Global NEST Journal, Vol 25, No 3, pp 78-86

Performance and emissions parameters optimization of thermal barrier coated engine tested with Tamanu blended diesel fuel: a novel emission pollution-preventive approach

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Received: 27/11/2022, Accepted: 04/01/2023, Available online: 05/01/2023
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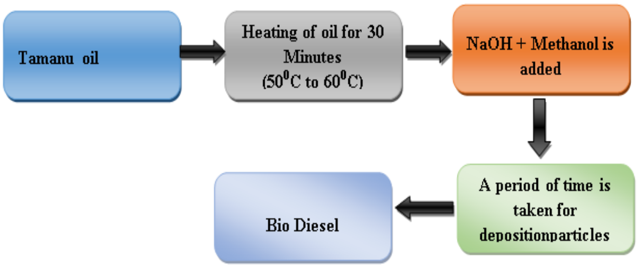
https://doi.org/10.30955/gnj.004594

Graphical abstract



Abstract

Diesel engines cause major pollutants such as hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx). These emissions affect environmental systems and lead to global warming and climatic change effects. These pollutants also affect humans and lead to health problems like lung cancer, breathing problems, and headaches, etc. Hence, some necessary action has to be taken to minimise these pollutants. There are several steps available to control these emissions. The coating of the piston using catalytic material is an effective method and novel approach of reducing emissions in diesel engines with alternate fuel operated diesel engines. The copper-chromium-zirconium alloy (CuCr1Zr) is known for its good thermal conductivity and good catalyst material, and the piston is coated bycopper-chromium-zirconium alloy with 250µm thickness. Tamanu oil was blended with diesel fuel in a 20% (B20) to 40% (B40) ratio and used as an alternate fuel for the coated engine. The results showed a significant reduction in emissions and improvements in performance. In this research, the Taguchi with grey relational analysis (GRA) optimization technique is also used to study the effect of engine operating parameters on the emission level such as load and fuel for copper-chromium-zirconium alloy-coated diesel engine. Based on experimental results found that fuel is the most influential factor for CO and HCexhaust gas emissions reductions for coated type diesel engines.

Keywords: Piston coating, performance, emission, optimization, grey relational analysis

1. Introduction

Piston thermal barrier coating is very much useful for preventing heat loss during the working of IC engine combustion process. During the combustion process the complete combustion is not possible due to various reasons. One of the reasons for incomplete combustion is heat loss in combustion chamber. Rajasekaran *et al.* (2017) stated the purpose of piston thermal barrier coating is not only preventing heat loss is also helpful for thermal fatigue protection and emission reduction. In this research work theengine heat loss is prevented through piston thermal barrier coating material by copper-chromium-zirconium (CuCr1Zr). Piston thermal barrier coating material by CuCr1Zr is a novel approach and tested with Tamanu blended diesel fuel. Raj Kumar *et al.* (2017) conducted an investigation on coated IC engine; the piston was coated with Ni-Cr with a thickness of 0.2mm by the plasma spray technique. Mamey spotty oil was used as a biodiesel. As a result, thermal efficiency increased by 1%, Carbon monoxide (CO) emissions were also reduced. Ponnusamy *et al.* (2011) investigated the performance evaluation of copper coated single cylinder IC engine. The results showed that copper coated piston and combustion chamber engine reduces HC and CO emissions. Krzysztof *et al.* (2000) Studied the effects of plasma sprayed zirconium coatings on the piston. One promising technologies for improving IC engine performance and reducing the CO and HC emission is thermal barrier coating on piston and combustion chamber. Winkler *et al.* (1992) stated that coated diesel engine gives better performance. Jeyakumar *et al.* (2019) stated that cotton seed bio diesel can be used as an alternative fuel for control the emissions like CO, HC of a diesel engine. El-seesy *et al.* (2019) stated that the cotton seed bio diesel was used as an alternative fuel to control the emissions like CO and HC of a diesel engine.

