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Research Article

Effects of Thermal Barrier Coating Using Various Dosing Levels of Aluminium Oxide Nanoadditive Fuel on Diesel in Compressed Ignition Engine

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Environmental effects of vehicle exhausts from internal combustions engines which accounts for about 90% of vehicles on the roads is posing a major threat to environmental safety, and it only continues to surge at an alarming rate now than ever. With diesel engines being the most cost-effective prime mover readily available, their contribution to environmental pollution problems is humongous. The harmful contaminants from diesel exhausts are particulate matter (PM) and hydrocarbon and nitrogen oxides (NO_x). So, efforts to curb environmental pollution are the need of the hour by making necessary improvements to reduce their local and global environmental impact. In this study, examine the effects of yttria- and alumina-stabilised zirconia coating on the piston head and cylinder lining of a single-cylinder diesel engine, as well as its performance and emissions. Various dosing amounts of nanoparticles of aluminium oxide were utilised as additives to diesel fuel in this study, on both coated and uncoated internal combustion engines. Many coated engine metrics improved significantly as a result of the research. The brake thermal efficiency has increased by 2.1 percent as compared to a conventional uncoated diesel engine, while brake-specific consumption has dropped by 3%, resulting in a reduction in dangerous chemicals.

1. Introduction

The prime reason for ecological issues, global warming, climate changes, etc. are because of human's ambitious need for material sophistication. With transportation being the major contributor among all, rapid industrial growth and urbanization have also surged the demand for electricity which in turn is majorly derived from noneco-friendly practise like coal, oil, natural gas, and nuclear energy. Additionally, because of the competitive market practise, big industries compromise on environment-friendly approaches to produce the product at a faster rate. At present, because of the lack of stringent environmental policies and regulations, all these have aggravated and have already started to haunt life on earth. The most critical issue among all is air pollution is major because of automobile emission. Particularly, the internal combustion engine has a hard effect on the environment than anything else among automobile emissions, and it is more commonly used over gasoline engines because of its better fuel economy. According to Navigant Consulting, the worldwide stock of motor vehicles will exceed 2 billion units in 2035.

In an internal combustion engine, the chemical energy of the fuel is converted to thermal energy, which is then used to perform mechanical work in the form of piston movement. In this process, toxic compounds are released from the engine exhaust. A number of researchers have proposed a variety of approaches to reduce this harmful emission by in-cylinder treatment; however, only a significant portion of proposals have proved to be effective practically. Further, catalytic prereaction treatment reduces the minimum threshold ignition energy required while also amplifying the flame velocity. This approach also seemingly formulates the catalytic surface temperature along with the contact between gas-phase reactants and the catalyst. Aluminium oxides, copper oxides, cobalt oxides, and iron oxides have also been used as fuel additives to change the composition of diesel fuel in order to minimise emissions.

Researchers were able to minimise engine emissions and improve the performance of a diesel particle filter in the lab by using an aluminium diesel fuel borne catalyst and bimetallic platinum [1–4]. One of the findings of the study reveals that there is a substantial difference in particle density, light-off temperature, and oxidation kinetics in accumulation mode. Despite the fact that the rate of oxidation increased following the addition of aluminium to the fuel, the amount of dosage had no effect [5–8]. Kamo et al. evaluated the impact of introducing aluminium oxide into biodiesel and discovered that it improved performance while also lowering NO_x and HC emissions [9, 10].

Currently, researchers around the globe are relentlessly working on discovering an automobile engine which does not emit toxic compounds in its exhaust fume while also not compromising on its performance. One of these breakthroughs is the application of thermal barrier coating (TBC) within the combustion chamber to improve thermal resistance and stability when working at many leap temperatures. It is important to keep in mind that the barrier coating material should have a greater thermal coefficient of expansion than the metal substrate in order to withstand more thermal shock [11]. Similar coating approaches with ceramic materials like TiO2, CeO_2, mullite, CaO/MgO–ZrO2, and YSZ were also employed for practical purposes for engine applications [12, 13].

