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ORIGINAL ARTICLE

Study of performance and emission characteristics of a partially coated LHR SI engine blended with n-butanol and gasoline

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Abstract To meet the present requirements of the automotive industry, there is continuous search to improve the performance, exhaust emission, and life of the IC engines. The meet the first two challenges, researchers are working both on newer engine technologies and fuels. Some of the published work indicates that coating on the combustion surface of the engine with ceramic material results in improved performance and reduced emission levels when fueled with alternate fuel blended fuels, and this serves as a base for this work. Normal-Butanol has molecular structure that is adaptable to gasoline, and it is considered as one of the alternative fuels for SI engines. Blending butanol with gasoline changes the properties of the fuel and alters the engine performance and emission characteristics. This is because heat which is released at a rate as a result of combustion of the compressed air–fuel mixture in the combustion chamber gets changed with respect to change fuel properties, air fuel ratio, and engine speed. An experimental investigation is carried out on a partially insulated single cylinder SI engine to study the performance and emission characteristics when fueled with two different blends of butanol and gasoline. The cylinder head surface and valves are coated with a ceramic material consisting of Zirconium dioxide (ZrO_2) with 8% by weight of Yttrium Oxide (Y_2O_3) to a thickness of 0.3 mm by plasma spray method. Two different fuel blends containing 10% and 15% by volume of butanol in Gasoline are tested on an engine dynamometer using the uncoated and ceramic coated engines. The results strongly indicate that combination of ceramic coated engine and butanol gasoline blended fuel has potential to improve the engine performance.

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1. Introduction

N-butanol or butyl alcohol can be used as a fuel for IC engine, which is designed for use with gasoline without modification. N-butanol can be produced from biomass (biobutanol) as well as fossil fuels (petrobutanol). Both biobutanol and petrobuta-

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Nomenclature

BDC	Bottom Dead Center
BP	Brake Power (kW)
BTE	brake thermal efficiency
CA	crank angle (°)
CO	carbon monoxide
CTD	coated
EGT	exhaust gas temperature (°C)
GNB	gasoline & n-butanol
HC	hyrdocarbon
SFC	specific fuel consumption (kg/kJ h)
TBC	thermal barrier coating
TDC	Top Dead Center
UCTD	uncoated

nol have the same chemical properties. N-butanol is less corrosive than ethanol and has higher energy content than ethanol and closer to that of gasoline. In comparison with ethanol, n-butanol is less prone to water contamination. As a result, it could be distributed using the same infrastructure used to transport gasoline. It can be used a sole fuel in SI engines, or it can be mixed with gasoline and used. There were four types of butyl alcohol, and they all have the same chemical composition, consisting four carbon atoms, ten hydrogen, and single oxygen and also have identical chemical pattern $C_4H_{10}O$. They differ each from others with respect to their structure. The chemical structure of different butanol is given below:

- 1-butanol: (n-butanol) $CH_3–CH_2–CH_2–CH_2OH$,
- sec-butanol: $CH_3CH(OH)CH_2CH_3$,
- tert-butanol: $(CH_3)_3COH$,
- iso-butanol: $CH_3(CH_2)_3OH$.

In addition, each of the fuels has different thermodynamic properties and combustion characteristics. For the tests described in this paper, n-butanol (1-butanol) was used as a fuel. Characteristics of n-butanol in comparison with gasoline and other alcohol fuels are given in Table 1.

However, when taking into account the latent heat of vaporization of these fuels, n-butanol is less attractive than gasoline. For port fuel injection systems, when the fuel vaporizes in the inlet port, it affects a temperature decrease in the intake charge [1]. Therefore, fuels of higher latent heat of vaporization have larger decreases in temperature of intake charge with complete vaporization in the intake port. This increases the density of combustible mixture and increases the charge mass. Furthermore, the cost of n-butanol production is higher in comparison with ethanol [2]. However, there are some promising circumstances for n-butanol production from fermentation process of agricultural feedstock by cellulosic enzymes [3] that have the potential to reduce its production cost. Govindarajan et al. [4] investigated the effects of unleaded iso-butanol and additives of ethanol to gasoline to study the performance and emission characteristics on a SI engine. Their work concluded that there was an increase in brake thermal efficiency (BTE), volumetric efficiency, and reduced fuel consumption when the engine was operated with blends of 5% iso-butanol, 10% ethanol, and rest gasoline. Significant reductions in exhaust emissions levels for entire engine torque range were noted. Apart from performance, exhaust emission plays a prime factor in any type automobile testing due to concerns over environmental issues and regulations set by regulatory bodies.