Sureshbabu *et al.* (2019) concluded the copper coated piston and combustion chamber engine reduced the HC and CO emissions. Many researchers investigated the effects of plasma sprayed zirconium coating on diesel engine pistons in a similar manner. The zirconium coating reduced CO and HC emissions and improved the efficiency of the IC engine. The compared the emission level of a diesel engine by varying the fat oil and mixing it in different proportions (10%, 20%, and 30% contracted as B10, B20, and B30 individually). Biodiesel mixes were about 5% lower for biodiesel mixes when contrasted with ordinary diesel fuel. Along these lines, from this examination, we came to realise that fat biodiesel could be utilised with no motor adjustment and would be harmless to the ecosystem as a fuel concluded by Gautam *et al.* (2020). Ezekoye*et al.* (2019) stated thatthe blends and portrayal of biodiesel from Citrus sinensis seed oil. The removed Citrus sinensis seed changed the biodiesel utilising an antacid synergist transesterification strategy at a consistent temperature, and it gave a great yield of 76.93% .The emanation boundaries of CO and HC for B20 (MECSO, MERBO) mixes were lower by 18.4%, 17.5% 3.86% and3.13% individually contrasted with diesel (Sundar *et al.,* 2020; Rozhdestvensky *et al.* 2016) they explored whether heat protecting covering on the cylinder crown diminishes the warmth stream from the working gas in the ignition office of the diesel motor on the outside of the cylinder. Thus, a decrease in the most extreme temperature of the cylinder crown of 12–14 °C, and of the cylinder skirt of 5–6 °C, is assessed by Sivakumar *et al.* (2014). Jalaludina*et al.* (2013) studied the ceramic coated piston crown for compressed natural gas direct injection. From the test it was concluded, that normal heat flux of coatedpiston crown displayed 98% lower than the uncoated piston crown. Dharanikumar *et al.* (2013) carried out investigation on emission characteristics analysis on copper coating over piston crown and cylinder head and found that the emission has reduced significantly in coated engines. Hence in this research it was decided to experiment with copper alloy, copper-chromium- zirconium (CuCr1Zr). CuCr1Zr is a high copper alloy containing a small amount of chromium and zirconium that improves its mechanical properties. The alloy composition is typically 0.8% chromium, 0.06 to 0.08% zirconium, remaining 98% is copper. CuCr1Zr is similar to copper in its resistance to corrosion. Zirconium has higher wear resistant properties. The alloy offers high thermal conductivity with enhanced strength compared to pure copper. Thermal conductivity of CuCr1Zr is 300 W/m^{o}C and CuCr1Zr also has good stress relaxation resistance. Gautam *et al.* (2020) stated that the most of the studies focus on to reduce the emission of diesel engine by alternating bio fuels. From the literature, it was noticed that most of the studies focused on reducing the emissions of diesel engines by alternating bio fuels. This paper presents the effect of emissions on copper–chromium-zirconium thermal barrier coated pistons by varying the diesel engine's operating parameters such as load and compression ratio. The plasma coating technique was adapted to coat the copper-chromium-zirconium on the crown side of the piston. The main purposes of the investigation is study the effect of Copper-chromium-zirconium coating on combustion chamber and piston of the coated diesel engine with blended bio fuel operation and improve the engine performance. The objective of this research work is to find the optimum engine operating parameters for copper –chromium-zirconium coated pistons to reduce emissions. Taguchi with grey relational analysis (GRA) optimization techniques was used to find the optimum engine operating parameters for reducing emission.