Thermal barrier coating materials like partially stabilised zirconia (PSZ) and nearly stabilised zirconia with 6-9 percent yttria (YSZ) are commonly utilised. Even under harsh circumstances absorbed in gas turbines, diesel engines, and other engines, these materials have been shown to function better [14]. The efficiency of a diesel engine covered with 0.1 mm thickness and 0.5 mm breadth of YSZ was enhanced by 6% in Ramalingam et al.'s experiment at all speeds and loads. The heat barrier coating is applied to the piston crown, piston, and cylinder head to fully use the finding [15–17] Because of its wide variety of physical qualities, such as a high coefficient of thermal expansion, a high Poisson's ratio, low thermal conductivity, and structural stability at high temperatures, YSZ was chosen as a feasible material for TBC I [18–21].

In this discussion, the performance and combustion of a diesel engine, as well as the emission difficulties develop when yttria- and aluminium-stabilised zirconia coatings are applied to the cylinder liner and piston head and when aluminium oxide additive is added at various amounts (35 ppm, 45 ppm, and 55 ppm). The goal of this experiment is to reflect the engine's changes in performance and emission characteristics [22–25]. This research's findings are analysed, examined, reviewed, and presented in a systemic manner. At first, the diesel engine coated with aluminium oxide nanoparticle is subjected to varying level of dosage (35 ppm, 45 ppm, and 55 ppm, respectively). Then, on the second phase, the same engine is modified and experimented with thermal barrier coating to compare the outcome from both the methods.

2. Experimental Methods and Specification

2.1. Test Engine. The test was conducted in a single-cylinder, water-cooled, 4-stroke diesel engine (Tv1 type Kirloskar, India) that produced 5.2 kW at 1500 rpm. An eddy current dynamometer was used for the loading. The engine's drive shaft is attached to the dynamometer. To determine the mass of airflow rate, an orifice metre and a manometer with a 1% error are employed. The engine's specifications are summarised in Table 1(a). In addition, Figure 1 and Table 1(b) shows the experimental setup and component description of the tested engine. By manual calibration, a glass tube is utilised to calculate the amount of fuel consumed. The calculation was done by comparing the time necessary for a normal diesel engine to consume 10 cc of fuel.

Engine parameters:

A piezoelectric pressure transducer (AVL INDIMICRA 602-T10602A) was used to monitor cylinder pressure, while a magnetic pickup was used to assess crank angle. An AVL 365C Angle Encoder Indi Advanced was fitted at the front-end of the engine crank to measure the engine speed. After 50 repetitions of cylinder pressure at steady-state, an average value is determined. Heat dissipation at different cylinder pressure was determined carefully and loaded into the system. The data were then compared to a graph of a conventional diesel engine. A five-gas analyser was used to measure CO, HC, NO_x, CO_2, and O2 emissions (AVL Digas 444). A K-type chromyl alumni thermocouple was used to measure the temperature of the exhaust gas, while an AVL437 smoke metre was used to detect smoke.

The entire process was done at a steady speed of 1500 rpm in a nominal functioning state. To arrive at an average result, the tests were repeated three times. After allowing the engine to attain its ideal operating state, all emission characteristics were recorded. The data was personally checked and placed into the system to be analysed further.

2.2. Thermal Barrier Coating Synthesis by Plasma Spraying. Physical vapour deposition, atmospheric plasma, and other forms of thermal spraying techniques were used to grind the top facet of the cylinder liner and piston, respectively. Spray,

Table 1

(a) Engine specification

Parameters	Values
Type	Kirloskar TV-1
General arrangement	Diesel engine test setup, vertical cylinder, water cooled
Power	5.2 KW @ 1500 rpm
Speed	1500 rpm
Number of cylinder	1
Number of strokes	Four
Compression ratio	17.5 : 1
Cylinder diameter	87.5 mm
Stroke length	110 mm
Type of ignition	C.I

