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Research Paper

Analysis of the Temperature Variation of Bizarre Thermal Barrier Coatings and their impacts on Engine

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Abstract

The modern vehicle industry is concerned with lowering greenhouse gas emissions, which have been responsible for warming the planet. Used Ansys simulations and experimental tests to determine how TBC influences engine performance and emissions. In this research, two distinct thermal barrier coatings have been identified, and the same coating materials were subsequently sprayed onto the pistons of an internal combustion engine. Transient thermal analysis reveals that TBC-1 and TBC-2 coatings reduce surface temperature distributions by 35% and 18%, respectively, and that these engines improve Brake Thermal Efficiency (BTE) by 8.71% and 7.62%, respectively, compared to non-coated engines operating under full load. TBC-1 and TBC-2 coated engines are found to have Brake-Specific Fuel Consumption (BSFC) reductions of 27.13% and 18.81%, respectively. Complete combustion reduces emissions of CO and HC, as the heat balance sheet indicates because the conversion of energy and mechanical work are enhanced by 3.56 percentage points and 2.0 percentage points, respectively.

Keywords: CI Engine; Impact of coating; Characteristics of Performance; Combustion; Pollutants

1. Introduction

Global warming is associated with releasing greenhouse gases into the atmosphere as a by-product of the combustion of crude oil fuels. The engine manufacturers have been motivated towards diverse design concepts such as increased fuel costs, rapid depletion of fossil fuel reserves, increasing demand, and environmental issues. The engine's main problems are that it uses more fuel, puts out more pollution, and has a poor life of parts. The thermal insulation of the engine's combustion chamber can overcome these limitations. The piston can expand at high temperatures, leading the engine to seize. These phenomena can be reduced by applying ceramic coatings on the piston. The Thermal Barrier Coatings (TBC) on the piston surface can significantly reduce heat to waste and use the energy of heat for maximum work output. TBC is applied on the crown of the piston to minimize the losses of heat to cooling systems, enhancing the higher energy conversion without significant changes in the engine. It can extend the ability of the engine to operate at high temperatures. It also improves the engine's efficiency at higher temperatures, significantly reducing harmful exhaust emissions.

Schulz et al. [1] Stated gas turbines and internal combustion engines typically use YSZ, a zirconium-based compound, as their top coat material. When an engine is cooled, pure zirconia (ZrO_2) changes from tetragonal to monoclinic. This can cause problems and failure for coatings, so 6–8% yttria is incorporated into the zirconia matrix to prevent this. When yttria is combined with zirconia, the material's thermal conductivity can be reduced further. Parlak et al. [2] examined the effects of $CaO–ZrO_2$, $MgO–ZrO_2$, and NiCrAl-coated combustion chambers on turbo diesel engines. It shows that fuel consumption was reduced by 6 % compared to a conventional engine, and BTE increased by 2 %. The study found that secondary heat recovery systems were needed to collect exhaust gas energy, the largest energy source. Compared to conventional engines, the LHR engine accessible exhaust gas energy by almost 3–27 %. Salman et al. [3] ceramic coating effect was studied experimentally on high-temperature surfaces. The Al_2O_3, Cr_2O_3, and ZrO_2 were coated on the cast iron. The coatings were applied in the engine without any bond coat. The most acceptable ceramic coating was identified and utilized for the engine test. The coated materials have a stronger resistance to high temperatures. The study concluded that the ZrO_2 provides the best characteristics on engine parts. Skopp [4] used two new sub-stoichiometric titania (TiOx) coatings for cylinder liners. First, $TinO_{2n-1}$ was coated by atmospheric plasma spraying. Second, $TiO_{1.95x}$ was coated utilizing a vacuum plasma spray technique using commercial, fused, and crushed powder. The cylinder received both TiOx coatings for wear resistance due to their high carbon content. The study found that the $TinO_{2n-1}$ coating had lower wear rates than $TiO_{1.95-x}$. Buyukkaya & Cerit [5] investigated the thermal analysis of $MgO-ZrO_2$ coated Al-Si alloy and conventional steel pistons using ANSYS. At the end of the study, each piston's results (2 coated and two uncoated) are compared. A piston is coated with a 350 μm layer of $MgZrO_3$ and a 150 μm layer of NiCrAl in this study. The effects of coatings on piston thermal behavior were examined. Test results showed that AlSi alloy and steel-coated pistons with low thermal conductivity material had 48 percent and 35 percent higher maximum surface temperatures, respectively. Shrirao & Pawar [6] examined diesel engine performance and mullite coating. At maximum load conditions, the turbo-charged engine showed a 2.18 % decrease in BSFC for the coated engine. There was a 12.1% increase in exhaust gas temperature and a 20.6% increase in NOx emission while maintaining the same operating conditions. However, the concentration of CO and HC was reduced by 22.05 % and 28.2%, respectively. Cerit [7] analyzed the temperature and stress distributions of a PCC (Partially Ceramic-Coated) piston used for an SI engine. Comparisons were made between the coated and uncoated piston in terms of temperature and stress distributions. The temperature of the coated surface was increased at a decreased rate as the thickness of the coating increased. With a coating thickness of 0.4 mm, the surface temperature of the piston was increased to 82 °C in this experiment. As the coating thickness increased, the stress on the coated surface decreased until it reached a low value of around 1 mm. However, the stress was increased when the thickness of the coating exceeded 1.0 mm. Finally, the study concluded that the optimum coating thickness was 1.0 mm under the above conditions. Modi [8] stated that lowering the amount of heat rejected from the system would improve thermal efficiency. The goal of Low Heat Rejection (LHR) engines is to reduce the amount of energy that is wasted as heat in the coolant system. Using fully insulated LHR engines with 0.5 mm thick zirconia coatings, it is possible to recover the 7 to 12 percent of heat lost to cooling water. Exhaust gas heat loss is also reduced by 5-9% compared to non-coated engines. Combustion and exhaust gas emissions in SI engines running on a mixture of gasoline and n-butanol were studied by Mittal et al. [9]. In this experiment, a ceramic material consisting of 8% yttrium oxide (Y_2O_3) and 2% zirconium dioxide was applied to the cylinder head and valves (ZrO_2). The material was coated to a thickness of 300 μm using the standard plasma spray method. According to research by Hoffman et al. [10], a magnesium zirconate TBC applied to the top of pistons in HCCI engines mitigates deposits caused by the increased surface temperature of the engine's combustion chamber. In their survey, the late desorption and deficient fuel burning in the piston bowl areas in the remaining cylinder charge increased HC emissions. In another experimental research by Hoffman et al. [10], magnesium zirconate (MgZr) coating on engine pistons reduced 50 % of combustion chamber deposit accumulation. Further, the coating improved the net HRR with low HC and CO emissions. To identify the improvement in engine performance operated with biodiesel on the coated engine, Ultra-low sulfur diesel blended with 20% waste-frying frying vegetable oil was used to power a TBC engine in experiments conducted by Aydn et al. [11]. In this research, a ZrO_2 coating 400 µm thick was applied to the combustion chamber. The findings show that compared to an uncoated engine, the coated one has a higher BTE. The authors also noted that the higher HRR occurred earlier in the coated engine with a slight increment in NOx emission. Purwar & Mahapatra [12] have developed a new TBC system with multi-layer ceramics for higher-temperature applications. The study proposes an upper, intermediate, and binding layer over a metal substrate. The top layer was made out of LaZr, the middle layer out of YSZ, and the bond coat out of Co-NiCrAlY. High heat protection has evolved in this system. This was reported by Raja et al. in 2016: methanol fuel was tested in the TBC engine and achieved better performance [13]. Surface hydrogenated diamond-like carbon coatings, as studied by Jeng et al., elevated the substrate materials' hardness, Young's modulus, toughness, and friction coefficient [14]. Garud et al. [15] aimed to reduce engine emissions by coating YSZ on the piston crown. By coating the conventional engine with YSZ at a thickness of 250 µm, we were able to transform it into an LHR engine. Compared to a conventional engine, the LHR engine with a thermal coated piston showed an increase in BTE upto 1.4 % and NOx emission. Due to effective coating, the heat loss through the piston top surface was reduced. Banka and Ramesh [16] conducted experiments to verify the improved performance of the modified TBC engine. The engine had a coating applied to it to shield the underlying metal from the higher operating temperatures. The piston crown was made of aluminum alloy and coated with YSZ (400 µm thick) and NiCrAl alloy (100 µm thick) for this study. The temperature profile of the piston head, both coated and uncoated, was analyzed statically. The piston's coated surface maintained a more consistent temperature than its uncoated counterpart. The piston's thermal fatigue was mitigated because of the coating's effect on the piston's surface temperature. The coated engine outperformed the uncoated engine in terms of performance and fuel efficiency. The investigation report by Selvam et al. [17] offers some conclusions about the YSZ-coated piston crown. According to the experimental results, the stabilized zirconia-coated engine over the piston crown performs better than the conventional engine. The coated engine has significantly reduced emissions of major pollutants like HC and CO. Three different piston coatings (zirconia, zirconia + aluminum oxide, and zirconia fused) were evaluated in a four-stroke DI diesel engine by Abbas & Elayaperumal [18]. Plasma spray techniques were used to apply the coating (at a thickness of 500 µm). The experimental results showed that the fused zirconia showed the best mechanical efficiency and BTE, which were increased by 10 % and 5 %, respectively. Fuel efficiency is improved by nearly 16 percent when using fused zirconia in place of conventional coatings in internal combustion engines. Meanwhile, both HC and CO emissions were drastically cut attributable to the coating. In 2019, Venkadesan and Muthusamy looked into how TBC affected diesel engine efficiency, combustion, and emissions [19]. The test findings revealed that the ceria/yttria stabilized zirconia coating exceeds the aluminum oxide/yttria-stabilized zirconia coating in terms of thermal cycling. The authors found that the engine performance characteristics such as BTE and BSFC increased in both coated and conventional engines. Vadivel & Periyasamy [20] focused on how a coated piston in a single-cylinder diesel engine affected performance and emission parameters. The research applied a 100 µm NiCrAl and a 150 µm YSZ, 4% MgO, and 8% TiO_2 coating to the piston crown via plasma spraying. The investigation found that coated piston engines had a BTE that was increased by 10% compared to an uncoated piston engine. Smoke, carbon monoxide, and hydrocarbon emissions were found to be drastically reduced in the coated engine compared to a regular engine. Brake Power (BP) was reported to have increased by 4% in the ceramic-coated engine compared to the standard engine by Reddy et al. [21]. Six percent less heat was lost to the coolant, and seven percent more heat was released into the exhaust gases. The engine's unaccounted-for heat loss is cut by 4% owing to the coating, too. The efficiency of the TBC engine with nano additives was measured by Vadivel et al. [22]. and their report shows that the TBC engine combustion is enhanced with the effect of nano additives. Gingrich et al. [23] investigated the piston top surface of an engine coated with TBC of different thicknesses and surface roughness. At the same load, the coated piston with Ra = 6.0 µm roughness and a TBC thickness of 0.325 mm demonstrated up to 3.5 percentage points greater thermal efficiency than the uncoated piston. Efficiency improved as a result of the additional late-cycle apparent heat release and decreased in-cylinder heat transfer.

