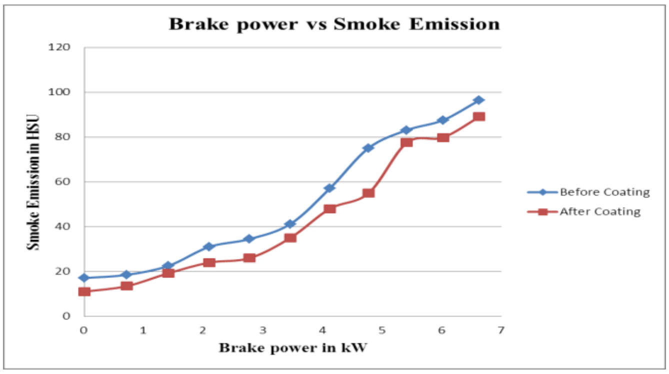


Fig 14. Effect of brake power on Smoke

V. CONCLUSION

In this experimental study, the piston surface, cylinder head, and valves of a diesel engine were coated with 225 µm Alumina by Plasma spray coating technique and the experiments are conducted as per the standards.

It was observed that heat transfer via these parts was reduced because all parts of the combustion chamber were coated with ceramics. Higher temperatures in the combustion chamber in such engines compared with conventional engines improved performance and emission values.

This study determined that the ceramic coating may be applied successfully without requiring any significant modifications to the structural characteristics of the internal combustion engine.

It is believed that, ceramic coating absorbs the effective effects such as overheating, friction, thermal shock, partial flame collisions, corrosion and oxidation and protects the substrate.

The following conclusions were obtained.

- The thermal efficiency of the engine is improved by 2%
- The specific fuel consumption is reduced by 6.6%
- The exhaust gas temperature on average increases by 25 °C
- On average, the outlet temperature of the cooling water decreases by 7 °C
- The emission of NOx increases by 5.16%
- At high loads CO emission decreases by 3.06% and at half load conditions the emission for both the engines remains closer.
- HC emission of LHR engine shows a decreased trend at all load conditions and the deterioration of HC in LHR engine is observed as 17.64% than base engine.
- 8.8% deterioration in smoke is observed in LHR engine.

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NOMENCLATURE

LHR	-	Low Heat Rejection
CI	-	Compression Ignition
BTE	-	Brake Thermal Efficiency
SFC	-	SpecificFuel Consumption
BSFC	-	Brake Specific Fuel Consumption
TBC	-	Thermal Barrier Coatings
NiAl	-	Nickel Aluminium
HC	-	Hydrocarbons
CO	-	Carbonmonoxide
TDC	-	Top Dead Center
BDC	-	Bottom Dead Center
NOx	-	Oxides of Nitrogen

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