(b) Engine component description

Temperature (°C)	Water flow liter/hour
T1 - engine cooling water inlet	F1 - fuel line
T2 - engine cooling water outlet	F2 - air inlet
T3 - calorimeter water inlet	F3 - engine cooling water (200 L/hr)
T4 - calorimeter water outlet	F4 - calorimeter water (100 L/hr)
T5 - calorimeter exhaust gas in	PT - pressure transmitter
T6 - calorimeter exhaust gas out	N - crank angle encoder

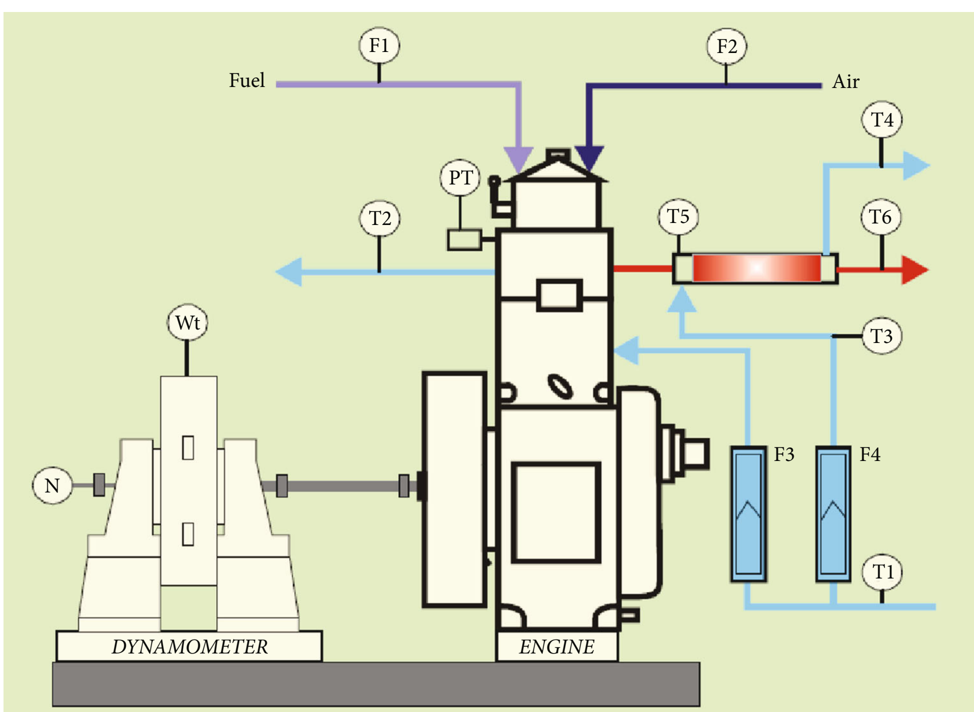


Figure 1: Experimental setup.

chemical deposition, and plasma arc methods were used in this technique. In this exploratory trial, the plasma spray technique is being used. The compression ratio in the cylinder liner and coated piston is maintained by a surface layer with a thickness of 0.30 mm and 0.15 mm. The sprayed powders and bulk were mechanically bonded by sandblasting the

Table 2: Parameters of plasma spray coating.

Parameter	Value
Plasma spray gun	3 MB
Arc voltage (V)	65-70
Arc current (I)	500
Spray distance (mm)	80
Primary gas flow–argon (L/min)	80
Secondary gas flow–hydrogen(L/min)	15
Deposition rate, kg/h	1.1

engine cylinder with alumina grits and piston. YSZ makes up 94% of the coating powder, with alumina making up 2% and ceria making up 4%. Table 2 shows the spray details for the piston and cylinder liner coatings of the engine, and Figure 2 depicts a plasma spray coating method.

2.3. Preparation of Test Fuel. Diesel is the primary fuel used in this research. Using a standard instrument, the calorific value and density of biodiesel were determined to be 850 kg/m^3 and 34.5 MJ/kg, respectively. This method used aluminium oxide nanoparticles with a size of 10 to 20 nanometers and a density of 7.13 g/mL as fuel additives. The volume levels of aluminium oxide nanoparticles in the base fuel were changed between 35 ppm, 45 ppm, and 55 ppm. The volume levels of the nanoparticle sample were then calculated using an electronic balance. With the aid of an ultrasonic shaker, the sample was blended with the fuel. To get a homogeneous suspension, agitation is conducted for 30 minutes. To avoid sedimentation, the produced fuel was used as soon as possible.