Table 1 Properties of different fuels.

Fuel properties	Gasoline	Butanol	Ethanol
Molecular formula	C_8H_{15}	C_4H_9OH	C_2H_5OH
Energy density (MJ/L)	32	19.2	19.6
Vapor pressure (kPa)	60–90	2.3	17
Density at 20 °C (kg/L)	0.715	0.81	0.79
Stoichiometric air/fuel ratio	14.6	11.1	9
Research octane number	91–97	113	129
Carbon (%)	84.9	64.9	52.1
Hydrogen (%)	15.1	13.5	13.1
Oxygen (%)	0	21.6	34.7
Cetane number	Below 15	Below 15	Below 15
Boiling point (°C)	30–225	108.1	78.3
Lower heating Value (MJ/kg)	42.9	32.01	26.83
Latent heat of vaporization (kJ/kg)	349	584	838

Alasfour [5] studied the characteristics of n-butanol and gasoline fuel blends as an alternative fuel to study the effect of butanol with gasoline on NO_x emissions. He varied the inlet air temperature between 40 °C and 60 °C along with air–fuel ratio and observed the influences over NO_x. A 9% reduction in NO_x levels was noted at low temperature while preheating the inlet air resulted in knock and misfire due to reduced ignition delay. The study of using n-butanol as an alternative fuel source with diesel was conducted by Karabektas and Hosoz [6]. Their studies involved testing of different blends of butanol diesel blends. By testing the diesel engine at different rpm, a considerable decrease in emissions was observed, while there was a strong increase in brake thermal efficiency. Yang et al. [7] performed tests on a spark ignition (SI) engine with different proportions of n-butanol and gasoline fuel blends. Butanol–gasoline blends ranging from 10% up to 35% were tested under normal operating conditions. Their results indicated variations in engine output when fueled with blended fuel along with reduction in levels of HC and CO emission. Authors have also observed increased NO_x emissions with blended fuels.

Several studies by automotive researchers have successfully demonstrated that thermal barrier coatings (TBC's) when deposited to the internal combustion engine, in particular the combustion chamber, simulate adiabatic condition. The objectives are not only for reduced in-cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also for possible reduction in engine emissions [8–10]. The application of TBC reduces the heat loss to the engine cooling-jacket through the surfaces exposed to the heat transfer such as engine head, liner, piston crown, and piston rings.

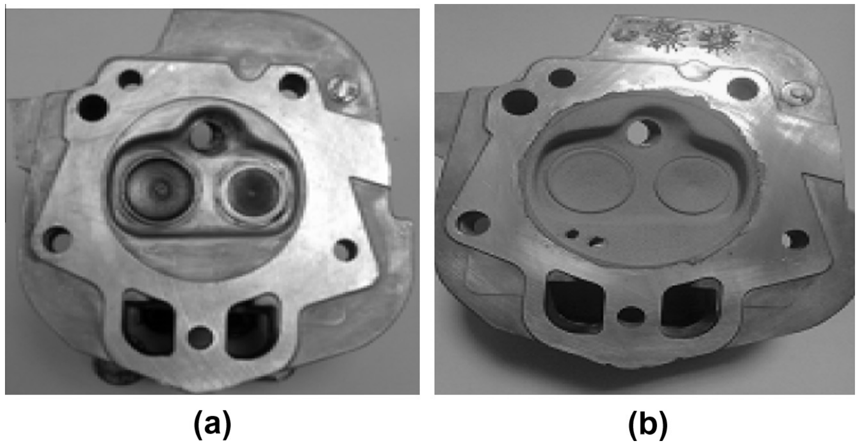


Figure 1 (a) Uncoated, (b) Coated cylinder head, inlet, and exhaust valves.

