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Research Article

Optimization of Dual Coating Using Electroless Ni-P-Nano-TiO_2 and Plasma Yttria-Stabilized Zirconia on Piston Crown and Cylinder Liner in CI Engine

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Most of the automobile engine components are made up of cast iron because of its low cost, damping characteristics, castability, and commercial considerations. In modern days, the blended biodiesels are introduced into the CI engine to reduce the usage of petroleum fuels. The following problems are identified in utilizing the biodiesels, they are lower efficiency, power, wear in the engine cylinder and piston crowns, more emission from the exhaust, and performance. To overcome the wear problem in cylinder liner and piston crown, the dual coating is developed using electroless coating and plasma spray coating, and this deposit acts as a thermal barrier to the engine. The electroless Ni-P-TiO_2 composite coating process parameters are optimized using the Taguchi technique with multiresponse grey relational analysis. The plasma spray coating is developed over electroless Ni-P coating using Yttria-stabilized Zirconia for the total thickness of 2 mm. The coated components are installed in the CI engine for further testing and analysis. The morphology of the coated surfaces is tested using the scanning electron microscope. The optimization process used to improve the Ni-P coating thickness, surface roughness, and thermal resistance of the engine components. Also, the performance and emissions in the engine are reduced significantly. The emission from the CI engine such as NOx, COx, and HC are reduced significantly. The emissions of CI engine such as NOx, CO_2, CO, and HC of the noncoated engine shows higher, and EPSCE engine condition shows less pollution. The percentage of improvement in terms of emissions are 27%, 70%, 6.4%, and 21%, respectively. The performance is improved to 3% and 27.8%, respectively, for specific fuel consumption and brake thermal efficiency.

1. Introduction

Once the automotive engines are discovered, the efficiency of human beings has increased significantly. Friction is the key parameter to influence the performance of the IC engines. Piston ring and cylinder liner are considered as the most important parameters because it takes up to 50% energy loss due to friction. In terms of consumption of fuel, 1/3 of the produced energy from the fuel was consumed by friction. Due to the gradual depletion of fossil fuels, biodiesel are deliberated as the best substitute for petroleum-based fuels [1]. The common way to produce biodiesels by traditional chemical reactions called transesterification from vegetable oils and animal fats. Biodiesel are more suitable for house hold applications, and same amount of power can be developed. In the pursuit of performance and emission, biodiesel shows superior charachերistics than petroleum fuel [2]. Thus, many academician and scientist are focused to reduce the friction and wear of engine components, through it the fuel consumption and energy can be enhanced. Even with so many positive things and high consumption rate throughout the world, some challenges need to be faced to use the biodiesel in any applications. Biodiesel have oxidation instability delinquent which results in promoting the acidic nature of the fuel and cause corrosion over the engine cylinder liner and piston. Through corrosion, the free particles evolved and increased the rate of wear and friction inside the engine cylinder [3]. The prospective method to increase the wear, friction, and corrosion resistance of the components such as piston ring and cylinder liner materials is protective surface coatings. There are many surface coating techniques that have been utilized for the past five decades to improve the tribological properties. Among them, the coating of automotive components using electroless Ni-P coating has been widely used because of its high corrosion and wear resistance, high hardness of the deposits, and irregular shape can be coated easily; no electricity is utilized during the process etc. [4]. Another method to improve the wear resistance is plasma spraying; the Yttria-stabilized Zirconia (YSZ) is commercially the applied material composition to enchance the wear resistance [5].