2.4. Determination of Fuel Properties. Flash and fire points, as well as pour and cloud points, were used to determine the viscosity of gasoline. The flashpoint was measured with the Cleveland open flash and fire point equipment (ASTM 2007), and the viscosity was determined with the Redwood viscometer (British Standard Section 2000). The characteristics of the fuel sample utilised are shown in Table 3.

Fuel properties:

2.5. Procedure for Testing. Readings were observed three times after attaining the engine steady state, and mean value was determined. Enhanced combustion was witnessed when air intake is provided while using aluminium oxide as an additive in diesel. As a result, full oxidation of hydrocarbons occurred. In addition, the additive aluminium oxide was miscible with fuel. Different volume levels of 35 ppm, 45 ppm, and 55 ppm were added with diesel, following which the mixture is agitated for 30 minutes with help of ultrasonic shaker. Following that, the engine was started with varied amounts of aluminium oxide-containing diesel. The readings were removed. The coated piston and cylinder liner were reinstalled, and the process was repeated after the baseline piston and cylinder liner operation was completed. The combustion, emission, and performance metrics of coated and uncoated engines were compared between additive-containing diesel and regular diesel. The coated engine was removed after roughly 100 hours of operation to look for any changes in the coated piston crown and cylinder liner. Before starting the engine, the coated piston crown and cylinder liner are shown in Figure 3. Figure 4 shows the coated piston crown and cylinder liner after the engine has been operating. The images also show that the coating used had small cracks around the margins of the piston crown. The outstanding sections, on the other hand, showed almost no fractures or abnormalities, indicating that the thermal barrier coating was stable under all loading conditions of engine running.

3. Results and Discussion

In terms of pollution, performance, and combustion, the coating's effects on the cylinder liner and piston head were investigated. The operation was carried out in a water-cooled single-cylinder, four-stroke engine using diesel fuel containing aluminium oxide additions at volume levels of 35 ppm, 45 ppm, and 55 ppm. Several performance parameters were observed and analysed for discrepancies under engine loading conditions, including BTE, BSFC, NO_X, CO, CO_2, and HC emissions and smoke.

3.1. Engine Performances

3.1.1. BSFC. Figure 5(a) shows the difference in TBC BSFC in uncoated and coated engines with different load and volume levels of aluminium oxide. When compared to regular diesel, aluminium oxide diesel has a lower BSFC (Kannan, Karvembu, and Anand 2011). The BSFC for diesel and diesel with aluminium oxide additions drops even more for engines with TBC. This is due to a greater combustion temperature, which results in a faster energy conversion rate during combustion. This ultimately leads to better combustion and better conservation of fuel [19]. A significant 3% lesser BSFC has been observed for coated engines with diesel containing various volumes of aluminium oxide than diesel-employed coated engines at part load conditions. From the preceding condition, it clearly illustrates that the presence of aluminium oxide improves the performance of the engine at part load conditions. In addition, an increased temperature is observed because of TBC. The BSFC of the coated engine is increased by 1% and 2% when diesel is added with aluminium oxide of 45 ppm and 55 ppm, respectively, in comparison to diesel operated engine at 75% load. At 75% load, 3% lesser BSFC is noticed for diesel-operated coated engine than standard diesel operation.

3.1.2. BTE. Figure 5(b) illustrates the difference in BTE of TBC coated and untreated engines with load for all tested fuels. When aluminium oxide is introduced, the BTE value rises. The addition of aluminium oxide nanoparticles to the fuel promotes complete combustion, as opposed to typical aluminium oxide fuel, which acts as an oxygen barrier, releasing or keeping oxygen depending on partial pressure. Finally, the BTE is increased when the aluminium oxide is used as a fuel additive. The coated diesel engine with aluminium oxide has a higher thermal efficiency than the base diesel. This happens because the piston crown has thermal resistance, which inhibits heat from being transported to the coolant or other media. As a result, the combustion is more uniform. At 85 percent load, the TBC engine with diesel improves BTEby 2.1 percent over conventional diesel performance.

