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EFFECT OF TBC ON COMBUSTION PARAMETERS OF COMMON RAIL DIESEL ENGINE

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ABSTRACT

The main object of this study was to examine the effect of thermal barrier coating on combustion parameters of a common rail diesel engine. To achieve this, combustion chambers of the pistons were coated with 100 µm thickness Ni-Al bond coat by using plasma spray coating technique. 400 µm thickness 8% yittria stabilized zirconia was the main coat. Experiments were conducted on four different engine loads as 50 Nm, 75 Nm, 100 Nm and 120 Nm respectively at 1750 rpm constant speed. It was observed that cylinder pressure, heat releases and cumulative heat releases increased, ignition delays decreased with thermal barrier coating application

INTRODUCTION

Decreasing fuel consumption and emissions of internal combustion engines are major problems of researchers in recent years. Fuel prices and environmental concerns force the researchers to find alternative ways. With applying thermal barrier coatings (TBC) to engine components not only heat loss can be decreased but also thermal efficiency and durability of engine components can be increased [1].

The efficiency of most commercially available diesel engine ranges from 38% to 42%. In the light of these ratios, it can be said that more than 58% of the fuel energy is removed by cooling systems and exhaust gas. But second law of thermodynamics limits this increment. TBC is used for increasing thermal efficiency thanks to reduce heat transfer through the engine walls. On the other hand, rise of exhaust energy can be effectively used in turbocharged engines [1, 2].

Thermal barrier coatings can be used for to insulating and protecting the metal components of the engine from the hot combustion products. When TBC application, metal surface temperatures of the engine decreases about 573 K. Thus durability of the metal component and performance of engine improve [3]. TBCs provide better heat insulation thanks to their low thermal conductivity. Because of that engines can be run at higher temperatures and load of cooling system reduces. There are two layers of typical TBC application. These are a ceramic top coat and an oxidation resistant bond coat [4].

Pistons, inlet and exhaust valves and cylinder head can be coated with thermal barrier to make thermally insulated engine. Because of the increased cylinder temperatures, thermal strains may rise. To avoid this only pistons [5, 6], cylinder head, inlet and exhaust valves [7], cylinder liners [8] are coated. Al_2O_3-TiO_2 [9], Mo [10], ZrO_2 [11], Al_2O_3 [12] can be used as thermal barrier in engines. One of the most attractive thermal barrier coating materials is zirconia. Zirconia is a ceramic metal which has very low thermal conductivity. Its thermal expansion coefficients are similar to metals [13]. On the other hand high temperatures change phase of the zirconia. To restrict the phase changes, zirconia is stabilized with using some compounds. Zirconia was stabilized with compounds as MgO-ZrO_2 [14], CaO-ZrO_2 [15], Al_2O_3-ZrO_2 [6], Y_2O_3- ZrO_2 [7]. The thickness of the thermal barrier can change depending on its material. If the material of the thermal barrier is chosen as Y_2O_3-ZrO_2, optimum thickness is under 0.5 mm [6].

The thermal strain between ceramic top coat and metallic substrates is minimized by bond coat. It helps enhancing the oxidation resistance of metallic substrate. Because of the different thermal properties such as specific heat, thermal diffusivity and conductivity of top coat and metallic substrate, bond coat is needed as an interlayer between them. [16]. There are many bond coats as NiCrMo [6], NiAl [10], NiCrAl [17, 18].

One of the most widely used coating technique for diesel engines is plasma spray coating technique. Plasma spray technique is applicable for ceramics which are thicker and have low thermal conductivity. To reduce the oxidation problem, argon (Ar), hydrogen (H_2) or nitrogen (N_2) gases are used in plasma spray process [19].