2. Materials and methods

The main reason of this study is to reduce the emissions and improve the performance characteristics of a Tamanu blended diesel fuel operated engine with a CuCr1Zr coated combustion chamber and piston type engine. Initially the engine was tested with diesel fuel by varying the engine performance and emissions parameters like load and fuel. Thediesel fuel blend with tamanu oil, the ratio was varied from 20 % to maximum 40%. Kiran A.V.N.S. *et al.* (2016) stated that the piston coated with copper to a thickness of 250 microns, as a result, diesel fuel consumption reduced by 10-12% and thermal efficiency improved by 1.02 %, the hydrocarbons (HC) emission reduced by 28%. GoutamPohit *et al.* (2013) stated that grey relational analysis had been applied for solving a multiple response optimization problem. It was concluded that B50 blend was found to be most suitable blend for diesel engine without significantly affecting the engine performance and emissions characteristics. Jeyakumar and Narayanasamy (2019) conducted experimental study deals with the analysis of performance and emission characteristics of Cotton Seed oil biodiesel with the addition of natural antioxidant extract of clove. Results showed that the addition of antioxidant to biodiesel blend has increased the Brake Thermal Efficiency to a maximum of 4.71% and decreased the Brake Specific Fuel Consumption to a maximum of 8.05%. Investigations were carried out (Rasim, 2011; Jaichandar and Annamalai 2011; Arslan 2011) on low heat rejection (LHR) engines with diesel fuel operation and it was concluded that ceramic coated engines provides good sufficient heat insulation and resulted improved brake specific fuel consumption (BSFC). Experimental Studies were carried on (Xue et al., 2011; Dharanaikumar et al., 2013; Lin, 2004) ceramic coated diesel engines with blended vegetable oils and concluded that performance deteriorate with un-coated type diesel engine and smoke levels significantly increased. Based on experiment results of various research works (Rasim, 2011; Jaichandar and Annamalai 2011), Ceramic coatings improved brake-specific fuel consumption (BSFC) and provided sufficient heat insulation. According to Srikanth *et al*. (2013) reported that high cylinder temperatures helped in improved evaporation and faster combustion of the fuel injected into the combustion chamber. Nurun Nabi *et al.*, (2009) biodiesel was produced from cotton seed oil by transesterification process. A maximum of 77% bio diesel production was found at 20% methanol and 0.5% NaOH at 55 degree reaction temperature. Biodiesel mixtures showed less CO, PM, smoke emissions than diesel fuel. Anh Tuan Hoang (2021) stated biodiesel is reliable fuel. In addition to its well-known advantages, high viscosity, density, and surface tension have drawbacks that must be taken into account when operating a diesel engine. Jeyakumar N, Huang Z, Balasubramanian D, *et al*., (2022), Biodiesel's oxidation stability was enhanced by the addition of natural antioxidant compounds, enabling extended storage and biodiesel cost is decreased by using a binary blend. Based on the literature review, the following research gaps were identified. Most of the researchers focused on pure metal for the coating of combustion chamber and piston of the IC engine. In this present investigation,a hybrid alloy of CuCr1Zr was prepared for coating the combustion chamber and piston to study the emission characteristics and engine performance. Moreover, in this investigation Tamanu oil based bio diesel is also used in the CuCr1Zr coated engine and its performance and emission characteristics are studied in detail. The difference between this research and other studies is without major modification of IC engine, the performance can be improved with alternative fuel. This study experimentally proved Cu-Cr-1Zr coated piston diesel engine to run on Tamanu oil blended diesel is a viable alternative fuel for improving the performance of diesel engine.

2.1. Piston coating

CuCr1Zr is a high copper alloy containing a small amount of chromium & zirconium that improves its mechanical properties. The alloy composition is typically 0.8% chromium, 0.06 to 0.08% zirconium, and the remaining 98% is copper. CuCr1Zr is similar to copper in its resistance to corrosion. Zirconium has higher wear resistant properties. The alloy offers high thermal conductivity with enhanced strength compared to pure copper. CuCr1Zr has a thermal conductivity of 300 W/m°C and CuCr1Zr also has good stress relaxation resistance. So in this investigation, CuCr1Zr (copper -chromium-zirconium) alloy material was selected for the combustion chamber and piston coating material. The combustion chamber and piston are coated with this alloy, which also has good corrosion resistance (Balu *et al.,* 2020; Balasubramanian *et al.,* 2022; BhanuTeja *et al.* 2022). The properties of the copper-chromium-zirconium alloy material are listed in Table 1.

A plasma spray coating technique was adopted to coat the copper on the surface of the aluminium piston. Prior to the application of the coating, a surface of the piston was well cleaned using acetone (Ravi Theja *et al.,* 2022), (Saravanan *et al.,* 2021), (Vinayagar et al 2022). It helps to enhance the bonding of copper to the piston surface. However, for better adhesion bond coating, Ni-Cr Alloy was coated with a thickness of 75 µm followed by copper-chromium-zirconium, which was coated up to a thickness of 250 µm thickness. The process parameters for piston coating are listed in Table 2.