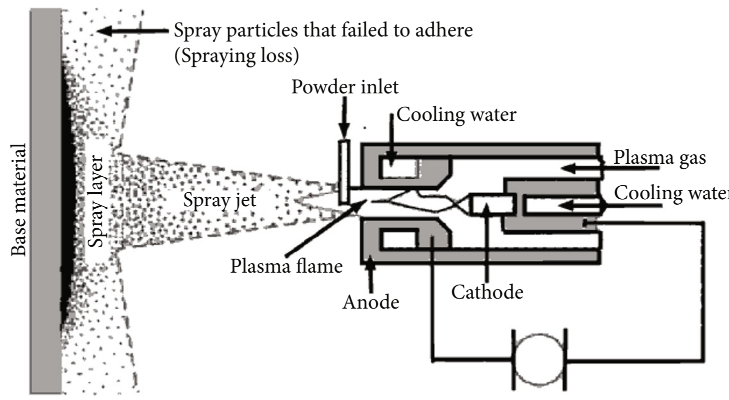


Figure 2: Plasma spray technique.

Table 3: Properties of fuel.

Property	Normal diesel	Diesel +45 ppm Al_2O_3
Density of test fuel	849	843
Calorific value MJ/kg (ASTM D240)	42.2	41.584
Flash point °C	50	53
Fire point °C	58	61
Kinematic viscosity @40°C (centistokes) (ASTM D445)	2.41	2.59

Figure 3: Coated engine for piston and cylinder liner.

Figure 4: After 100 hours of operation, the piston and cylinder liner are coated.