Selvam et al. performed coating on piston ring, and reported that the BTE and fuel consumption is improved. When compared to uncoated piston, the plasma spray coated piston reduce the HC and CO emissions. The NOx is inceased however it can be reduced by varying the different parameters of the CI engine [6]. Similarly, Powell et al. [7] reported that the emission and performance of the HCCI engine are improved significantly after the YSZ coating on cylinder liner and piston head of the engine. The YSZ coating on the components of the engine not only improve the performance and emission charchteristics but also increase the wear and friction behaviour of the engine [8]. The use of biodiesel in CI engine is reported as highly corrosive in nature and affect the materials in the engine cylinder. The existence of H_2O and O in the biofuel stimulating the evolution of corrosive chemical reactions [9]. To enchance the corrosion resistance of the material, electroless Ni-P deposited are incorporated. On the other hand, the electroless coating on engine cylinder liner and piston head are never done before. So the optimization of process parameters is required to choose the best parameters to obtain the required thickness. Taguchi technique is a robust design to optimize the process parameters of any system with minimum number of experimental trials. It reduces both the time, money, and resources of the system. The L9 orthogonal array is used to optimize the single objective functions [10]. The grey analysis is used to solve the multiobjective system using Taguchi technique in many industrial applications. The hybrid Taguchi-grey-AHP method is employed by Hoang and Pham [11] to optimize the parameters in casting process and reported the best optimized condition obtained with high level of accuracy. The variable parameters in the electroless coating to obtain the high quality deposits are nickel source, reducing agent, complexing agent, stabilizing agent, wetting agent, and percentage of hydrogen. Among these variables, the highly influencing factor to control and improve the quality of the deposits is the percentage of hydrogen, wetting agent, and stabilizer according to the survey [12–16].

In this research work, the biodiesel powered CI engine piston head and cylinder liner are dual coated with Ni-P and YSZ using electroless and plasma spraying techniques, respectively. The process parameters of the electroless coating with multiresponse objectives are optimized using Taguchi-grey approach. The factors selected for optimization are pH of the electrolyte, stabilizer in the bath, and surfactant concentration in the solution. The variable responses are thickness of the deposit, thermal resistance of the coated material, and surface roughness of the deposit. The optimized combination obtained from the optimization is verified by confirmation test. Based on the obtained results, the performance characteristics such as break thermal efficiency, specific fuel consumption, and emission characteristics such as carbon monoxide, oxides of nitrogen, hydrocarbon, and carbon dioxide are measured and reported.

2. Experimental Details and Procedure

2.1. Engine Experimental Setup. Kirloskar CI engine model Tv1 is used in this study; it can generate the power of 5.2 kW at 1500 rpm. The engine output shaft is coupled with eddy current dynamometer for applying the load from the engine. Figure 1 shows the experimental setup. It is a single cylinder four stroke engine having a bore diameter and stroke length of 87.5 and 110 mm, respectively, and the compression ratio of 17.5 : 1. The schematic diagram of the engine is provided in our previous study [17]. AVL Digas 444 and AVL437 are used to determine the emission and temperature from the engine. The performance characteristics and combustion properties are investigated in a 5 HP direct injection CI engine. The consumption of fuel and air was measured using mass flow sensor and burette technique, respectively. Eddy current dynamometer is used to apply the variable load on the engine. The IC engine soft software is used to read and write the data from the experiment. AIRREX HG540, 4Gas analyzer is engaged to detect the various emissions such as HC, CO, CO_2, NO_X, etc.

2.2. Preparation of Biodiesel Blends and Plasma Spray Coating. The total quantity of each sample is fixed to the blend of 1000 ml in which 700 ml of diesel, 300 ml of Momordica charantia seed biodiesel, and 45 PPM of cerium oxide are added into biodiesel. The properties of diesel and prepared biodiesel are given in Table 1.

Yttria-stabilized Zirconia is chosen as the primary material for coating the piston crown because of its desirable physical properties such as high coefficient of low thermal conductivity, high Poisson's ratio, thermal expansion, and stable phase structure at higher temperature conditions. A composition of the coating powder is Yttria-stabilized Zirconia 94%, alumina 2%, and Ceria 4%.

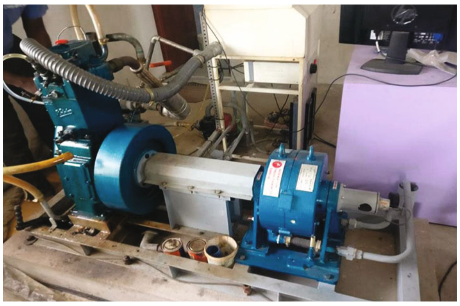

Figure 1: Experimental setup.

2.3. Electroless Ni-P-TiO$_2$ Coating on Cylinder Liner and Piston Head. The cylinder liner and piston head is used to coat electroless Ni-P deposit for various conditions. Initial weight of the substrate is weighed using digital weighing machine with 1 mg accuracy. The chemical required for preparing the electrolyte is purchased from Sigma Aldrich scientific grade 99% purity. The nano titanium dioxide is also purchased with the size of 50 nm size. The salts obtained are nickel chloride as a source of nickel, sodium hypophosphite as reducing agent, sodium chloride as complexing agent, and tri sodium citrate as stabilizer. To regulate the pH during the process, ammonium chloride is added and adjusted the value as needed. Prior to coating, substrate must be cleaned using acetone and ethonal, and surface must be prepared using concentrated sulfuric acid. The coated surface of the component is shown in Figure 2. The nickel, phosphorus, and titanium dioxide particles are seen in the image.