Iscan coated piston surface and valves of the engine with zirconium oxide. Based on his observations there were no abnormalities on TBC layer. On the other hand minor cracks were seen at the edges of pistons [20]. Krishna et al. used ethanol, methanol and crude jatropha oil at different injection timings. They found that TBC engine increased its cylinder pressures (CP) and rate of heat releases (ROHR) comparison with the standard engine [21]. Abedin et. al. reviewed critically and comprehensively the possibilities of the TBC engines. According to authors; power, fuel consumption, thermal efficiency, and emissions of TBC engine improved except NO_x and volumetric efficiency [22]. Jalaludin et al. coated the piston of the compressed natural gas direct ınjection engine to decrease thermal stresses. The bond coat was NiCrAl and the main coat was yittria partially stabilized zirconia. TBC provided extra protection during combustion operation [23].

Based on the open literature review, it can be said that TBC has a positive effect on engine performance and emissions. In addition to this different liquid or gaseous fuels can be used as energy source for TBC engines. The main aim of the study is examining the effects of TBC on diesel combustion without any regulation of the injection timings.

EXPERIMENTAL SET-UP and PROCEDURE

Schematic diagram of experimental setup is shown in Fig. 1. A Cusson-P8602 type multi cylinder test bed fitted with a strain gauge load sensor and switches for load remote control was used in tests. A water-cooled electrical dynamometer rated at 150 kW and 8000 rpm was used to load the test engine. The tests were carried out on a four cylinder, four stroke, water cooled, turbocharged, diesel engine with Common Rail fuel system. Engine specifications are summarized in Table 1.

Table 1. Engine specifications.

Type	In-line, turbocharged
Cylinder volume	1461 cm^3
Bore	76 mm
Stroke	80.5 mm
Number of cylinders	4
Number of valves	8
Compression ratio	18.25:1
Maximum power (4000 d/d)	48 kW (65 hp)
Maximum torque (1750 d/d)	160 Nm
Fuel injection	Common-Rail

8% yittria stabilized zirconia was used as a TBC on combustion chamber. Combustion chambers were coated with 400 µm thickness 8% yittria stabilized zirconia main coat over a 100 µm thickness nickel-aluminum (Ni-Al) bond coat using atmospheric plasma spray method.

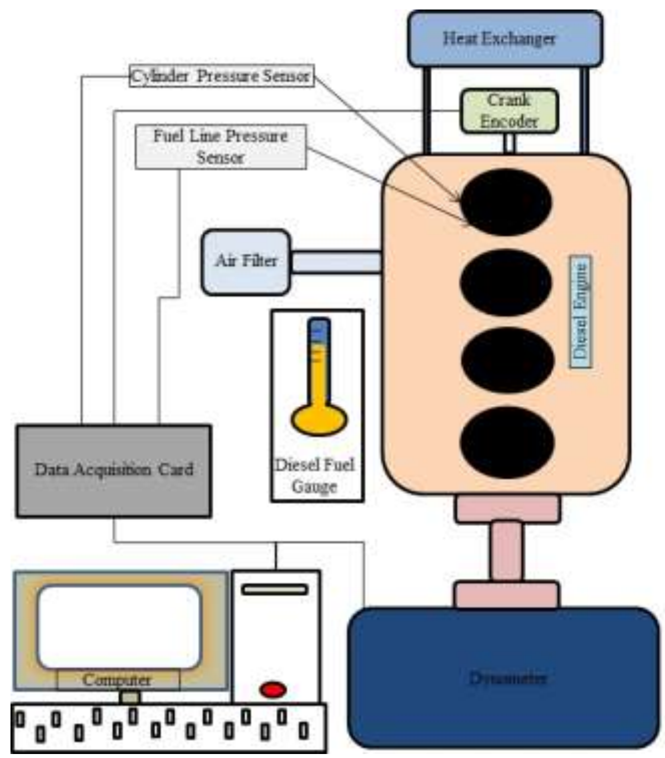

Fig. 1. Schematic diagram of experimental setup

Before each experiment, the engine was stabilized and then all data were collected. The engine was warmed up to 85-90 ºC to reach steady state conditions. The test procedure was repeated three times and average of the results were given in this study. All test were conducted at 1750 rpm constant speed, 50 Nm, 75 Nm, 100 Nm and 120 Nm engine loads (ELs).