After reviewing the relevant literature, that concluded that bond-coating materials are crucial to the successful application of thermal barrier coatings and have discovered an extensive range of thermally resistant materials; however, many gaps remain in our understanding of bond coatings for high-temperature applications. The novelty of this research is formulated Ti and Cr-based bond coating. The study's distinctive aspect is its examination of the impact of two distinct TBC coatings, each with a novel bond coating, on the combustion process in an engine.

2. Materials and Methodology

2.1. Coating Materials and Process

In this investigation, two coatings were designed for use with the plasma spray technique on the piston crown of an internal combustion engine [22], [24]. An Argon gas pressure of 100-120 PSI with a flow rate of 80-90 LPM, a Hydrogen gas pressure of 50 PSI with a flow rate of 20-25 LPM, a particle moving velocity of 20-100 m/s up to 450 m/s, and an arc temperature of 16000 °C are all shown in **Figure 1** for the plasma sprays and coating process.

The first piston utilized for this study is coated with bond material (first layer) of 200 µm thickness of $TiCrAl_2O_3$ (TCA) (80 % Al_2O, 13 % TiO_2, and 7 % Cr). The second layer has 300 µm of $MgZrO_3$ (92 % ZrO_2 and 8 % MgO) over the first layer. The crown is shrouded with a 500 µm thickness. In TCA, 80 % of Al_2O_3 aids in bonding, while 13 % of High corrosion resistance is achieved with TiO_2, and 7 % of Cr is used to provide better penetration and enhance the bonding quality among the coating materials [25]. $MgZrO_3$ for the upper layer is selected for its low heat conductivity. The second piston consisted of the first layer coated with 200 µm of TCA, and the second layer was covered with 300 µm of PYSZ (12% PY_2O_3 and 88% ZrO_2). Stability, low thermal conductivity, a high melting point, and low thermal expansion were all factors in the selection of these materials [26], [27]. **Figure 2**, **Figure 3a**, and **Figure 3b** depict the uncoated and coated pistons.

The experimental setup consisted of a single cylinder, diesel fuel, an eddy current dynamo meter loading system, five gas analyzers, a digitalized data acquisition system, and a fuel flow system. It maintained a steady 1500 revolutions per minute. The experimental setup schematic and photo views are shown in **Figure 4**.

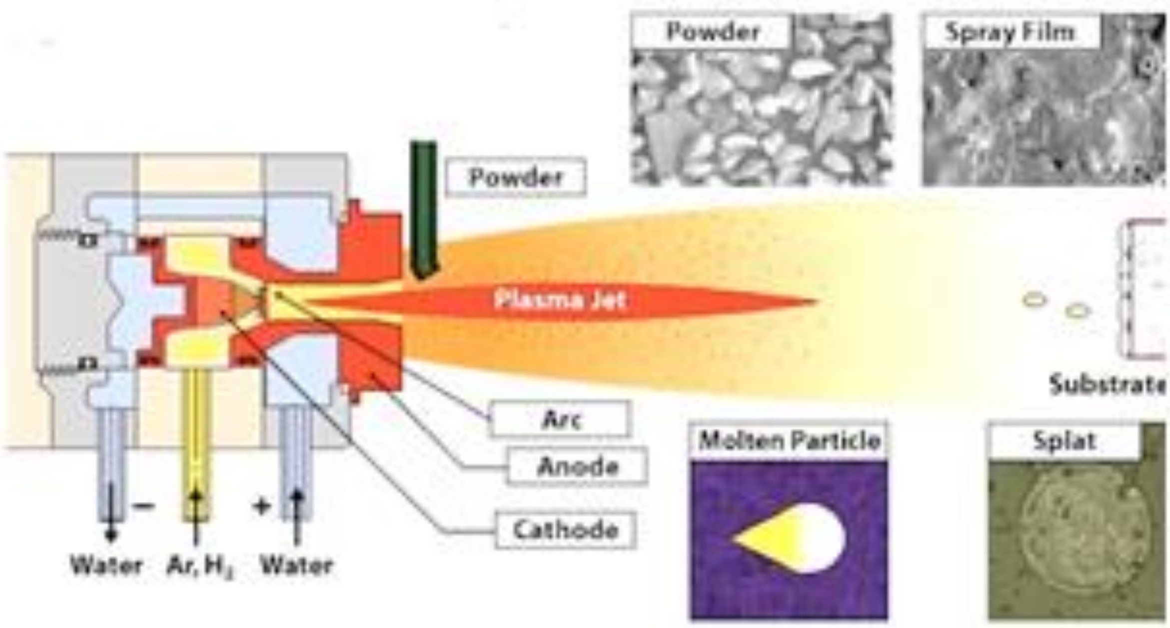

Figure 1. Plasma sprays process

3. Discussion of Findings

Results from the experiments are discussed in this chapter related to material strength, impact on various parameters, microstructure test, and hardness tests. Also presented was a discussion of using transient thermal analysis to determine the temperature profile of the piston coating. In this chapter, we also examine the engine's combustion, performance, and emissions with two distinct coatings on the pistons.

3.1. Thermal Analysis in Transition

Determining how the temperature is distributed across the piston is crucial to control thermal stresses and deformations. Before making the coating in the engine piston, the prototype is designed to optimize the piston's thermal design at a lower cost. From a different perspective, a thermal analysis of the piston is necessary. Usually, no piston should be hotter than more than 66 % of its melting point. In this context, the engine piston has a temperature limit of about 700 °C. Ceramics' thermal durability is higher than metals, so cooling them as quickly as metals is unnecessary. Ceramics with low thermal conductivity regulate the temperature and heat flow. TBC has the potential to improve engine thermal efficiencies and reduce emissions.

On the other hand, ceramics have superior wear properties than conventional materials. Since a thermally insulated combustion chamber rejects less heat, more energy is available for in-cylinder work, and exhaust gases carry more energy. The transient thermal analysis of an Al-Si alloy conventional diesel engine piston as well as two different ceramic-coated pistons is described in this section.

3.1.1. Properties of the Coating Materials

The bond coat's main priority is to keep the ceramic topcoat from peeling off the metal base. Generally, base materials have a higher coefficient of thermal expansion than ceramics. The metallic base material expands more than the ceramic coating.