2.4. Optimization of Process Parameters. The selected responses are optimized using Taguchi and GRA theory because traditional Taguchi cannot handle multiobjective function. During the experiment, variable parameters are identified and controlled to reduce the errors in the system that reflect as noise factor. In the year 1982, Ju-long introduced a theory called GRA created with the aid of grey set by connecting the ideas with numerous philosophy such as control, space, and system theory [18]. Taguchi Grey relational analysis is a globally recognized methodology to optimize the multiobjective response system in voluminous of the industrial applications predominantly in the area of engine performance analysis and research [19–21]. Based on the knowledge obtained from the literature review, the factors selected are pH, stabilizer, and surfactant. Table 2 shows the factors and its levels for optimization, and based on Taguchi design, the L9 orthogonal array is shown in Table 3. The orthogonal arrays are generated, and Taguchi techniques are analysed using Minitab software.

2.4.1. Calculation of Signal to Noise Ratio. According to the responses, signal to noise ratio can be calculated in three ways; they are maximize, nominal the better, and minimize. In this research work, larger the better condition is used for brake thermal efficiency; smaller the better is used for emissions (NOx and CO), and brake specific fuel consumption are selected to find the values of S/N ratio using the following Equations (1) and (2), respectively.

$$x_k^o(i) = -10 \log_{10}\left(\frac{1}{n}\sum_{k=1}^{n}\frac{1}{y_k^2(i)}\right), \tag{1}$$

$$x_k^o(i) = -10 \log_{10}\left(\frac{1}{n}\sum_{k=1}^{n} y_k^2(i)\right), \tag{2}$$

where n is the no. of trials; $Y_k(i)$ is the obtained data of variable (i) from the trails (k).

2.4.2. Normalizing the Obtained Data. Next step is to normalize the obtained value from S/N ratio to acquire the dimensionless value, and it is needed to integrate the values into one value, and comparison is simple. The normalization can be performed using the Equations (3) and (4).

$$x_k^*(i) = \frac{x_k^o(i) - \min\ x_k^o(i)}{\max\ x_k^o(i) - \min\ x_k^o(i)}, \tag{3}$$

$$x_k^*(i) = \frac{\max\ x_k^o(i) - x_k^o(i)}{\max\ x_k^o(i) - \min\ x_k^o(i)}, \tag{4}$$

where max $x_k^o(i)$ and min $x_k^o(i)$ are the maximum and minimum responses of i in L9 experiment.

2.4.3. Calculate Grey Relational Coefficient. GRC helps to express the association among normalized value with the ideal value, and the same is given in Equation (5).

$$\gamma_k(i) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_k(i) + \zeta\Delta_{\max}}, \tag{5}$$

where ζ is the distinguishing coefficient of range 0-1 (0.5 prefered); $\Delta_k(i)$ is the difference of normalized value and reference sequence for ith response; Δ max is the maximum value of $\Delta\_k\,(i)$, respectively; Δ min is the minimum value of $\Delta\_k\,(i)$, respectively.

$$\Delta_k(i) = |x_o^*(i) - x_k^*(i)|, \tag{6}$$

where $x_o^*(i)$ is the maximum value of $x_i^*(k)$.

2.4.4. Calculate Grey Relational Grade. Grey relational grade can be calculated by taking the mean value of grey relational coefficient and add the value with the value of weight decided for all the response variables. The simple equation for calculating GRG is given in Equation (7).

$$\delta_k = \sum_{i=1}^{h} w_i\, \gamma_k(i). \tag{7}$$

2.5. Plasma Coating over Optimized Electroless Ni-P Deposit. A polishing of substrate is done on the piston and cylinder liner before the plasma thermal spray coating. The substrate prepared for coating are blasted with known composition of powder materials (YSZ 94%, alumina 2%, and Ceria 4%) for the interlocking for sprayed particles [17]. The parameters

Table 1: Fuel properties.