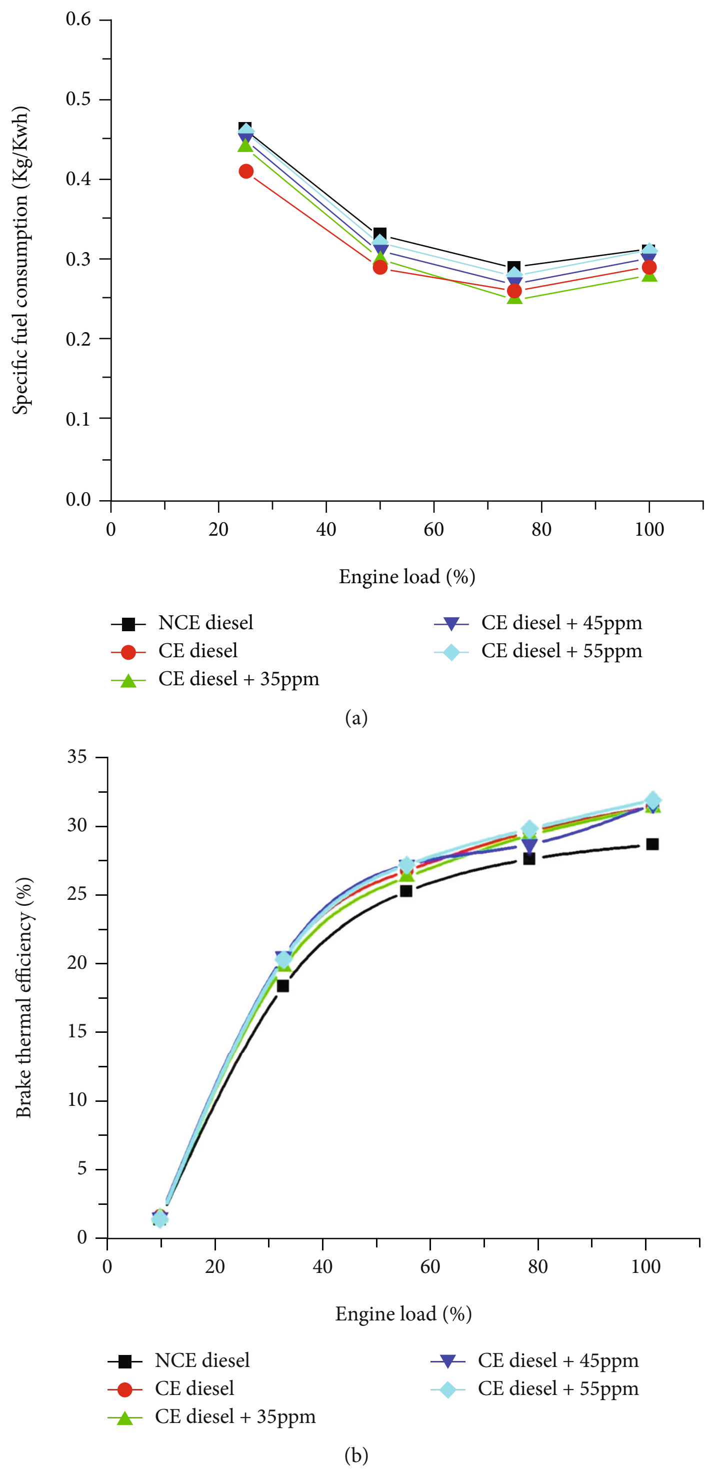
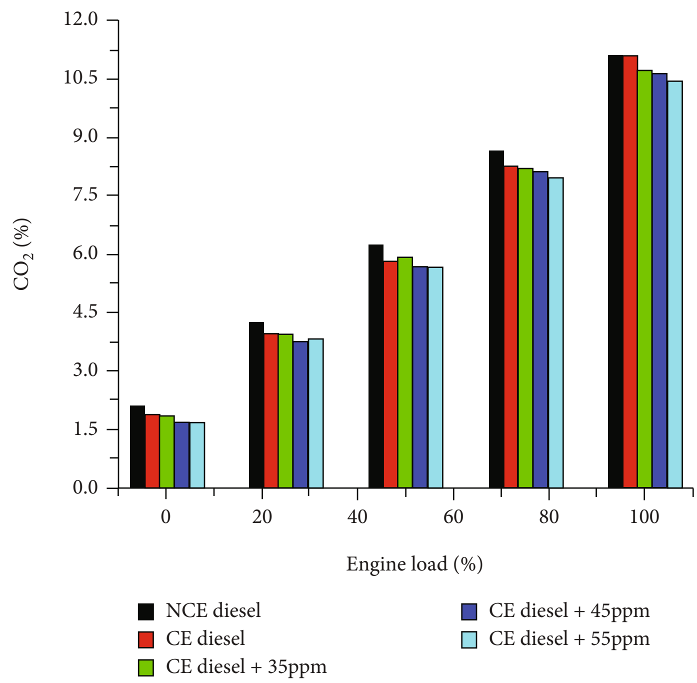
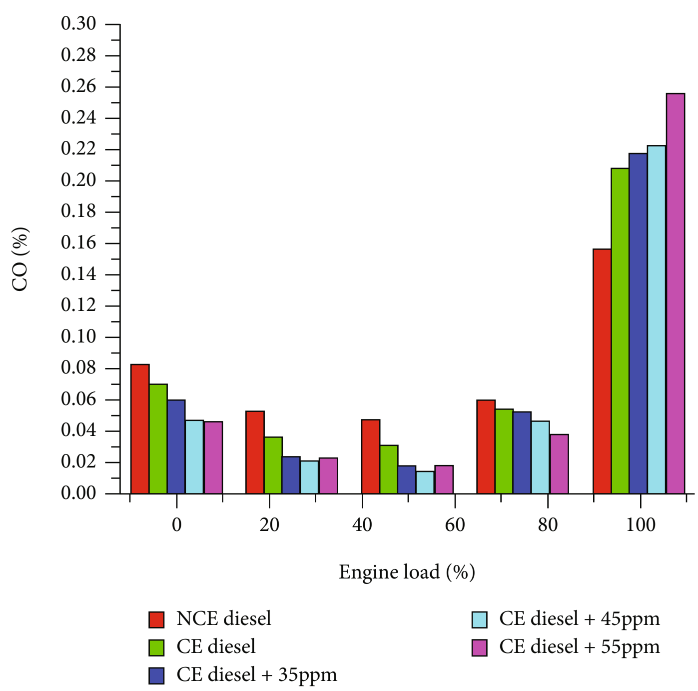


Figure 5: (a) BSFC vs. engine load. (b) Brake thermal efficiency vs. load on engine.