Table 1. Properties of Copper -Chromium -Zirconium

Sl.No	Parameters	Values
1	Tensile Strength	380 N/mm^2
2	Yield Strength	300 N/mm^2
3	Elongation	15%
4	Brilnell Hardness (HV)	130
5	Coefficient of Thermal Expansion 0-250°C	16.45
6	Thermal Conductivity	320 W/m°K
7	Melting Point	1070°C -1080°C

(Ref: www.copperalloys.net)

Table 2. Piston Coating Process Parameters

Sl.No	Parameters	Description
1	Coating material	Cu(Copper)
2	Coating thickness	250 microns
3	Bond coating	Ni-Cr Alloy
4	Bond coating thickness	75 microns
5	Current	500 A
6	Voltage	60 V
7	Power feed	30-45 gram/minute
8	Spray distance	63.5 mm
9	Gun	3 MB
10	Nozzle	FH

2.2. Biodiesel preparation

Nowadays, due to high demand and shortages of crude oil, the cost of automotive fuel is increasing gradually. The biggest issues facing today's world are the depletion of fossil fuel reserves and the rising price of gasoline and diesel. Two solutions are offered for this issue: the first is the production of alternative fuel or diesel engines, and the second is the improvement of combustion efficiency. A variety of processes, including emulsification, pyrolysis, and transesterification have been developed for the manufacturing of biodiesel fuel. Arun *et al.* (2014) was investigated the diesel engine with bio fuel operation. They followed the two-stage esterification procedure to produce biodiesel from Tamanu oil. When the load is increased the Specific Fuel Consumption (SFC) was lower than B10 and B20 fuel. So in this investigation used blends maximum up to 20% with a marginal increase in brake thermal efficiency and emissions substantially reduced CO_2, HC. In this investigation, tamanu oil is used as a bio-fuel. Tamanu oil is pressed from nuts of calophylluminophyllum (NagarajaGanesh *et al.,* 2022) (Ramkumar *et al.,* 2022). Tamanuoil from dried and peeled tamanu seeds is extracted by mechanical presses, followed by a filtering process and degumming, and finally, the tamanu oil is converted into bio-fuel using a transesterification process. Trans-esterification is a chemical process. The transesterification process flowchart is shown in Figure 1 and Figure 2.

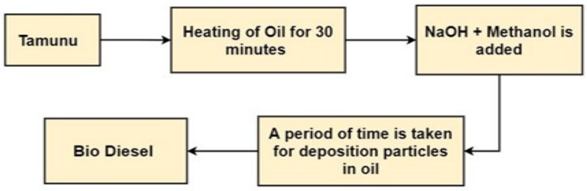


Figure 1. Transesterification process

Figure 2. Biodiesel Preparation

In the transesterification process, tamanuoil combines with alcohol to form alcohol esters and glycerol. In this investigation, tamanu oil is blended with diesel fuel with a ratio of 20% (B20) and 40% (B40). Bio diesel and glycerol are produced through a chemical reaction. After the sedimentation process, the glycerol and biodiesel are separated. Then the separated biodiesel is mixed with diesel fuel in a ratio of 20:80 to 40:60 to produce the blended biodiesel (B20) and (B40). Various blend ratios of diesel and tamanu oil were studied. Based on the review, the blend ratio of the fuel is selected as 20% and 40% tamunuoil blended with diesel. Anh Tuan Hoang, (2019) stated however, some problems may be occurring in coated diesel engines with bio fuels operations like smoke levels significantly increased due to increase in lacquer deposits, and excessive carbon formation in the injectors, it is frequently to be cleaned by decarbonising process. Table 3 shows the properties of the tamunu oil compared with diesel fuel and various blend ratios.

2.3. Experimental set up

The schematic experimental set up diagram was shown in Figure 3. A four stroke Kirloskar 150cc diesel engine is used for experimental work. The detailed specifications of the 150cc Kirloskar VCR engine are listed below in Table 4. The setup enables the study of the diesel engine's performance. To change the load, the engine is coupled to an eddy current dynamometer. With the help of a data collecting system, this engine setup is connected to a computer.

Table 3. Bio Diesel Properties Comparison with Diesel

Properties	Diesel	Tamanu oil (B0)	B20	B40
Density(g/cm^3)	0.840	0.905	0.853	0.866
Kinematic Viscosity (m^2/s)	3.06	4.21	3.34	3.76
Flash Point (^{o}C)	65	146	80	95
Fire Point (^{o}C)	84	160	104	130
Cetane Number	40 to 55	63	53.9	56.7
Calorific Value (MJ/kg)	43.06	37.7	41.54	39.62