CALCULATION OF HEAT RELEASE

The analysis of heat release (HR) and study of combustion characteristics were examined in the light of CP data. The signals of CP sensor were obtained for every 1 crank angle (ºCA). Data acquisition process was done in 200 cycles. The average CP data of 200 cycles was used for determining combustion parameters and analysis of HR. HR analysis has an important role on achieving information of different conditions on the combustion process and engine performance [24].

ROHR is a simplified thermodynamic model determined by using CP data. It is assumed that air and combustion products form a homogeneous mixture in cylinder. This homogeneous mixture is at uniform temperature and pressure through the combustion process. The ROHR at each ºCA was determined by the following formula [25].

$$dQ = \frac{\gamma}{\gamma-1}(PdV) + \frac{1}{\gamma-1}(VdP) + dQ_w \quad (1)$$

Where dQ is the ROHR (J), γ is the ratio of specific heats, P is the CP (Pa), V is the instantaneous volume of the cylinder (m^3) and dQ_w is heat transfer rate (J) from the cylinder wall determined with Hohenberg correlation [26] and wall temperature was assumed to be 400 K. Cylinder contents were also assumed to act as an ideal gas (air) with the specific heat being dependent on temperature and blow-by through the piston ring was neglected. Therefore, determining of ROHR is only notable between inlet valve closure and exhaust valve opening.

The ignition delay (ID) was defined as ºCA interval from the start of pressure drop of fuel line to the maximum ROPR. The combustion duration (CD) was calculated as CA interval from the maximum ROPR to the maximum cumulative heat release (CHR) [27].

IGNITION DELAY

Figure 2. shows the variation of IDs with different ELs in both TBC and uncoated engine operations. The ID of the TBC engine is same level as uncoated engine's ID at the 50 Nm EL. However, depending on rising EL, TBC diesel engine's ID drops 7.14 %, 12.9 % and 6.9 % respectively at 75 Nm, 100 Nm and 120Nm ELs as compared to uncoated diesel engine. Because of the hot walls of the combustion chamber of TBC engine IDs reduced. Uncoated engine's IDs raised with increasing ELs. Because electronic control unit of engine tried to manage combustion and started injection early rather than TBC engine.

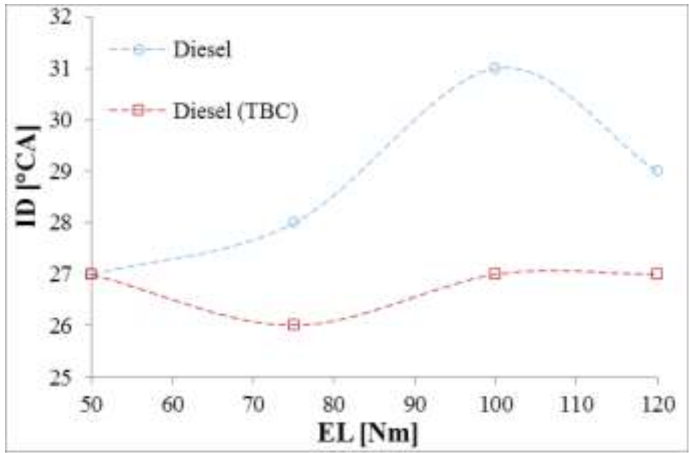

Fig. 2. IDs versus ELs

CYLINDER PRESSURE

The amount of the fuel burned during the premixed combustion period influences the CP. Start of injection, air fuel mix, start of combustion etc. have an effect on premixed combustion period. The more fuel burn in the premixed combustion period, the more peak pressure occurs. Besides of these, due to higher combustion chamber temperatures, it is observed from Figure 3. that, CPs of TBC engine increased. CPs of TBC diesel engine were 6,47%, 8,04%, 8,63%, and 3,93% higher than the uncoated diesel at 50 Nm, 75 Nm, 100 Nm and 120Nm ELs respectively.