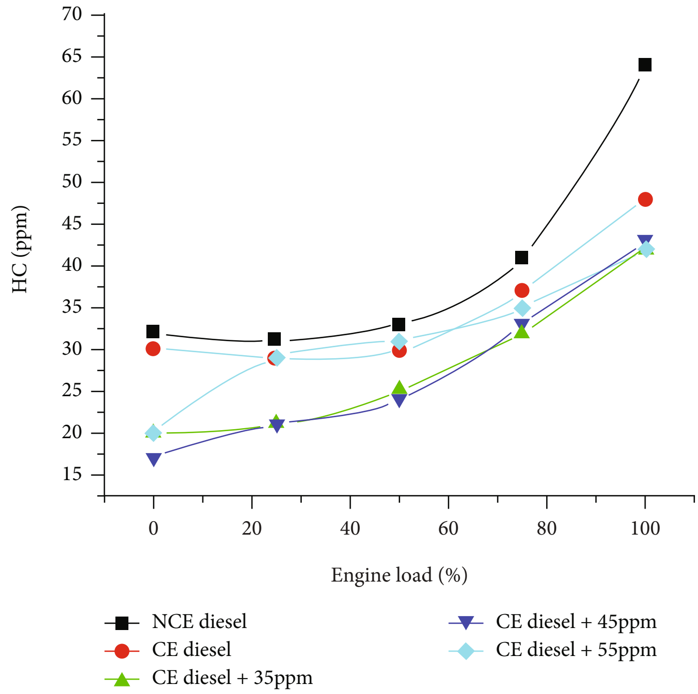


(a)

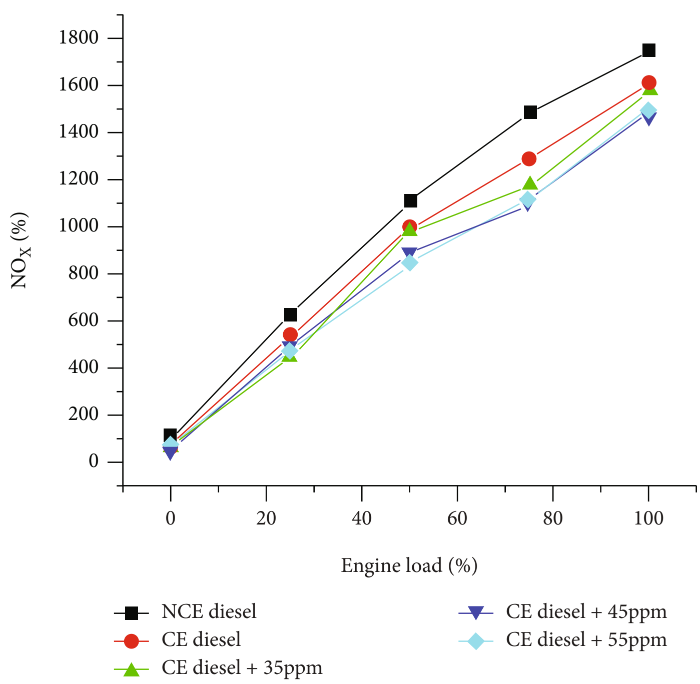


(b)

Figure 6: Continued.



(c)



(d)

Figure 6: (a) CO_2 vs. load on engine. (b) CO vs. engine load. (c) HC vs. load on engine. (d) NO_x vs. engine load.