Figure 2. Uncoated piston

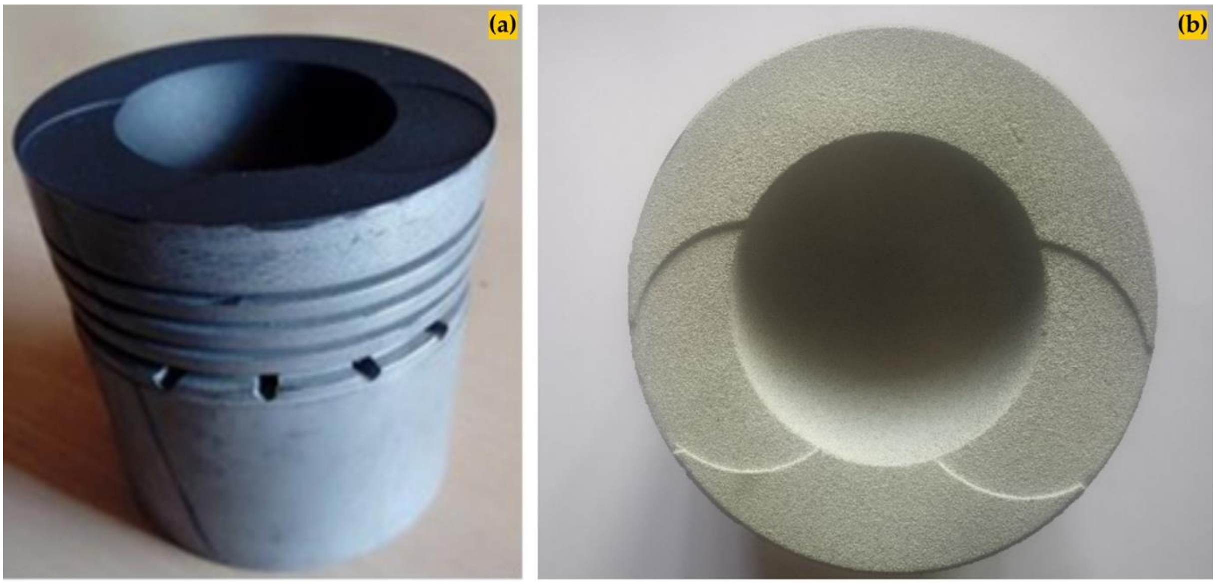

Figure 3. (a) TBC-1 coated piston; (b) TBC-2 coated piston

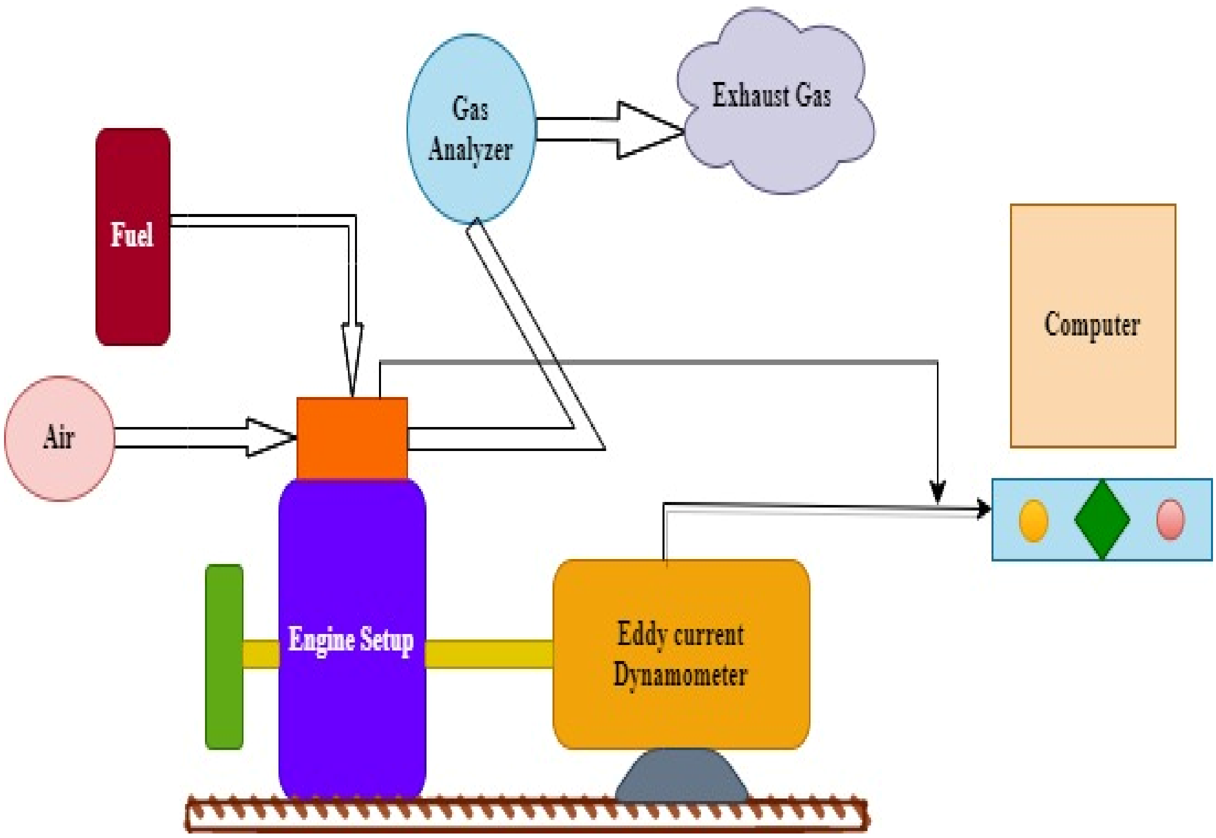

Figure 4. Experimental design schematic

To decrease the temperature difference between the substrate and the ceramic materials, a bond coat with a compatible coefficient of thermal expansion between the two should be used. It needs to be dense, not easily deformed, resistant to thermal shock and fracture, and have a high fracture toughness. The TBC coating shields the substrate from high-temperature gases. Coating materials' various characteristics are listed in Table 1.

3.1.2. Boundary Conditions and Thermal Analysis

Pistons for both standard and ceramic-coated engines are analyzed here using transient thermal analysis. The tetrahedral mesh type was used in the concentrated zone.

The research assumes that the piston crown gets heated to a maximum of 652 °C and that the leftover surfaces are in proximity to air, resulting in convection heat transfer. Certain assumptions must be established to carry out a thermal transient analysis. The crown of the piston that has been coated is the part that produces heat, while the rest of the piston is open to the air. The top, 652 °C surface is heated via conduction, whereas the bottom, uncoated surface is heated via convection. The convective heat transfer coefficient is estimated to be 28 W/m2K at an air temperature of 30 °C. The temperature profiles of the coated and untreated pistons are displayed in Figure 5. The temperature variations of coated and uncoated pistons are compared through simulation analyses. In the piston with TBC-1, and TBC-2, temperatures at the top lane are 638 °C, and 410 °C, and the uncoated piston reaches 522 °C. The temperature distribution of the piston from the top lane to the oil lane was reduced by 18

Table 1. Piston and coating material characteristics [22], [26], [27]

Material	Thermal conductivity (W/m °C)	Specific heat (J/kg °C)	Density (kg/m³)
Al-Si (Base Materials)	155	960	2700
TCA	67	683	4050
PYSZ	2.5	545	5200
$MgZrO_3$	0.8	650	5600