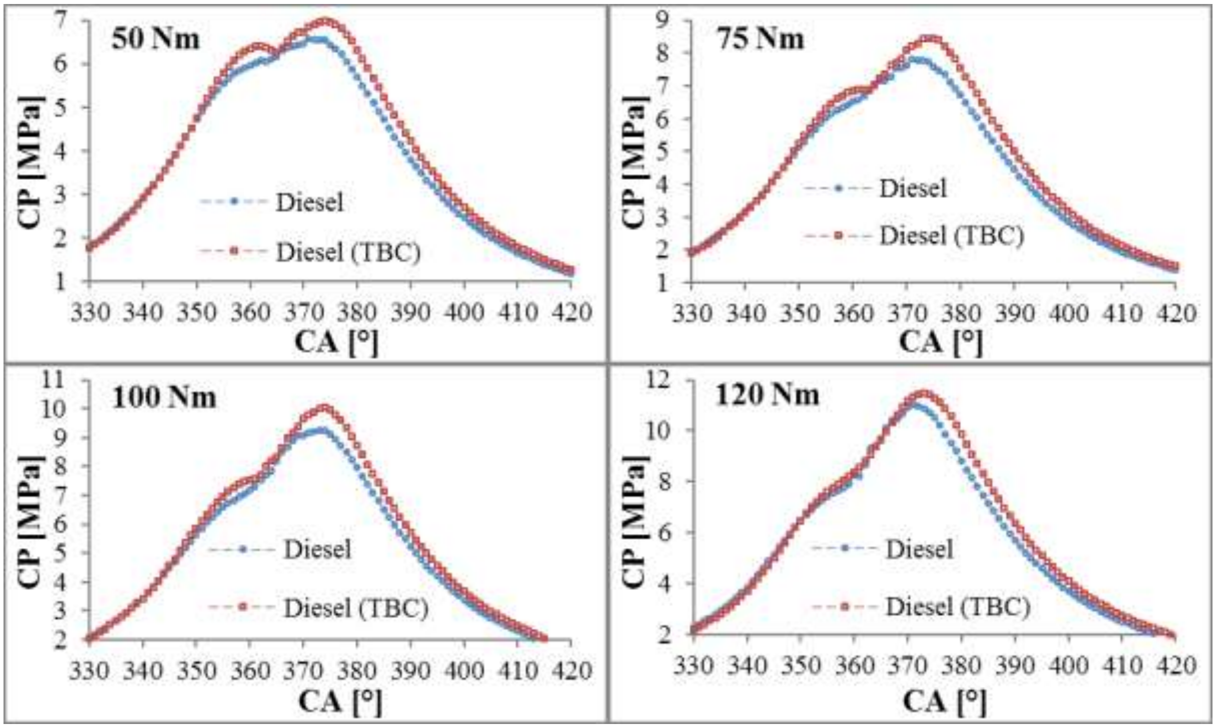

Fig. 3. CP in terms of ºCA for different ELs.

TBC avoids the heat transfer from the combustion chamber to the coolant system of the engine. This sparks off the higher temperatures in combustion chamber. CP raised because of the high cylinder temperature and heat release.

RATE OF HEAT RELEASE

Experimental studies show that, as compared to uncoated engine, TBC engine released 27.62 %, 30.96 %, 23.2 % and 18.57 % more heat respectively at 50 Nm, 75 Nm, 100 Nm and 120 Nm ELs. As it can be seen from Figure 4. ROHR increased with the raise of the EL due to more fuel was sent into combustion chamber to fulfill the torque need. TBC helped to improved ignition, better combustion and faster HR [28]. Higher operating temperature of TBC engine increased HR.