Fuel property	Instrument	Diesel	Biodiesel
Density at 15°C (kg/m3)	Hydrometer	836	910
Viscosity at 40°C (mm2/s)	Rotational viscometer	2.9	5.04
Calorific value (MJ/kg)	Bomb calorimeter	42.3	72.15
Flashpoint (°C)	Flashpoint apparatus	54	224
Fire point (°C)	Pour point apparatus	62	229

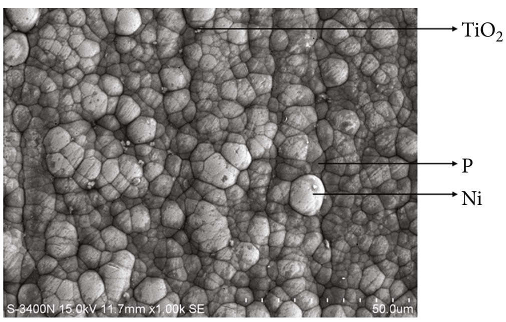

Figure 2: Coated surface of the engine component using electroless Ni-P coating.

Table 2: Factors and its level for optimization.

Description	Factors	Levels		
		1	2	3
A	pH (%)	5	7	9
B	Stabilizer (g/L)	20	25	30
C	Surfactant (g/L)	1	1.2	1.4

Table 3: Taguchi L9 orthagonal array.

S. no	pH (%)	Stabilizer (g/L)	Surfactant (g/L)
1	5	20	1
2	5	25	1.2
3	5	30	1.4
4	7	20	1.2
5	7	25	1.4
6	7	30	1
7	9	20	1.4
8	9	25	1
9	9	30	1.2

adopted for performing the coating on engine components are the following: applied voltage is 65-70 V; maximum power is 40; primary gas flow -Ar (SCfh) is 80; secondary gas flow -H_2(SCfh) is 15; spraying distance is 2. The yttrium-stabilized zirconium is coated for 2 mm in each sample after electroless Ni-P coating process.

2.6. Measurement of Coating Thickness, Thermal Resistance, and Surface Roughness. The coating thickness (T) of the deposit is measured as per the standard using weight gain method, and it is given in Equation (8). Initial and final value of the substrate is measured using weighing machine for five times, and average is taken as the final reading.

$$T = \frac{(S_2 - S_1) \times 10^4}{dA}, \tag{8}$$

where S is the initial and final reading of the substrate in g; d is the density of the substrate in g/cm^3; A is the area of the substrate in cm^2. The portable surface roughness tester connected with computer to record the evaluation profile (model SJ-210) is used for analysis. A probe is made to move through a straight line for the known distance. The peak and valleys of the substrate are detected and recorded in the storage device. Then, the average surface roughness of the substrate is determined by digital computer. The thermal conductivity of the coated component is measured using laser flash method (LFA427 and NETZSCH). The experiment is conducted at vacuum environment from room temperature to 1150 degree Celsius. The average of three readings from the evaluation is taken as thermal conductity.

3. Results and Discussions

3.1. Optimization of Electroless Ni-P Coating. The experiments are conducted in electroless Ni-P coating setup by varying the process parameters and obtained the responses such as thickness, thermal resistance, and surface roughness of the substrate as given in Table 4. From the obtained responses, the values of S/N ratio are obtained from Equations (1) and (2). The conditions selected are smaller the better and larger the better. The values are normalized using Equations (3) and (4) to stabilize the values for comparison. Now, the value of 0.5 is multiplied to each data obtained, which means providing equal weightage to all the obtained values. Table 5 shows the S/N ratio and the normalization value of each experiment. From the normalization data, grey relational coefficient is developed. The numerical values of normalization value after conversion and the GRC are given in Table 6.

In the next step, the GRC values of each experiment are incorporated with the weights assigned to each responses, and then GRG value is estimated. The GRG and the rank of each experiments are finalized, and it is given in Table 7. It is observed from the results that based on GRG rank the optimized combination is pH of 9, stabilizer of 25 g/L, and surfactant of 1 g/L. The optimized trail is denoted by A3-B2-C1.

Table 4: Responses value for DOE based on orthogonal array.