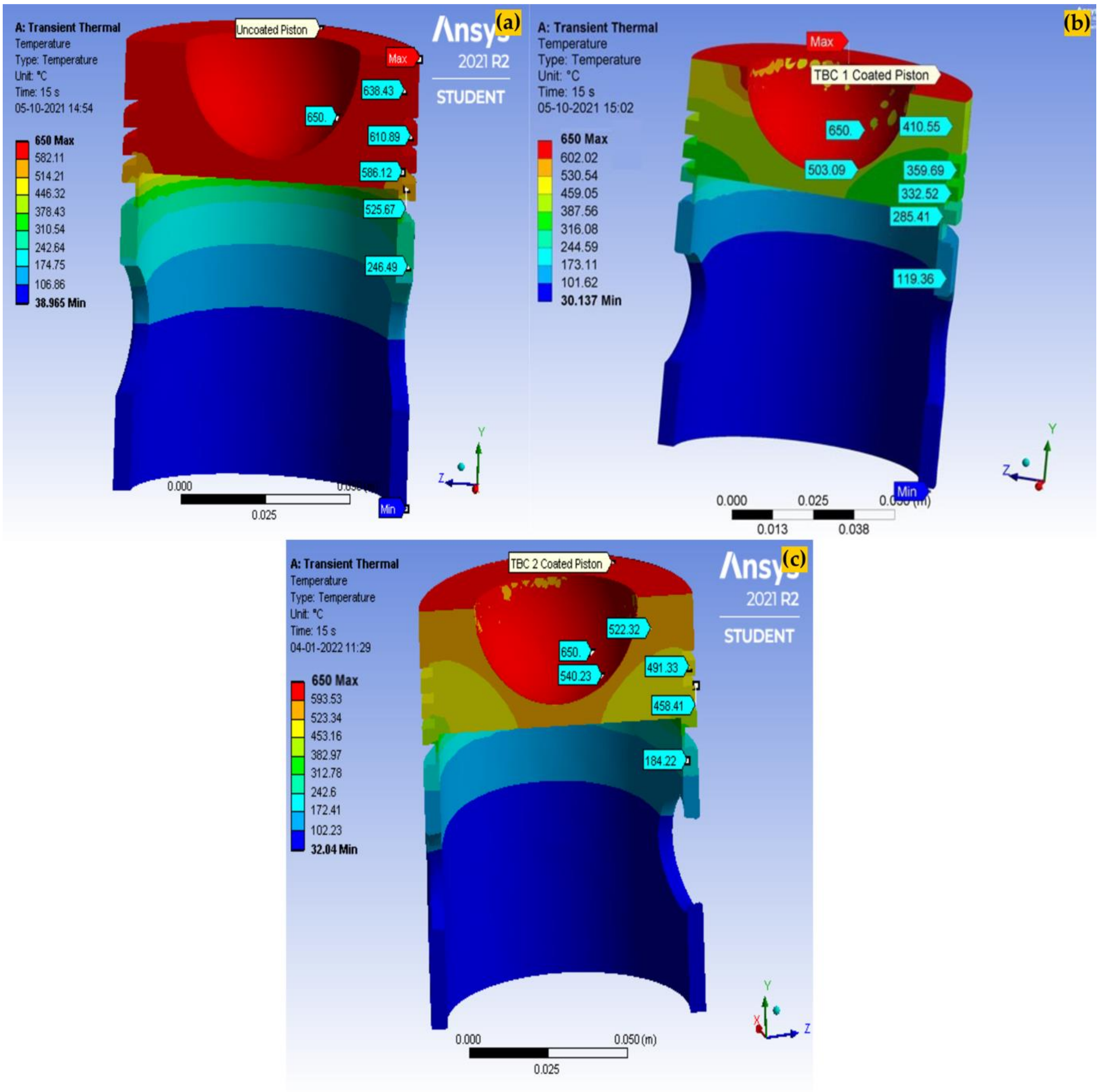

Figure 5. (a) Piston temperature distribution when not coated; (b) Temperature profile of the TBC-1 piston; (c) TBC-2 piston temperature dispersion

% for TBC-1 and 35 % for TBC-2 due to coating. The piston without coatings is compared, and the decreased value of temperature distribution for TBC-1 and TBC-2 pistons is shown in Figure 6.

3.2. *Coated Piston Engine Performance and Emission Analysis*

Detailed information about the engine's efficiency and emissions levels are presented here with MgO-ZrO_2-TCA and PYSZ-coated pistons operated at standard operating conditions. Combustion parameters are analyzed and compared with conventional (uncoated) engine-operated at the same operating conditions.

3.2.1. *Uncertainty and Errors*

Engine and gas analyzer performance was regularly regulated. After the engine's steady state, emissions were manually recorded. The measured parameter uncertainty is shown in Table 2. Parameter uncertainties are quantified using Eq (1). The Yi (mean value) and σi (standard deviation) of calculated parameters are determined from experiments. Repetition five times calculated these experiment values using each apparatus, procedure, and standard. The TUP was determined using Eq (2). The experiment has a total uncertainty of ± 2.11 percent across all aspects.

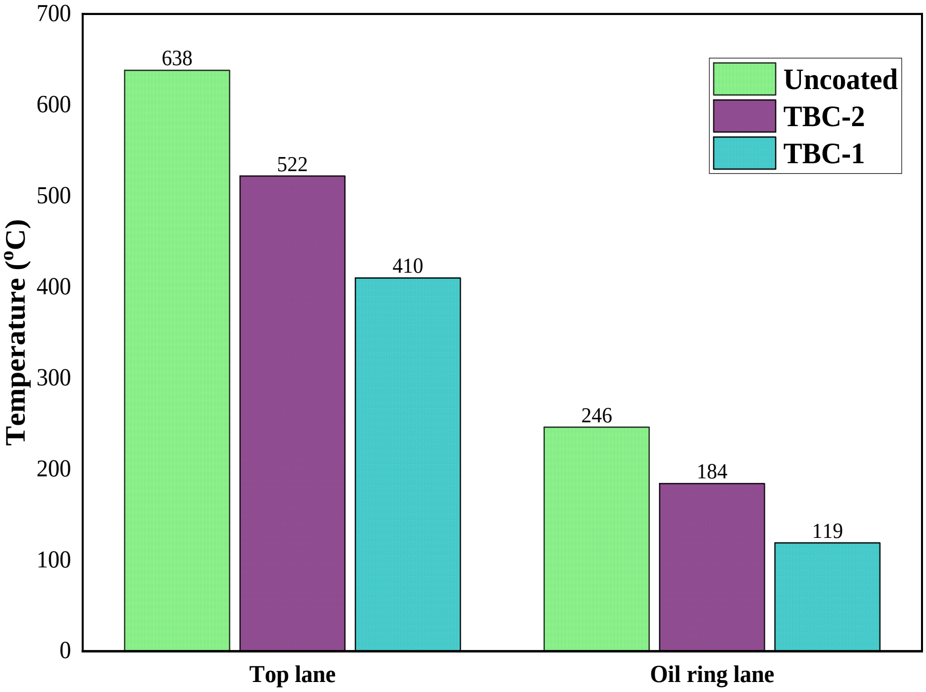

Figure 6. Temperature distribution of the pistons

Table 2. Measurement errors and uncertainties

Instrument	Measurement	Uncertainty (%)
Temperature indicator	Exhaust gas measurement	±0.4
Load cell	Loading device	±0.1
Burette	Fuel consumption	±1.4
Speed sensor	Speed	±2
Pressure Transducer	Cylinder Pressure	±0.2
Exhaust gas analyzer	CO	±0.01
	CO_2	±0.01
	HC	±0.1
	NOx	±0.4
Crank angle encoder	Crank angle	±2

$$\Delta\varphi_i = \frac{2\sigma_i}{\sqrt{Y_i}} \times 100 \tag{1}$$

$$TUP = \sqrt{\Delta\varphi_1{}^2 + \Delta\varphi_2{}^2 + \cdots\cdots\cdots + \Delta\varphi_n{}^2} \tag{2}$$

3.2.2. Engine Performance and the Role of Coatings

3.2.2.1. Brake Thermal Efficiency

Figure 7 illustrates the results of BTE on the conventional and coated engines under different load conditions. When comparing BTE between coated and uncoated engines under exactly equal loads, the figure clearly shows that the coated engine has a higher BTE, and the impact of coating on the piston achieves it. A turbulent flame was generated by the rough surface of the layer in the piston, as predicted by the theory of flame propagation. The turbulent conditions in the chamber ensure that the flame reaches all areas of the fuel source. As a result, the fuel burns completely, producing a high amount of heat. The coating in the piston resists the heat flow inside the piston material; hence it absorbs only less heat. Concerning the engine's maximum load, the BTE obtained from the TBC-1, TBC-2, and uncoated pistons are 32.3 %, 30.94 %, and 23.43 %, respectively. When the engine is running at full load with TBC-1 and TBC-2 pistons, respectively, the greatest gains in BTE are 8.87 percent and 7.51 percent. The TBC layer has a significant effect, leading to a high-pressure ratio. According to the fundamental ideal diesel cycle, increasing the pressure ratio by a small amount results in a much larger increase in engine brake power.