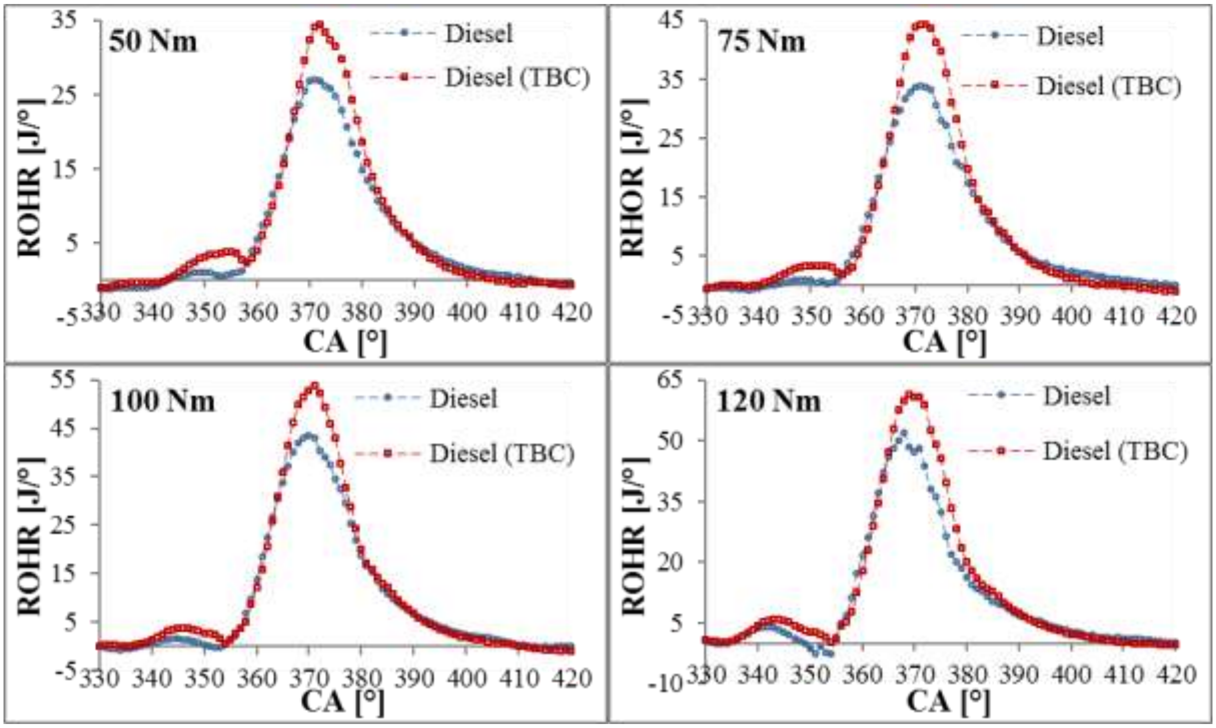

Fig. 4. ROHRs versus ºCA for different ELs

CUMULATIVE HEAT RELEASE

The calculated CHR values are shown in Figure 5. The result shows that CHRs of the TBC engine increased by 14.59 % for 50 Nm, 14.78 % for 75 Nm, 12.08 % for 100 Nm and 16.29 % for 120 Nm ELs when compared to CHRs of the uncoated engine.

CHRs increased with increasing ELs due to high fuel burning rate. The capability of thermal insulation of the ceramic coat helped to obtain high CHR values in TBC engine [22]. The increase is more observable in TBC engine as heat transfer to cooling system decreased significantly due to thermal barrier coating. Lower heat release rate of uncoated engine was the reason of high combustion duration. Combustion chamber temperatures acted an important role in this case.

The point where the maximum CHR comes into existence is assumed as the end of the combustion. The end of the combustion came closer to top dead center (TDC) depending on TBC and rising ELs. Combustion run out earlier thanks to hot cylinder temperatures.