S. no	pH (%)	Stabilizer (g/L)	Surfactant (g/L)	Thickness (μm)	Thermal resistance (K/W)	Surface roughness (μm)
1	5	20	1	22	13.4	0.26
2	5	25	1.2	24	13.6	0.28
3	5	30	1.4	26	13.5	0.3
4	7	20	1.2	35	14.3	0.38
5	7	25	1.4	34	14.7	0.35
6	7	30	1	36	14.5	0.3
7	9	20	1.4	42	15	0.46
8	9	25	1	41	15.5	0.45
9	9	30	1.2	40	15.3	0.43

Table 5: Signal to noise ratio and normalization values of the experiment.

S/N ratio			Normalization		
Thickness	Thermal resistance	Surface roughness	Thickness	Thermal resistance	Surface roughness
26.848	22.542	11.700	0.000	0.000	-1.000
27.604	22.670	11.056	0.135	0.102	-0.870
28.299	22.606	10.457	0.258	0.051	-0.749
30.881	23.106	8.404	0.718	0.447	-0.335
30.629	23.346	9.118	0.673	0.636	-0.479
31.126	23.227	10.457	0.762	0.542	-0.749
32.464	23.521	6.744	1.000	0.775	0.000
32.255	23.806	6.935	0.963	1.000	-0.039
32.041	23.693	7.330	0.925	0.911	-0.118

Table 6: Calculating the grey relational coefficient.

Converting normalized value into Δklm			Calculating Grey relational coefficient Gklm		
Thickness	Thermal resistance	Surface roughness	Thickness	Thermal resistance	Surface roughness
1.000	1.000	2.000	0.333	0.333	0.200
0.865	0.898	1.870	0.366	0.358	0.211
0.742	0.949	1.749	0.403	0.345	0.222
0.282	0.553	1.335	0.639	0.475	0.272
0.327	0.364	1.479	0.605	0.579	0.253
0.238	0.458	1.749	0.677	0.522	0.222
0.000	0.225	1.000	1.000	0.689	0.333
0.037	0.000	1.039	0.931	1.000	0.325
0.075	0.089	1.118	0.869	0.849	0.309

3.2. Confirmation Test. The confirmation test is mandatory to check the accuracy of data obtained through Taguchi optimization techniques. From Table 7, grey relational grade values are needed to predict the GRG, and it is calculated using Equation (9).

$$\delta_{pre} = \delta_{tot} + \sum_{i=1}^{n} \left(\delta_{opt} - \delta_{tot}\right), \tag{9}$$

where δ_{tot} is the total mean of GRG. δ_{opt} is the mean of GRG at the optimum level.

From the above equation, the predicted GRG value is obtained as 0.315. Table 8 depicts the values generated from confirmation test using the best combination. Based on the results, it is clearly understood that GRG is improved from 0.259 to 0.27, i.e., improvement 4.24%.

3.3. Engine Performance in Optimized Condition. The performance of engine is compared with noncoated engine (NCE), electroless coated engine (ECE), and optimised condition; electroless plasma spray coated engine (EPSCE) are shown in Figure 3. The optimised condition shows the significant improvement in performance of the CI engine.

Table 7: Calculation of GRG and GRG rank.

Thickness	Weight Thermal resistance	Surface roughness	GRG	GRG rank
0.100	0.133	0.060	0.098	9
0.110	0.143	0.063	0.105	8
0.121	0.138	0.067	0.109	7
0.192	0.190	0.082	0.154	6
0.181	0.231	0.076	0.163	4
0.203	0.209	0.067	0.160	5
0.300	0.276	0.100	0.225	3
0.279	0.400	0.097	0.259	1
0.261	0.339	0.093	0.231	2

Table 8: Confirmation test.

Setting level	Initial setting	Prediction	Experimental	Improvement %
A	41	—	42	
B	15.5	—	15.75	
C	0.45	—	0.4	
GRG	0.259	0.315	0.27	4.24

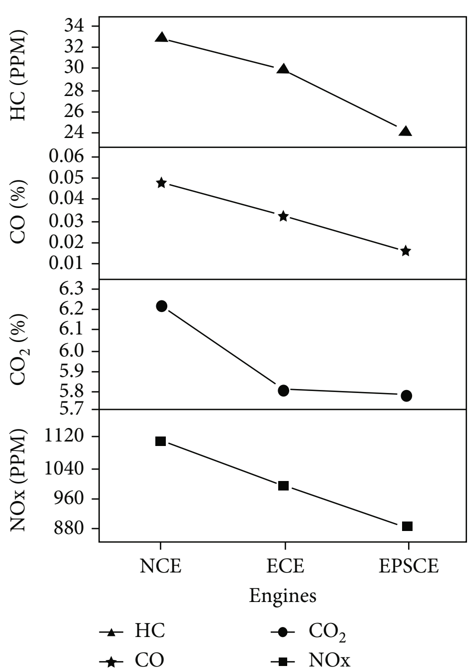

Figure 3: The performance of various categories of CI engines.