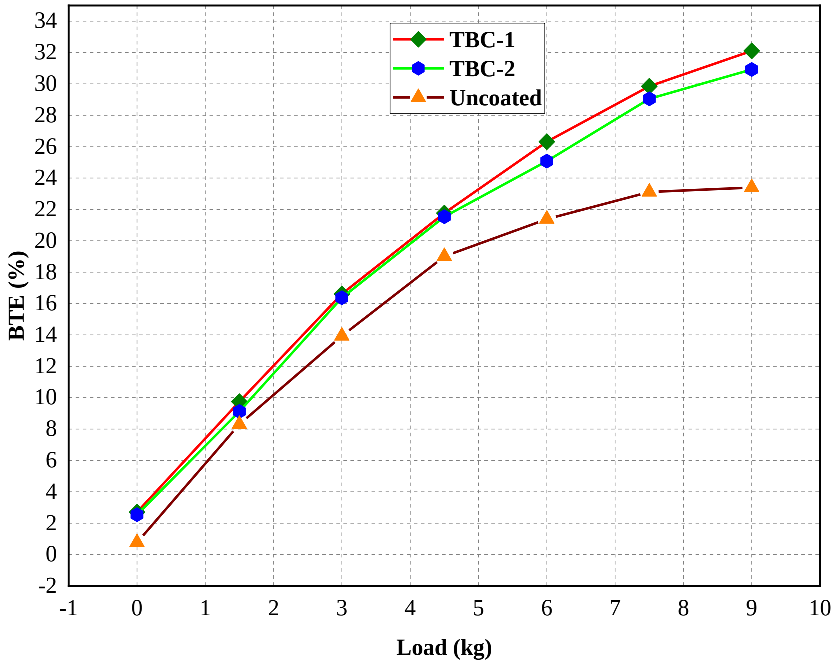

Figure 7. Engine BTE variants with and without coatings

3.2.2.2. *Volumetric Efficiency*

Due to the high density of the particles in the exhaust gases, the unburned gases are laid down inside the cylinder of an uncoated engine during the exhaust stroke. When the outside air comes in, it becomes stuck. The volumetric efficiency will suffer as a result. The coated engine, however, experiences none of these issues. By keeping the cylinder hot, the air-fuel mixture can continue to burn at its optimum rate. The result is a higher EGT. The volumetric efficiency of an engine is measured by the volume of air sucked in during the suction stroke. As a result, almost all of the exhaust gas leaves the cylinder. When compared to a similar non-coated engine, this improves volumetric efficiency. The volumetric efficiency of the TBC-1 engine is 80.60 percent, that of the TBC-2 engine is 80.35 percent, and that of the unpaved engine is 79.29 percent. Therefore, the engine achieves its greatest volumetric efficiency gains of 1.31 percent and 1.06 percent at full load. Coated engines have higher volumetric efficiency under all loads. The volumetric efficiencies of a coated and non-coated engine under different loads are shown in Figure 8. The volumetric efficiency of coated engines increased under all load levels.

3.2.2.3. *Consumption of Specific Fuel*

During a compression stroke, the engine's parts absorb some of the heat and pressure generated by the combustion of fuel inside the cylinder. During this, the piston takes in more thermal energy. Due to the above heat losses, an uncoated engine may need to use more fuel to maintain a constant power output. The piston in a coated engine absorbs much less heat energy, as the coating has a low thermal conductivity. Therefore, under the same conditions, more power is produced by the coated engine while using the same amount of fuel.

Figure 9 shows how the TBC-1, TBC-2, and conventional engines' brake-specific fuel consumption varies across a range of loads. The BSFC of TBC-1 and TBC-2 engines is shown to be lower than that of a conventional uncoated engine in Figure 9. At full power, the BSFC for a non-coated engine is 0.378 kg/kWh, while it is 0.267 kg/kWh for a TBC-1 engine and 0.312 kg/kWh for a TBC-2 engine, representing reductions of 27.03 percent and 18.91 percent, respectively. In most cases, the DI engine must burn a higher amount of fuel to maintain engine speed. The maximum burning process occurs in the coated chamber due to the TBC, and the coated engine can keep running at full speed without any additional input of energy. It helps the TBC engine run more efficiently by decreasing the amount of fuel that isn't burned. Energy conservation in the coated engine at all loads contributes to the decrease in BSFC. A hotter combustion chamber could be held responsible for this.

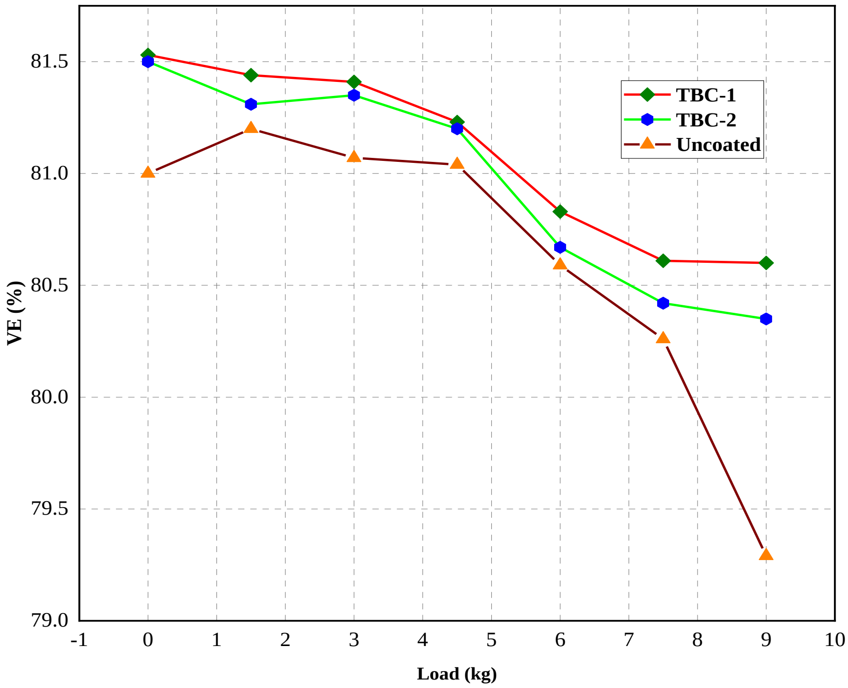

Figure 8. Differences in volumetric efficiency between coated and uncoated engines

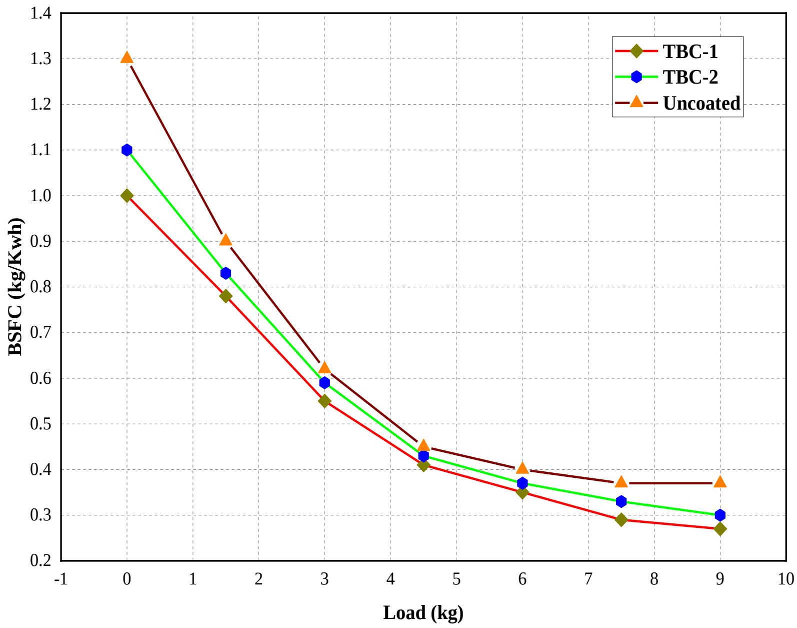

Figure 9. Coated and uncoated engine BSFC variants

3.2.3. Effect of Coating on Combustion

3.2.3.1. Heat Release Rate

Figure 10 shows the HRR for TBC engine-1, TBC engine-2, and uncoated engine operated at maximum load. The higher HRR for the TBC-1 engine and TBC-2 engine is somewhat more significant than the uncoated engine. Diesel fuel running at TBC engine-1 and TBC engine-2 engines show higher HRR of 61.85 J/deg and 58.83 J/deg, whereas the value for the uncoated engine was 43.0 J/deg. Compared to an engine that had not been coated, the effect of the coating on the increase in HRR was observed at a crank angle of 3 degrees before TDC, with the peak value appearing at 5 degrees after TDC. The heat insulation provided by the coating enhanced the higher heat release, indicating efficient use of injected fuels and complete combustion. As this coating's rough surface causes a turbulent flame, the coated engine extracts more heat energy from fuel, as shown in the figure. The turbulent flame travelled in all directions inside the combustion chamber and burned to a maximum level.

3.2.3.2. *Cylinder-Internal Pressure*

Diesel engines develop maximum in-cylinder pressure primarily based on how much fuel is burned during combustion. **Figure 11** compares the in-cylinder pressure and crank angle of fully loaded TBC-1 and TBC-2 engines with uncoated engines.