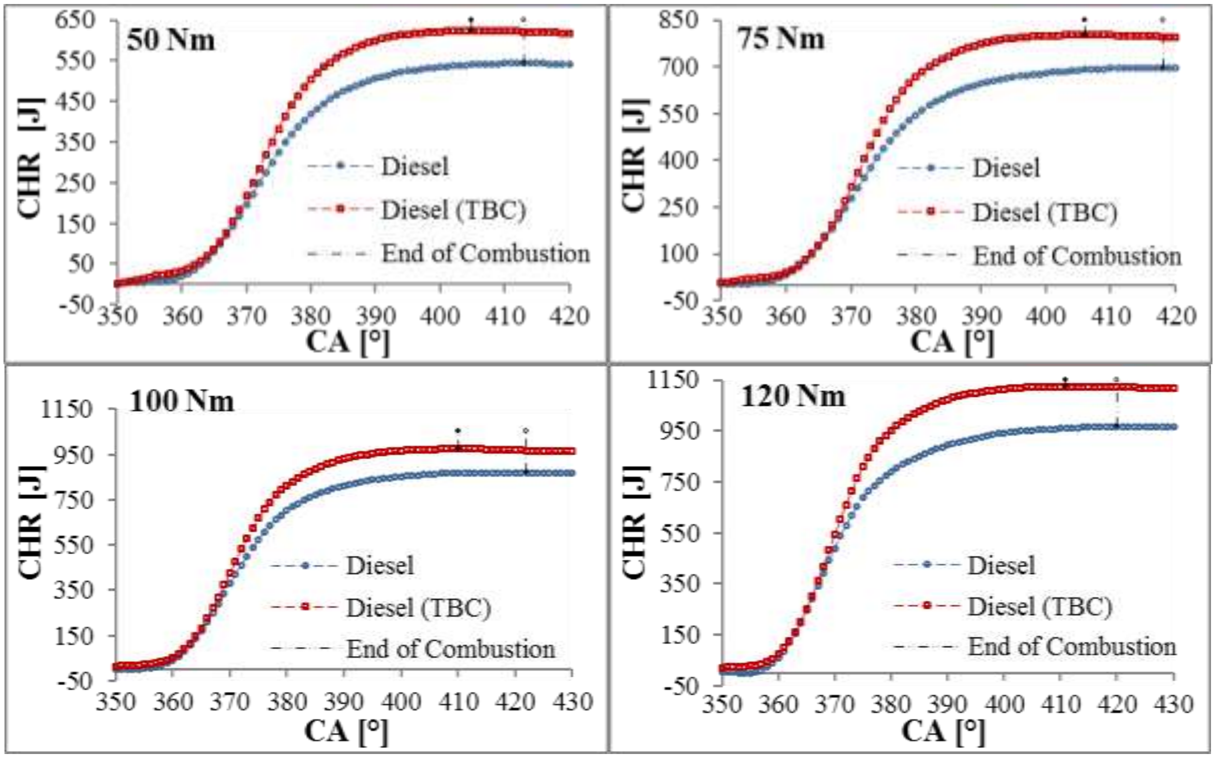

Fig. 5. CHR versus ºCA and COHR for different conditions

CONCLUSION

In this study effect of TBC on combustion parameters of a common rail diesel engine has been investigated. The experimental findings are listed as below:

- IDs slightly decreased in TBC engine at all ELs except 50 Nm EL.
- CPs of TBC engine increased in comparison with CPs of uncoated engine at all ELs. High CPs were obtained thanks to high cylinder temperatures.
- ROHRs of TBC engine were higher than ROHRs of uncoated engine due to rapid combustion.
- CHR values showed that TBC approached the end of the combustion point to the TDC and enhanced total HR.

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NOMENCLATURE

Argon: (Ar)
Hydrogen: (H_2)
Combustion duration: (CD)
Crank angle: (ºCA)
Cumulative heat release: (CHR)
Cylinder pressure: (CP)
Engine loads: (ELs)
Heat release: (HR)
Ignition delay: (ID)
Nickel-aluminum: (Ni-Al)
Nitrogen: (N_2)
Rate of heat release: (ROHR)
Thermal barrier coating: (TBC)
Top dead center: (TDC)

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