The emissions of CI engine such as NOx, CO_2, CO, and HC of the noncoated engine show higher among other conditions, whereas the EPSCE condition produces very less pollution when compared to other conditions. The main reason is that the coating provides the insulation effect on the walls of combustion chamber, thus, the combustion temperature increases gradually. Therefore, the emissions in the coated engine reduced by improving the combustion, and the intake oxygen is utilized effectively. Hence, the CO emission is reduced [22].

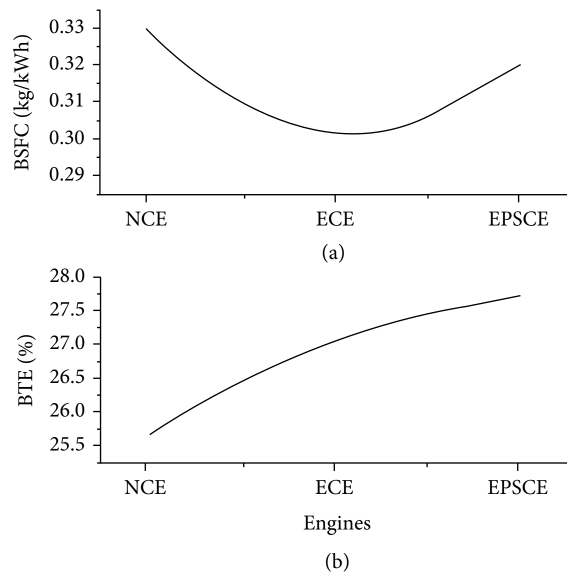

Figure 4: The efficiency of CI engines, (a) specific fuel consumption; (b) brake thermal efficiency.

The performance of the CI engine is improved; owing to the combustion, chamber wall heat transfer is reduced. Due to this effect, the incylinder temperature is increased and produce more temperature and pressure to the combustion. Thereby, the mean effective pressure is increased which leads to improve in high power and torque of the CI engine [23]. Figure 4 shows the brake thermal efficiency and specific fuel consumption of CI engine.

The possible reason for obtaining the improved efficiency of the CI engine is alumina inclusion in yttria-stabilized zirconia in plasma coating. Also, nickel coating has good wear resistance of the material and improve the oxidation and thermal resistance of the engine components, where the coatings are made. When the alumina is coated alone, it does not show superior results but when the alumina is added with yttria-stabilized zirconia, the performance and efficiency of the engine is significantly improved.

4. Conclusions

The CI engine is coated with zirconia using plasma spray technique, and Ni-P coating using electroless plating is prepared, and fuel is added with nanoadditives. Based on the research carried out using the experimental setup, the following conclusions are derived.

(i) based on GRG rank, the optimized combination is pH of 9, stabilizer of 25 g/L, and surfactant of 1 g/L. The optimized trail is denoted by A3-B2-C1.

The GRG value is improved from 0.259 to 0.27, i.e., 4.24% improved

(ii) the performance of engine is compared with noncoated engine (NCE), electroless coated engine (ECE), and optimised condition, i.e., electroless plasma spray coated engine (EPSCE).

(iii) the emissions of CI engine such as NOx, CO_2, CO, and HC of the noncoated engine shows higher and EPSCE engine condition shows less pollution. The percentage of improvement interms of emissions are 27%, 70%, 6.4%, and 21%, respectively

(iv) the performance of the CI engine, i.e., specific fuel consumption and brake thermal efficiency is improved to 3% and 27.8%, respectively

Three diverse engines are selected to study the performance and emissions in the CI engine. The life of the engine components is improved by the thermal barrier coating incorporated in the CI engine. The hybrid vehicle is the future of transportation by the integration of electric and commercial engines. Therefore, the biodiesel can be used efficiently to reduce the emissions through engine modifications.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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