The in-cylinder pressure at various crank angles was determined by averaging the results from 100 cycles. For an engine without a coating, the combustion started when the pressure rose quickly after the fuel injection started, which was about 11° before TDC and ended about 56° after TDC. In a coated engine, combustion begins 13° before TDC, indicating a quicker start of combustion and reduced ignition delay compared to an uncoated engine. This results in a change in peak pressure near TDC, with combustion ending about 52° after TDC. Coated engines experience the highest cylinder pressure at full load. The graph reveals that the peak pressure of the TBC engine -1 and TBC engine -2 engine was 59.33 bar and 58.01 bar, 12.23 and 11.29 % more than the conventional engine (51.92 bar). This is due to enhanced fuel combustion at the coated piston engine, which results in greater in-cylinder temperatures and a shorter delay period.

3.2.3.3. *Heat Balance of Engine*

Figure 12 shows the total heat energy dissemination of the uncoated, TBC engine -1 and TBC engine -2. The percentage of useful work (break power) heat energy has been improved by coating the piston at the full operating condition, which is increased by 3.5 % and 2 % for TBC engine -1 and TBC engine -2 engines compared

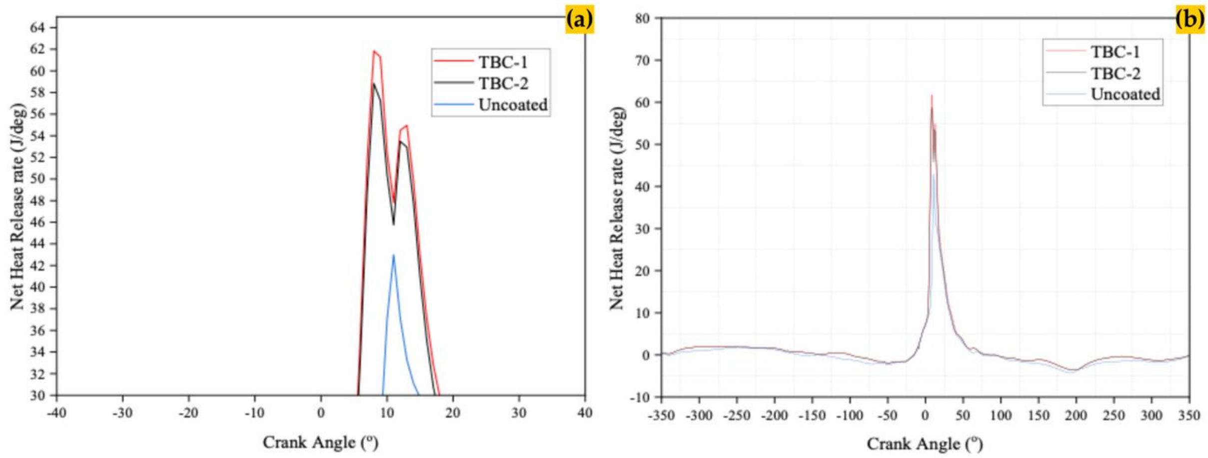

Figure 10. Combustion engine heat dissipation, coated vs. uncoated: (a) engine 1 and (b) engine 2

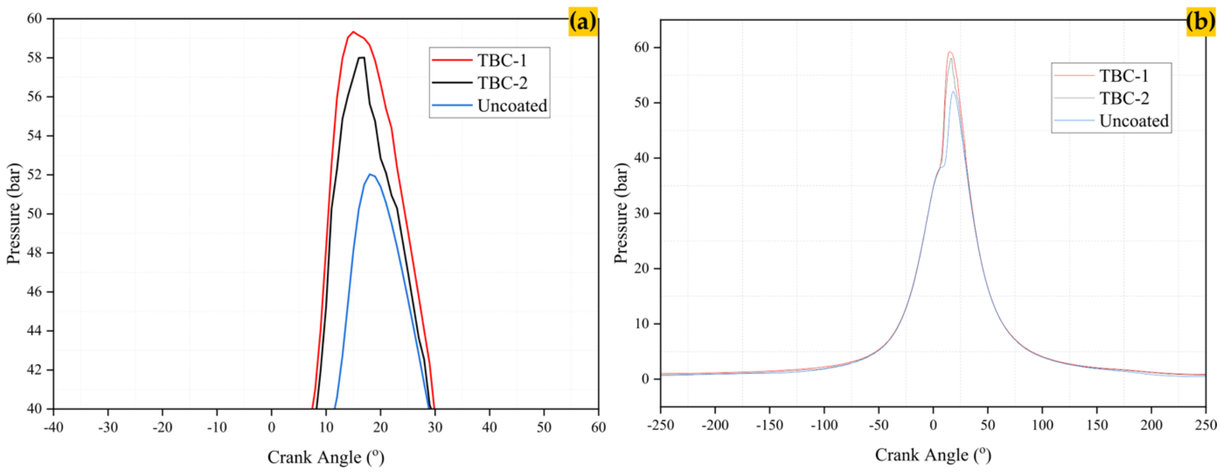

Figure 11. The Effect of Coating on engine pressure: (a) engine 1 and (b) engine 2

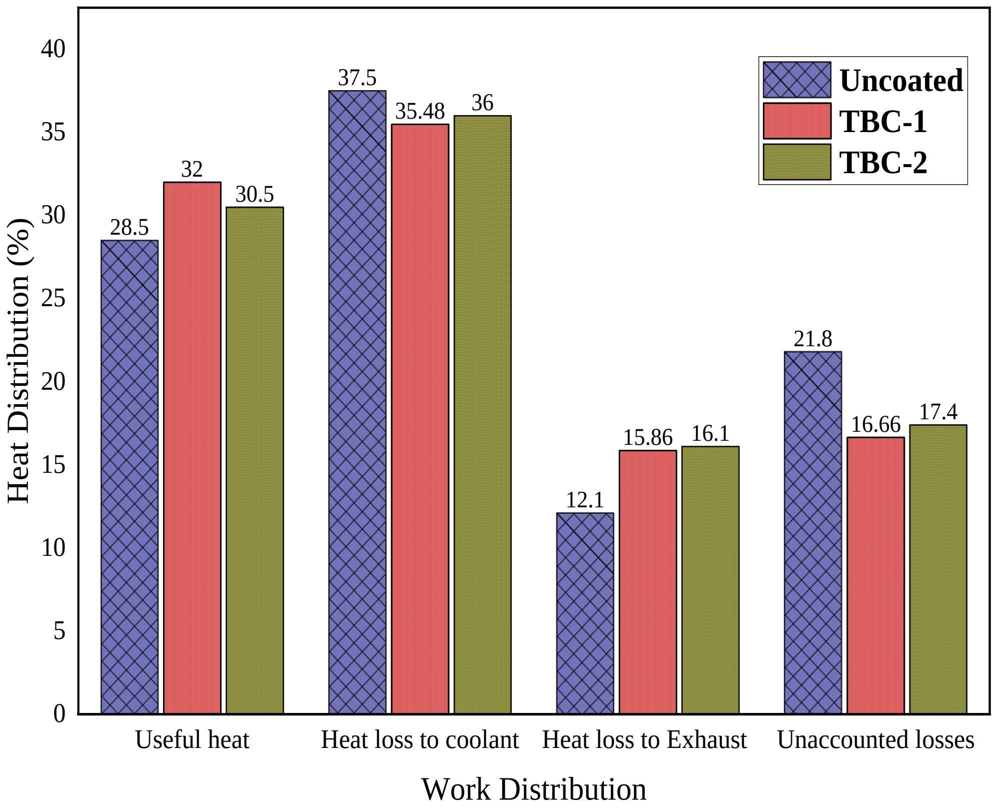

Figure 12. Heat balance sheet for coated and uncoated engine

with the uncoated engine. Due to coatings on the piston, the HRR is increased for all loads, producing higher heat energy. Generally, the fuel burning inside the cylinder is converted to heat energy. The piton then observes significant heat and transfers it to engine components and lubrication oil. Piston tops coated with low thermal conductivity materials reduce piston heat absorption. At all load conditions, the coated engines produced as much heat energy while using less fuel. Both TBC engine -1 and TBC engine -2 have slightly higher exhaust gas temperatures due to the piston coating's resistance to heat energy loss to the coolant. The net heat carried by coolant is decreased by 2.02 % and 1.5 % for TBC-1 and TBC-2 engines.

3.2.4. Effect of Coating on Engine Emissions

3.2.4.1. Carbon Monoxide

The most common cause of carbon monoxide emissions is low combustion chamber temperatures. The CO emissions from the TBC engine -1 and TBC engine -2 engines, as well as the uncoated engines, are shown in **Figure 13**. Coated engines have drastically reduced carbon monoxide emissions compared to their uncoated engine. Coated engines reduce carbon monoxide because the combustion chamber gets hotter and more fuel gets burned. Combustion of fuel within the coated combustion chamber results in less CO being released. Changes in CO at a steady 1500 rpm are shown in **Figure 13** as a function of varying loading conditions. **Figure 13** shows that lowering CO emissions is a consequence of increasing brake power. Experiment results show that under full load conditions, CO emissions are 0.01 percent for TBC-1 and TBC-2 engines and 0.02 percent for uncoated engines due to proper fuel combustion. When compared to their respective uncoated engine, the CO emissions of both coated engines are reduced by a whopping 50%. The complete combustion of the fuel results in lower CO emissions.