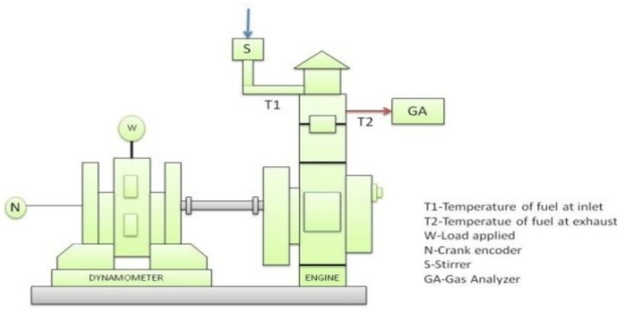


Figure 3. Experimental Setup Layout

It is controlled by the "Engine soft LV" software package. The findings of the engine performance evaluation were saved to the computer. The emission levels were measured using an AVL make DC-5 GAS analyser. The DC-5 GAS analyser's probe was connected to the engine exhaust tailpipe or muffler. It detects five emission gases in the exhaust gas: hydrocarbons (HC), carbon dioxide (CO_2), oxygen (O_2), carbon monoxide (CO), and nitrogen oxides (NOx).

Table 4. Engine Specifications

SI.No	Specifications	Details
1	Make	Kirloskar
2	Bore	87.5 mm
3	Stroke	110 mm
4	Rated output	3.5 kW
5	Speed	1500 rpm
6	Compression ratio	12 to 18
7	Type	Vertical Engine
8	Number of strokes	4

3. Results and discussion

The experiment was conducted for the biodiesel blended diesel with the proportions of B0, B20, and B40 and was conducted on a coated piston engine. The results are compared with the un-coated diesel fuel operated engine and finally the optimum results was found using Taguchi with GRA technique.

3.1. Taguchi withgrey relational analysis (GRA)

The main contributing factors for improving performance and reducing emissions were identified as fuel (A) and load (B). Two factors and four levels are implemented in this research. Experiments are carried out with two input parameters: fuel (B20), and load (B40) (kg).In total, nine trials were conducted. The values of various parameters utilized in studies are shown in Table 5.

Table 5. Parameters and Levels

Factors	Level 1	Level 2	Level 3
Fuel	Diesel	B20	B40
Load (kg)	8	10	12

Minitab-17 statistical software was used to choose the orthogonal array for the experiment. Table 6 shows the experiment table suggested by Minitab-17 for the L9 orthogonal array.

Table 6. L9-Orthogonal Array

Experiment	Fuel	Load (kg)
1	Diesel(B0)	8
2	Diesel(B0)	10
3	Diesel(B0)	12
4	B20	8
5	B20	10
6	B20	12
7	B40	8
8	B40	10
9	B40	12

The experimental results are tabulated in Table 7. Coating with CuCr1Zr material resulted in 30.34% better brake thermal performance and lower emissions.CO emissions were lowered by 71.42 % and HC emissions were reduced by 80.76 %, respectively. Because of the coating, complete combustion took place inside the combustion chamber.Both coated and un-coated engines produced the same BP and not much variation was observed in SFC. NO_X emissions increased in the coated engine due to the high temperature inside the engine. The optimal combinations for better responses were identified as B0 fuel and 12 kg load, at constant rpm (1500 rpm), using Taguchi with grey analysis.

The brake power (BP) of the engine remains same for coated and un-coated piston type engine. However, slight increase in torque (T) was noticed in the coated piston type engine. According to ANOVA studies, fuel was found to be the most influential parameter of the coated type IC engine. It's also been suggested that Tamanu oil-blend diesel (B20) can be utilised as an alternative fuel for reducing CO and HC emissions.If B40 blended fuel is used as a fuel in a diesel engine, it leads to a slight increase in HC due to the lower calorific value of bio-diesel (B20) as compared to diesel.

3.2. Grey relational analysis (GRA)

The coated engine experimental data are first normalised in the range of one to zero in this study. Grey Relational Coefficients (GRC) is calculated using normalised experimental data. Finally, by averaging the grey relational coefficients corresponding to each process response, the overall grey relational grade (GRG) is calculated.

The grey relational grade is used to evaluate the multiple process response. This method is used to reduce a multi-response optimization problem in an IC engine to a single-response problem.