3.2. Emission Parameters

3.2.1. CO_2 Emission. Figure 6(a) presents the change in CO_2 discharge with engine load. When the amount of aluminium oxide in diesel is changed, the CO_2 emissions rise when compared to regular diesel. As a result, enhanced combustion results from the use of all oxygen in the combustion chamber. This results in increased generation of CO_2 from CO [22], thereby reducing the levels of CO. CO_2 emission is increased for TBC engines. The combustion in the cylinder is improved by different dosages of aluminium oxide and high cylinder temperature. As a result, there is an increased CO_2 emission. At 75% of engine load with dosages of 35 ppm, 45 ppm, and 55 ppm of aluminium oxide, CO_2 emission is more than about 5.7%, 7%, and 8.9% for coated engines, respectively, when compared to that of the base diesel.

3.2.2. CO Emission. Figure 6(b) depicts a decrease in CO emissions as the engine load increases. This reduced CO emission is because of increased higher temperature in a cylinder with an increase in the load of the engine. Due to the aluminium oxide effect in the diesel, there is improved combustion, as a result of which CO emission is reduced. The additive aluminium oxide increases the oxidation of CO into CO_2. A further reduction in the emission of CO is noticed in engines with TBC. The coating generates high temperature which stimulates the conversion of CO into CO_2. Hence, TBC engines provide improved combustion [22]. CO emissions are reduced by roughly 0.8 percent, 1.4 percent, and 0.7 percent for coated engines at 75 percent of engine load with doses of 35 ppm, 45 ppm, and 55 ppm of aluminium oxide in diesel, respectively, when compared to basic diesel.

3.2.3. HC Emission. When there is incomplete combustion, there is an increased HC emission. Figure 6(c) gives the difference of HC emission with respect to engine load. When compared to base fuel operation, the addition of aluminium oxide to diesel results in lesser HC emission of about 7% at 75% load. This is due to the role of aluminium oxide in effecting the improved combustion. The coated engine has lesser HC emission compared to the uncoated one. This may be the result of high combustion temperatures after the burning phase by hindering the heat loss in coated engines. Eventually, effective use of air intake and increased oxidation of fuel [5] was carried out by improved combustion. Aluminium oxide dosages of 35 ppm, 45 ppm, and 55 ppm provide a 9%, 8%, and 6% reduction in HC emission, respectively, for coated engines associated with standard diesel-operated uncoated engines.

3.2.4. NO_x Emission. Figure 6(d) depicts the increase in NO_X emissions as engine load increases. The oxygen content and combustion temperature are determined by NO_X emissions. As aluminium oxide is added to diesel, it causes an increase in NO_X emissions when compared to base diesel. This increased emission is because of oxidation of nitrogen into its oxides by aluminium oxide while combustion. NO_X emission is higher comparatively in uncoated engine. This is due to high temperature that stimulates an early beginning of combustion. This changes the peak temperature and pressure to TDC proximity. Thus, increase in NO emission is due to burning of fuel in premixed state [11]. Aluminium oxide dosages of 35 ppm, 45 ppm, and 55 ppm provide a 21%, 26%, and 25.5% in NO emission, respectively, for coated engines associated to standard diesel-operated uncoated engine at 75% load.

4. Conclusion

Following conclusions are arrived through the experimental study and investigation.

(i) Ceria- and yttrium-stabilized zirconia-coated engine with different dosages of aluminium oxide and diesel provides an increase of 2.7% BTE and reduction of 3% BSFC at 75% load. Coated engines show a finer performance characteristics with test fuels at part load conditions

(ii) When 35 ppm, 45 ppm, and 55 ppm of aluminium oxide are added to diesel, CO, HC, and Knox emissions are reduced for both coated and uncoated engines when running on regular diesel

(iii) Influence of parameters like size of nanoparticle, dosing level, and preparation time has significant role in the fuel performance with fuel added with aluminium oxide nanoparticles as thermal barrier coating. For best performances of engine and emission reductions, Consistent effort has been put to get optimum combination of parameters. In parallel, a further research is being carried out on visualization techniques for analysing the characteristics of combination of additive fuels

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Disclosure

This study was performed as a part of the Employment Hawassa University, Ethiopia.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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