3.2.4.2. The Gaseous Element Carbon Dioxide

The combustion process produces a large amount of carbon dioxide gas. **Figure 14** compares the CO_2 emissions of the TBC engine -1 and TBC engine -2 engines to those of the uncoated engines under varying loads. Due to complete combustion, the coated engines produce more CO_2 emissions. The coated engines maximized

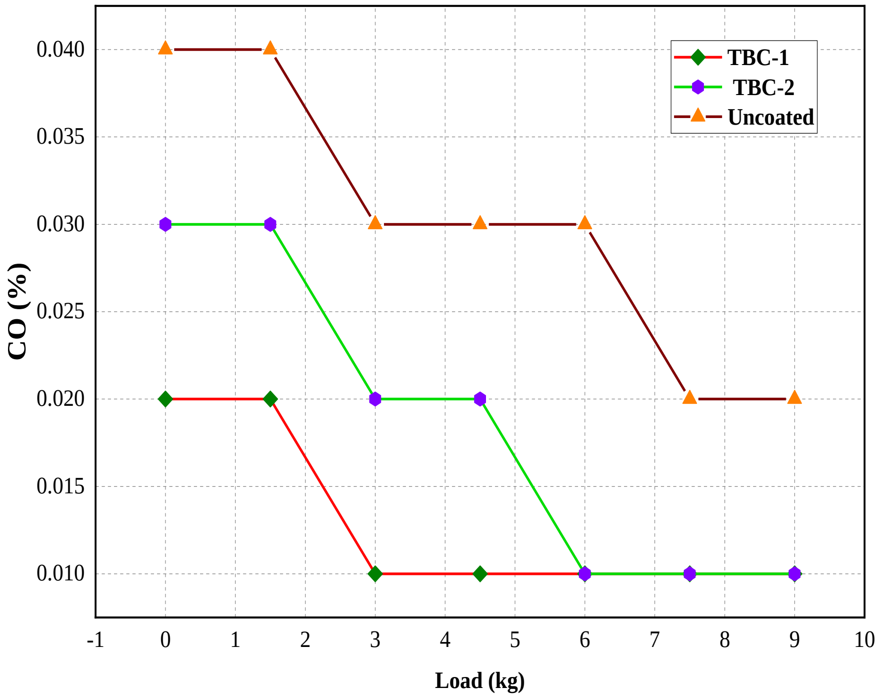

Figure 13. The Difference between coated and uncoated engines' CO emissions

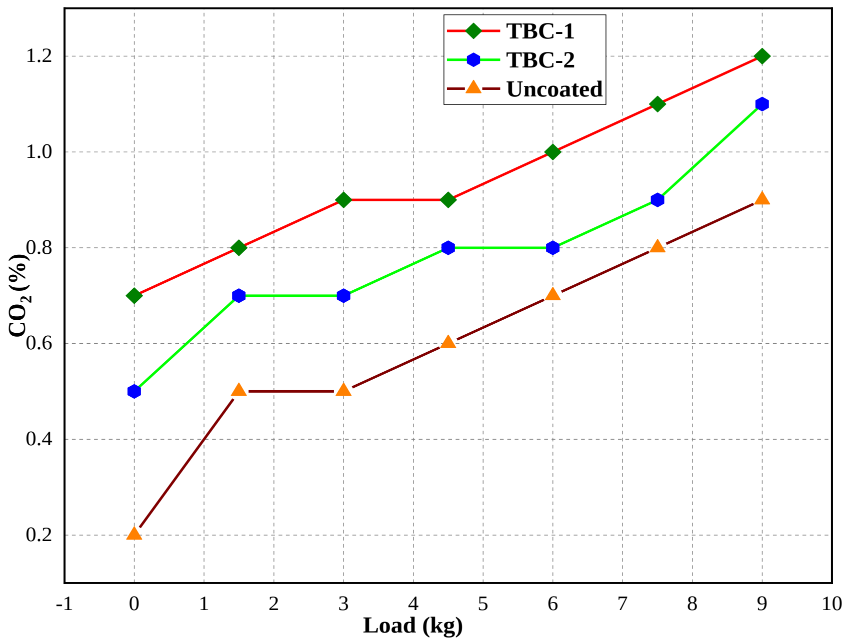

Figure 14. Differences in carbon dioxide emissions between coated and uncoated engines

energy output by converting all of the fuel they burned into thermal energy. This has led to a marginal rise in global CO_2 emissions. CO_2 emissions in TBC-1, TBC-2, and uncoated engines at 100 % load are 1.19 percent, 1.11 percent, and 0.89 percent, respectively. The CO_2 emission increases by 33.33 % and 22.22 % when the same fuel is operated at TBC-1 and TBC-2 engines under load conditions, the engine spins at a steady 1500 rpm. The TBC achieves the maximum fuel burning due to increased temperature in the combustion chamber, which aids in preventing carbon buildup on the piston.

3.2.4.3. *Hydrocarbons*

Figure 15 depicts variations in HC emissions of the TBC-1, TBC-2, and uncoated engines concerning different loads. HC emissions increase

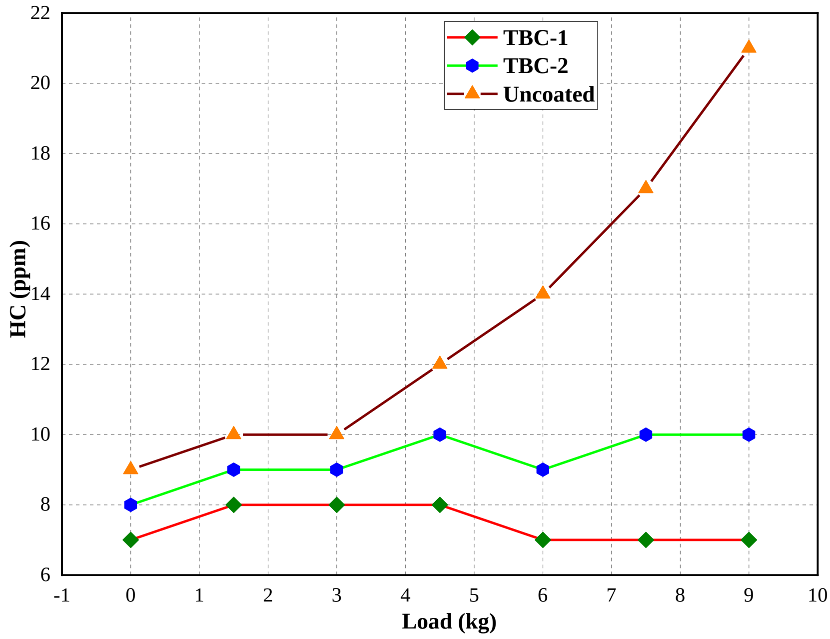

Figure 15. Variation of HC for coated and uncoated engine

with increasing load for uncoated engines, and some fluctuations are obtained for coated engines. The value of HC emissions for TBC-1, TBC-2, and uncoated engines is 7 ppm, 10 ppm, and 21 ppm, respectively. A drastic decrease in HC emissions of more than 50 % is observed for the coated engines. From **Figure 15**, the emission of HC by thermal coating is reduced by 66.67 % and 52.38 % for TBC-1 and TBC-2 engines at 100 % load. TBC-coated engines have much lower HC emissions because less heat is rejected by the coolant. The results indicate that the HC emission value for uncoated engines is greater than the coated engine for all loads. Coated engines produce less HC because their combustion chambers start out cooler.

3.2.4.4. NOx

Figure 16 represents the distinction in NOx emissions between the TBC-1 and uncoated engines. NOx is generally formed due to nitrogen oxidation at elevated combustion temperatures. The only factors that influence NOx emissions are the temperature of the combustion chamber and the maximum fuel burning rate. Coated engines have a higher NOx concentration than uncoated engines, and their exhaust gas temperatures are also higher.