The optimum engine parameter is determined by the level of engine parameters with the highest grey relational grade.The first stage in the GRA process is to standardize the responses. Torque, BP, and brake thermal efficiency are three important parameters that are determine the engine performance. Hence, these are essential response for the engine. The response are taken as "larger the better" because the above mentioned parameters will improve the performance of engine. If the response is "larger the better", then the original response can be normalized (Yunus *et al.*, 2016) as per the Equation (1).

$$xi(k) = \frac{yi(k) - \min yi(k)}{\max yi(k) - \min yi(k)} \quad (1)$$

Where,

i= Number of Experiments (i=1, 2, 3.......9)

k = Number of responses (k= 1, 2, 3.....7)

If the response is “smaller the better”, then the original response can be normalized as per the Equation (2).The three important “larger the better” engine emission responses are CO, HC and NOx.

$$xi(k) = \frac{\max yi(k) - yi(k)}{\max yi(k) - \min yi(k)} \quad (2)$$

Table 8 shows the computed normalised GRA performance and emission data. Using Equations (3), (4), and (5), find the grey relational coefficient (k) and grey relational grade (γ_i) (5).

$$\xi i(k) = \frac{\Delta\min + \phi\Delta\max}{\Delta 0ik + \phi\Delta\max} \quad (3)$$

3.3. Selection of optimum set of conditions

Finally, the overall grey relational grade (GRG) was obtained by averaging the grey relational coefficients corresponding to each response. The higher grey relational grade (GRG) is ranked as rank no.1 and it is shown in Table 9. Based on grey prediction concept, the GRG results are separated based on its level is tabulated in Table 10.

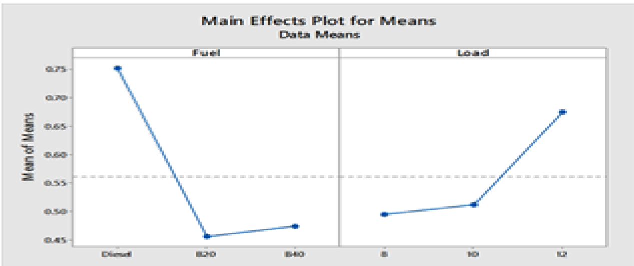


Figure 4. GRG mean vs Process parameter

After separation by comparing each level the highest grey relational grade is considered as the optimum parameter.

Figure 4 shows the main effect plot for mean. From the main effect plot it has been understand that the best condition for fuel factor is level 1 i.e. Diesel and for load is level 3 i.e. 12.Thus, the optimum conditions chosen were: A1-B3 combination. The optimized parameters are shown in Table 11.

3.4. XRD and SEM Results

The piston was examined using X-ray diffraction (XRD) and a scanning electron microscope (SEM) in two regions: coated and uncoated. XRD results of coated and uncoated regions are shown in Figure 5(a) and (b).

Table 7. Performance and Emission Results

Piston Type	Load (kg)	Torque (N-m)	BP (kW)	Bth (%)	CO (%)	HC (ppm)	NOx (ppm)
Uncoated(B0)	8	14.65	2.32	24.63	0.11	48	1078
	10	18.22	2.88	26.49	0.12	46	1275
	12	21.59	3.42	27.75	0.14	52	1409
Coated (B0)	8	14.74	2.34	29.18	0.05	11	578
	10	18.6	2.93	32.65	0.06	13	851
	12	21.84	3.42	36.17	0.04	10	1520
B20	8	14.48	2.3	26.03	0.09	40	1090
	10	18.24	2.89	27.99	0.1	65	1562
	12	21.82	3.42	30.2	0.11	49	1721
B40	8	14.62	2.33	28.51	0.09	49	1069
	10	18.2	2.89	30.08	0.1	53	1456
	12	21.97	3.45	31.19	0.12	61	1647

Table 8. GRA performance and emission Results

Fuel	Load (kg)	Torque	BP	B_{th}	CO	HC	NOx
Diesel(B0)	8	0.34123	0.341246	0.452194	0.833333	0.964912	1
Diesel(B0)	10	0.526353	0.525114	0.621098	0.714286	0.901639	0.676732
Diesel(B0)	12	0.966452	0.950413	1	1	1	0.563888
B20	8	0.333333	0.333333	0.362665	0.5	0.478261	0.527457
B20	10	0.501003	0.506608	0.41362	0.454545	0.333333	0.367406
B20	12	0.961489	0.950413	0.491482	0.416667	0.413534	0.333333
B40	8	0.337539	0.339233	0.429635	0.5	0.413534	0.537882
B40	10	0.498337	0.506608	0.486509	0.454545	0.390071	0.394274
B40	12	1	1	0.536744	0.384615	0.350318	0.348369