The insulation of the combustion chamber with ceramic coating affects the combustion process and hence the performance and exhaust emissions characteristics of the engines [11–14]. In addition, thermo-physical properties of the ceramic material, its surface roughness and porous characteristic, either in terms of pore size or porosity, have a direct influence on the unburned or partially burnt hydrocarbons through the effect of surface quenching and retention residual in the pores [15,16]. A detailed study on engine performance and emissions characteristics which was performed on a ceramic coated diesel engine (Low Heat Rejection – LHR) by Porai et al. [17] also leads to a positive conclusion. A detailed literature on Low Heat Rejection engine also reveals that only minimum number of studies was carried out on LHR SI engine and specifically with blended fuels. The primary focus of this experimental work is to study the effects of using blended fuel on a LHR type SI engine in comparison with a standard SI engine.

2. Thermal barrier coating

Before the application of the partial thermal insulation, a standard cylinder head was machined to remove material equal to the desired coating thickness in order to maintain the compression ratio of the engine after the assembly of the same on to the engine. After machining, cylinder head was grid blasted, and then, both the valves and the cylinder head of the engine were coated first with a bond coat, and over it, Yttrium stabilized zirconia was coated using an atmospheric plasma spray gun. The cylinder head and valves were coated with a 100 μm thickness of NiCrAl bond coat. ZrO_2 was deposited over the bond coat to a thickness of 200 μm. With the spray coating applied, the original dimensions of the coated parts of the engine were restored. Fig. 1 shows the photograph of the base and ceramic coated cylinder head. Table 2 shows the specifications of the ceramic coating.

Table 2 Specifications of ceramic coating.

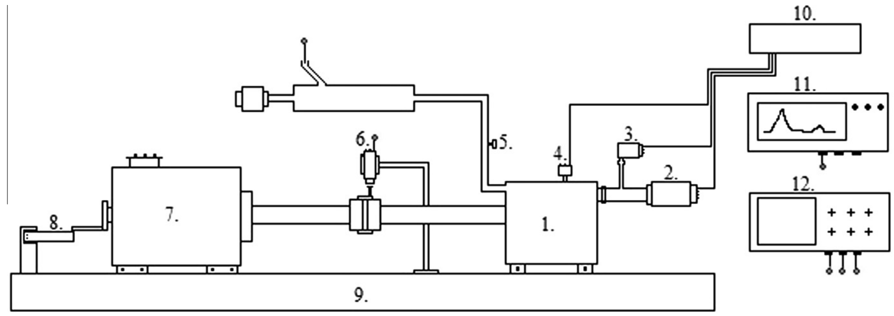
Parameters	Values
Particle velocity	500–550 mm/s
Oxide content	1–2%
Porosity	1–8%
Deposition rate	1–5 kg/h
Current	530 A
Voltage	72 V
Spray distance	100 mm
Torch nozzle diameter	6 mm

3. Experimental setup and test method

A 10 hp single cylinder, air cooled four stroke SI engine of Briggs and Stratton make, was selected for the study. The specification of the test engine is listed in Table 3. An eddy current dynamometer was connected to the engine, and the engine was operated at different brake loads by varying the torque at constant engine speed. Torque was measured by a strain-gauge based load cell. In order to measure the in-cylinder pressure, an uncooled type KISTLER piezoelectric type pressure sensor was flush mounted on to the cylinder head. The air flow rate was measured using a hot film type mass air flow sensor by placing it across the intake air stream. Experiments were conducted on base engine (without any modification) with gasoline and butanol–gasoline fuel blends for benchmarking. After completion of base readings, engine cylinder head which was coated with ceramic coating was installed on the base engine by replacing the original uncoated cylinder head.

Table 3 Engine specifications.

Type	Briggs and Stratton
Bore (mm)	79.24
Stroke (mm)	61.27
Compression ratio	8.1
Torque (N m, gross)	14.50
Engine displacement (cc)	305
Number of cylinders	Single
Engine configuration	Horizontal configuration
Lubrication system	Splash
Valve arrangement	Two vertical over head valves
Max power	7.46 kW @ 4000 rpm
Max torque	18.7 N m @ 2600 rpm



1. B & S Test Engine, 2. Mass Air Flow Sensor, 3. Manifold Pressure Sensor, 4. Cylinder Pressure Sensor, 5. Thermocouple(J), 6. Hall-effect Speed Sensor, 7. Eddy Current Dynamometer, 8. Load Cell, 9. Test Bed, 10. Data Acquisition Unit, 11. Oscilloscope, 12. Emission Analyzer.