The obtained results agree well with the existing research data. The results data indicate that NOx is high in the coated engines. Previous research has found that the level of NOx emissions from LHR engines is likely to be increased. Possibly, this is because of the increased heat, longer combustion duration, and more significant fuel-burning portion. At 100 % load conditions, the value of NOx for TBC-1, TBC-2, and uncoated engines is 300 ppm, 272 ppm, and 53 ppm, respectively. TBC attains proper combustion inside the combustion chamber. The investigation outcomes show that the EGT of the uncoated engine is 110 °C, whereas, for TBC-1 and TBC-2 engines, the values are 188 °C and 160 °C at full load operating conditions. The prime reason for the formation of NOx during engine operation is the reaction between O_2 and N_2. In the safety aspects of the environment from the NOx emissions, the exhaust gas recirculation can reduce the NOx emission up to 20 % and the catalytic converter can convert the NOx into harmless gas and it can help to meet the NOx value of an uncoated engine.

3.2.4.5. Comparative analysis

The break thermal efficiency of TBC-1 and TBC-2 has been compared with previous study work [22] as shown in **Figure 17**. According to the graph, the novel bond coating combination exhibited higher thermal efficiency when compared to previous research work. The heat conductivity of the top layers was not influenced by chromium-based bond coating, and this type of

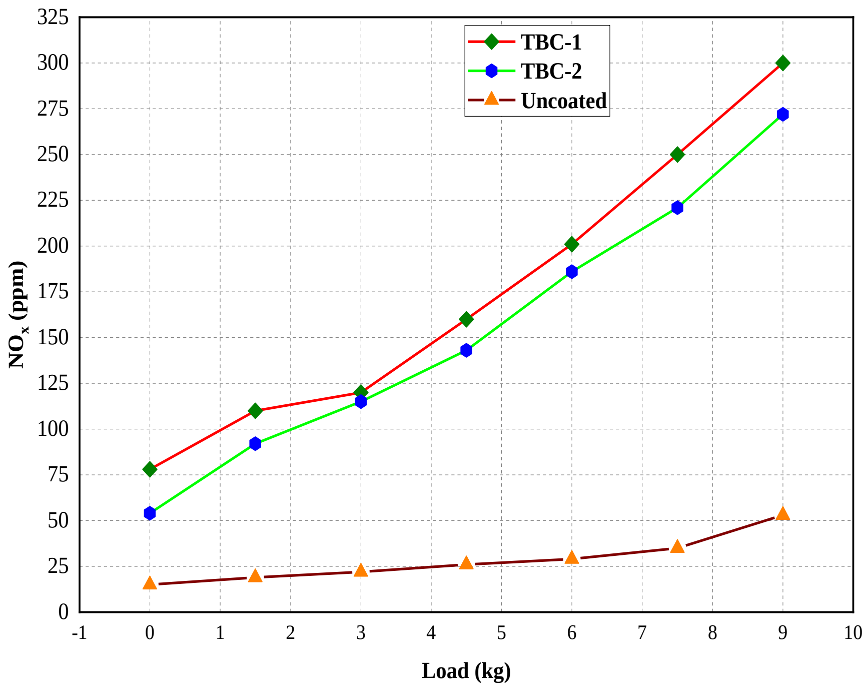

Figure 16. NOx emissions differ between coated and uncoated engines.

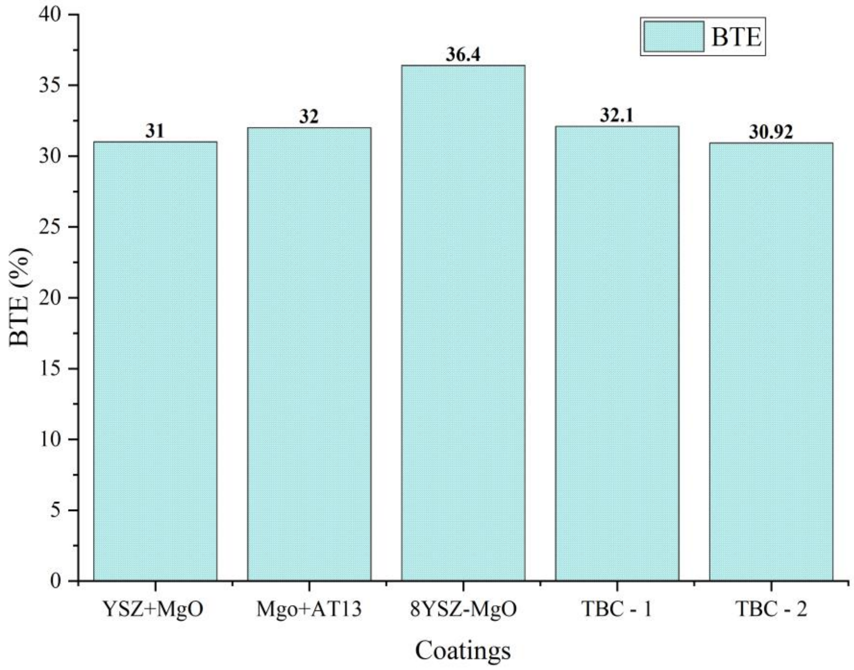

Figure 17. BTE of TBC's engine compared with existing work

bond coating provides superior penetration with base materials. However, it provides the greatest efficiency.

4. Conclusion

The current work's aim is based on a brief literature review of coated engines. The main conclusions drawn from the experimental results presented in the previous chapter are outlined here. Analyses of the performance, emissions, and combustion of two types of coated engines—TCA with MgO-ZrO2 (TBC-1) and TCA with YSZ—are presented (TBC-2). The first phase of the research work was presented with developing TBC on piston crown using plasma spray technique. Roughness hardness, microstructure, and salt spray test on the coated piston were conducted along with transient thermal analysis.

4.1. Temperature Distribution Analysis

A high thermal conductivity of the piston material results in a high rate of temperature transfer when the piston is uncoated. When applied to TBC-1 and TBC-2, the embroidered reduced the temperature distribution by 35% and 18%, respectively, due to its lower thermal conductivity. The strength and deformation of the material can be improved by applying a ceramic coating.

4.2. TBC-1's Impact on Engine Efficiency

The experimental study examined how MgO-ZrO_2 with TCA affected engine performance, and the following important conclusions were drawn:

- BTE varied by 32.3% for TBC-1 engines and by 23.43% for uncoated engines when both were operating at the same load. When compared to a standard engine running at full throttle, the BTE of a TBC-1 coated engine is 8.87% higher.
- The value of BSFC for a TBC-1 coated engine is observed to be lower than traditional for all loading conditions. The rate of fuel consumption is decreased with increasing load for both engines. At full throttle, the BSFC for a coated and conventional engine is 0.378, and 0.267 kg/kWh, respectively. which has decreased by 27.03%.
- Coating increases volumetric efficiency compared to uncoating. A maximum improvement of 1.31 % is observed when the engine is operated at 100 % load.
- For diesel fuel operating at TBC-1 engine shows a higher heating rate of 61.85 J/deg, whereas the value for the uncoated engine was 43.0 J/deg. Coated engine operation results in a higher maximum cylinder pressure of 59.33 bar, an increase of 4.6% compared to an uncoated engine operating at the same temperature.
- According to heat balance analysis, the percentage of useful heat was improved by 3.5%.
- High combustion efficiency and a higher combustion temperature allowed the TBC-1 diesel engine to emit less CO and HC and more CO_2 and NOx than an uncoated engine.

4.3. Effect of TBC-2 on Engine Performance

The effects of TCA with PYSZ coating on engine performance were investigated, and the following significant conclusions were obtained:

- At 100 % load conditions, the percentage variance in BTE for the TBC-2 and uncoated engines was 30.94 % and 23.43 %, respectively. When compared to a conventional engine, TBC-2 coated engine shows a maximum improvement of 7.51 % in BTE.
- The TBC-2 coated engine has a lower value for the BSFC throughout the loading conditions. As the load rises, fuel efficiency improves. The BSFC for a conventional engine at full throttle is 0.312 kg/kWh, while that of a TBC-2 coated engine is 0.37 kg/kWh, a reduction of 18.91%.
- Volumetric efficiency of the TBC-2 engine increases. Engine volumetric efficiency improves 1.06 percent at 100% load.
- The TBC-2 engine exhibits a higher heating rate of 58.83 J/deg, whereas the uncoated engine exhibits a heating rate of 43.0 J/deg. Maximum in-cylinder pressure was achieved.
- The engine ran with a TBC-2 piston, the percentage of useable heat was increased by 2%.
- Although the TBC-2 engine's CO and HC output were lower, the CO_2 and NOx output were higher.

4.4. Coating Suggestion

The superior characteristics of TBC-1 coated material over TBC-2 material result in better engine performance and emissions. From the experimental analysis, the bond coat material $TiCrAl_2O_3$ created better penetration with both TBC coating. $MgZrO_3$ and $TiCrAl_2O_3$ combinations provide better performance results in all aspects.

4.5. Future Plans of Research

This coated engine will study how ethanol fuel affects TBC engine performance and pollution in the future.

Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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