Table 9.GRG Performance and Emission Results

Fuel	Load (kg)	Torque	BP	B_{th}	CO	HC	NOx	GRG	Rank
D (B0)	8	0.341	0.341	0.452	0.833	0.964	1	0.6844	3
D (B0)	10	0.526	0.525	0.621	0.714	0.901	0.676	0.6882	2
D (B0)	12	0.966	0.950	1	1	1	0.563	0.8844	1
B20	8	0.333	0.333	0.362	0.5	0.478	0.527	0.4020	8
B20	10	0.501	0.506	0.413	0.454	0.333	0.367	0.415	7
B20	12	0.961	0.950	0.491	0.416	0.413	0.333	0.553	5
B40	8	0.337	0.339	0.429	0.5	0.413	0.537	0.401	9
B40	10	0.498	0.506	0.486	0.454	0.390	0.394	0.436	6
B40	12	1	1	0.536	0.384	0.350	0.348	0.587	4

Table 10. Coated Engine GRG Response for each level

Symbol	Parameters	Level	Level	Level	Main effect	Rank
		1	2	3	(max-min)	
A	Fuel	0.75239	0.45705	0.47512	0.29534	1
B	Load	0.49610	0.51317	0.67529	0.17919	2

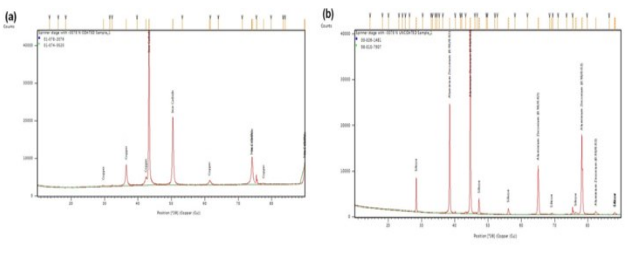


Figure 5. X-ray diffraction results (a) Coated region (b) Uncoated region

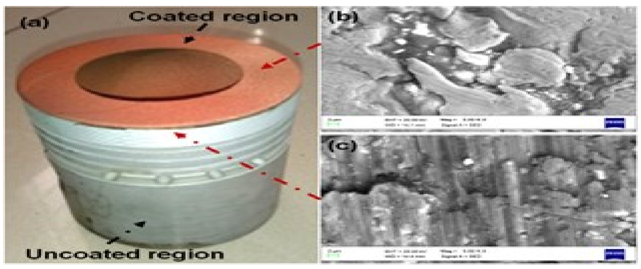


Figure 6. (a) Coated piston (b) SEM image of coated region (c) SEM image of uncoated region

XRD pattern of the coated region shows the appearance of Cu phase. The density of the copper bond coating characterizes greatly depend upon the absence Al phase Bârcã *et al.* (2015). Hence, it confirms the proper bonding occurs in the top surface of the piston. The Al and Zr were the major elements present in the uncoated region. However, the very minimum amount of Si was also observed in the XRD pattern. Most of the Al piston was manufactured by the die casting process. Hence, the addition Si helps to enhance the fluidity of aluminium. Figure 6(a) shows the photographed image of the copper-coated piston. Figure 6(b) and (c) depicts the SEM images of coated and uncoated regions. The deposition of copper coating in the aluminium composed the consecutive grains and it's usually known as splats. The splats were seen in the coated SEM image Figure 6(b). The splat geometry was formed due to the change of kinetic energy of the deposit particles. During the deposition, there was a chance of formation of pores at the interface region of splats. Yunus *et al.* (2016) stated that the pores were seen in the interface regions between the copper and aluminium alloy for the coated region. These pores are formed due to differences in the thermal properties of copper and aluminium. However, no pore was seen in the uncoated region Figure6(c).