Figure 2 Schematic layout of the system.

Using Hall Effect sensors, engine speed and TDC were measured. J type thermocouples were installed on the exhaust manifold to measure the exhaust temperature. To determine the quantity of fuel supplied to the engine, a high accuracy tuning fork type digital weighing scale with 0.01 g accuracy was utilized. All pressure sensors were interfaced to a data acquisition system of national instruments (NI), and the data were monitored using data acquisition tool (LabVIEW). Cylinder pressure data are acquired at 1 CA resolution. To estimate the concentration levels of hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) emissions, automotive emission analyzer (HORIBA) was used. Fuel blends of different proportions by volume such as 90% gasoline, 10% n-butanol (GNB10), 85% gasoline, and 15% n-butanol (GNB15) were used for testing the uncoated engine head (UCTD) and ceramic coated engine head (CTD). The tests were conducted by maintaining engine rpm at 3000, and the responses in performance characteristics due to variation in brake loads were noted down periodically. The schematic layout of the experimental setup is given in Fig. 2.

4. Results and discussion

In an IC engine, the combustion chamber parts operate under extreme conditions such as extreme temperatures and thermal shocks. Flame front does not always spread uniformly when combustion starts in the combustion chamber and at the end of combustion duration. Irregular spread of the flame front in the combustion chamber forms negative effects such as flame collisions and knocking. Therefore, combustion chamber parts are exposed to thermal tension and thermal shocks. These combustion negativities cause the parts constituting the combustion chamber to tense irregularly and to operate under higher thermal load which is heavier than the normal level. Due to the fact that ceramics have exceptional corrosion resistance high melting points, they are seen as alternative for the parts which operate under high temperatures. Changing the surface modifications of the combustion chamber parts causes these negative effects to be dealt by the coating. Therefore, main materials (substrates) are not damaged, and the lifetime of these parts increases. The negativities occurred during the burning duration in the combustion chamber such as thermal shock, extreme temperature, and irregular thermal tension are dealt by the applied ceramic coating.

Comparison of engine performance characteristics of 10% and 15% of n-butanol and gasoline blended fuels in two configurations of engine (uncoated and coated) against the performance of unleaded gasoline in base engine is done for different engine operating loads.

4.1. In-cylinder pressure

Fig. 3(a and b) shows comparison of in-cylinder pressure with respect to crank angle for both the base and the ceramic coated engines with all three fuels. The peak cylinder pressure of ceramic coated engine is higher than baseline engine (at 5.4 kW) when fueled with gasoline GNB10 and GNB15. When fueled with gasoline, GNB10 and GNB15 ceramic coated engine registers maximum pressure higher by 2 bar, 7 bar, and 8 bar than that of gasoline in base engine. The difference in peak in-cylinder pressure between GNB10 and GNB15 fuels when tested in ceramic coated engine is less than 5% at all the loads. The combined effect of reduced heat rejection and advanced peak heat release raises the peak cylinder pressure in ceramic coated engine. From kinetic theory of gases, increased in-cylinder gas temperature due to reduced heat transfer increases the mean square velocity of gas molecules, which simultaneously increases the gas pressure.

4.2. Heat release

The gross heat release analysis reveals that combustion process in ceramic coated engine is advanced as the heat gained due to partial insulation advances the beginning of the heat release. The peak gross heat angle appears very close to TDC which is earlier than as it appears in baseline engine. Fig. 4(a and b) shows the variation in heat release rate in both ceramic and baseline engine at 5.4 kW when fueled with gasoline GNB10 and GNB15 fuels. Ceramic coated engine has 10–20 J/° CA higher heat release rate when fueled with gasoline, GNB10 and GNB15 fuels, and the peak heat release angle also advances by around 10° CA in ceramic coated engines. Due to higher temperature, the rate combustion reaction increases and gets completed in shorter duration in ceramic coated engine.