Table 11. Optimized Parameters

Control Factor	Fuel (A1)	Load (B3) in kg
Optimum Value	Diesel	12

By comparing the results obtained in the investigation, it was found that the catalytic coated diesel engine operated with cotton seed bio fuel shows better results in terms of performance and emission level. Taguchi with GRA technique can be very efficiently used in the optimization of performance and emission parameters of coated diesel engine. The optimum process parameters are determined by the grey relational grade for multi performance characteristics that is fuel and load. From the response table of the average grey relational grade, it is found that the largest value of grey relational grade is obtained for diesel fuel and 12 kg load respectively, this condition has resulted in best responses such as, BP, Torque, B_{th}, CO and HC. The HC emission is reduced when compared to uncoated engine significantly because at high temperature engine have sufficient quantity of oxygen that combines with HC and separate in to hydrogen and carbon and combine with O_2 and reduced HC emission. So, the performances of the coated engine improved and reduce the exhaust gas emission characteristics. So, the performances of the coated engine improved and reduce the exhaust gas emission characteristics. Combustion analysis is a standard method of determining a chemical formula of a substance that contains hydrogen and carbon. At High Temperature carbon easily combine with O_2 and form CO_2, SO, CO emission reduces drastically. The result also indicates that NOx emission increased due to engine high temperature. The brake thermal efficiency (B_{th}) of copper chromium and zirconium coated engine has marginally improved by 30.34% and CO, HC emissions have significantly decreased by 71.42% and 80.76% respectively. This revealed that complete combustion takes place inside the combustion chamber due to piston coating on copper -chromium-zirconium alloy coating material on the piston. It can also be understood that the both the coated and un-coated type engine producing the same brake power (BP).The ANOVA of grey relational grade for multi-performance characteristics reveals that the fuel is the most significant parameter in influencing the engine performance and emission characteristics. Based on the confirmation test, reveals that output results of final experiments are close to the Taguchi-GRA values. Comparing with diesel blended fuel operated engine, pure diesel (B0) coated engine had given better results. Murugu Nachippan *et al.* (2022) evaluated the performance of a PCCI engine running on multi-walled carbon nanotube -blended Tamanu biodiesel due to its, catalytic performance, excellent atomization and high surface-to-volume ratio the performance is improved. Hence it can be also reported that tamanu oil-bio diesel can be used as an alternative fuel for controlling the emissions like CO and HC of a diesel engine. The B20 and B40 blends shows slight improvement in performance and emission characteristics while comparing with un-coated diesel engine.

4. Conclusions

The brake thermal efficiency (B_{th}) increased by 30.34% due to complete combustion. This is due to the heat retention of the coated piston and combustion chamber. The CO and HC emission also decreased by 71.42% and 80.76% respectively, due to complete combustion. However, NOx increases due to engine operating at high temperature.

The brake thermal efficiency of the coated engine is improved compare with un-coated engine with bio diesel operation. This is this is due to the reduction of heat loss to surroundings from the engine. From that it is obvious that the coating helps to gain an excess heat in the engine, when compared to the amount of heat gain engine without coating, in this manner the brake thermal efficiency of the coated engine is increased.

In the present scenario, all the IC engine operated vehicles could be easily modified through piston and combustion chamber catalytic coating by plasma thermal spray coating process. It is the simple and effective way to improve the engine performance and reduce the emissions and its leads to control the environmental pollution on better manner. This is one of the most suitable techniques for currently operated IC engine vehicles to reduce the toxic pollutions and improve the engine performance and also the engine modification is economical and eco-friendly.

Hence these experimental study investigations suggest that catalytic coating is the simple and effective method to increase efficiency and reduce exhaust emissions. Commercialization of this research is also simple as it only involves a coating process. Thus catalytic coating on the piston and combustion chamber is the most reliable way for controlling the environmental vehicle pollution during the transition period of IC engine technology to electric vehicle or fuel cell technology. The experimental work can further be improved by nano coating of piston with biodiesel on hybrid vehicle by improved advanced injection timing, increase of injector opening pressure.

Abbreviations Used

Al	Aluminum
BP	Brake horse Power in kW
BFSC	Brake Specific Fuel Consumption
Cu Cr1Zr	Copper Chromium Zirconium Alloy
C_V	Calorific Value
CO_2	Carbon dioxide
CO	Carbon monoxide
CC	Cubic Centimeters
EGT	Exhaust Gas Temperature
GO	Graphene oxide (GO)
MFC	Mass of Fuel Consumption
HC	Hydrocarbon
UHC	Un-burnt Hydro Carbon
VCR	Variable compression ratio
NOx	Oxides of Nitrogen
Pt	Platinium
Pbm	Brake mean effective pressure (BMEP) in N/m^2
SFC	Specific Fuel Consumption
SEM	Scanning Electron Microscopy
ηbth	Brake thermal efficiency
XRD	X-ray diffraction

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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