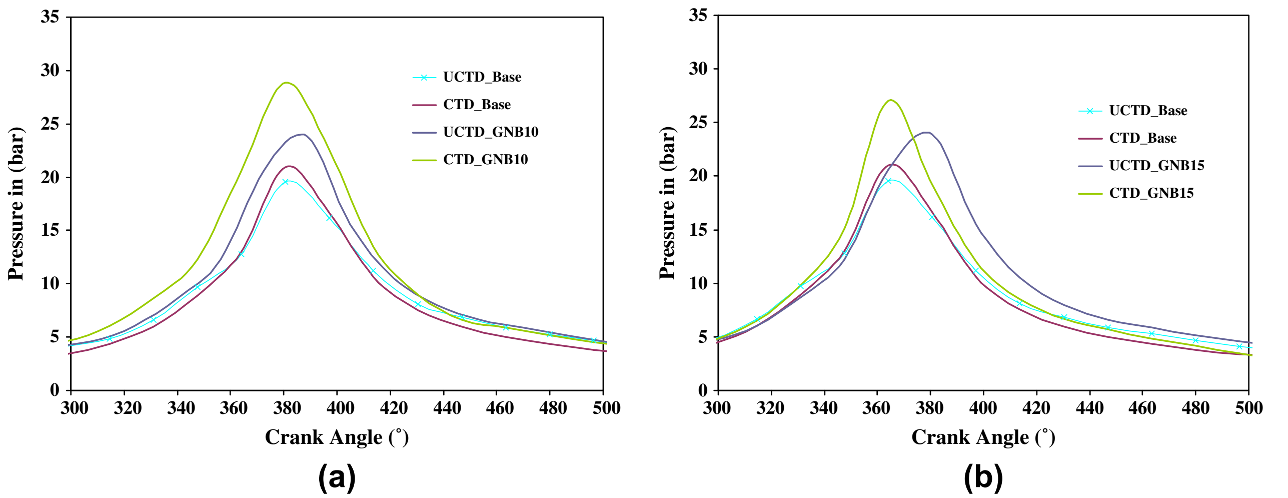


Figure 3 Comparison of in-cylinder pressure with respect to crank angle with (a) blend GNB10 and (b) blend GNB15 to gasoline as baseline.

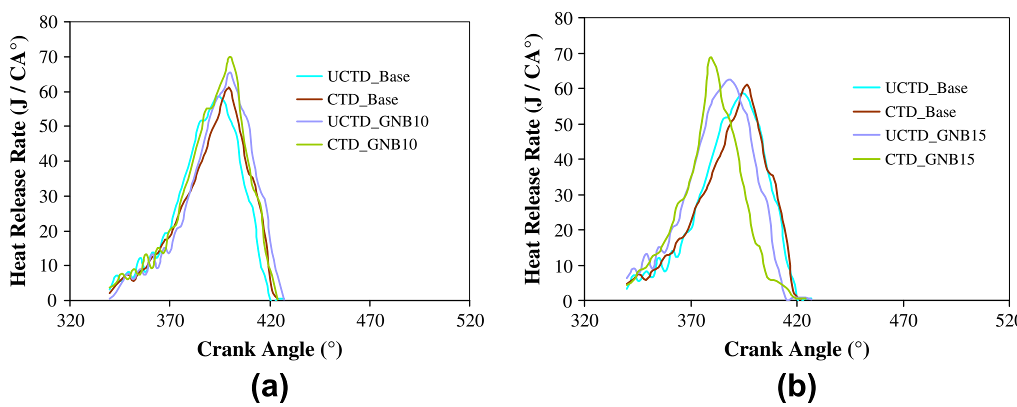


Figure 4 Comparison of heat release rate with respect to crank angle with (a) blend GNB10 and (b) blend GNB15 to gasoline as baseline.

4.3. Specific fuel consumption

Comparison of specific fuel consumption (SFC) of both the base and the ceramic coated engines when fueled with Gasoline, GNB10 and GNB15, is shown in Fig. 5(a and b). The energy content of n-butanol blended fuel is lower than that of unblended gasoline fuel; therefore, SFC values of n-butanol and its mixtures are higher than that of base gasoline fuel in both base and uncoated engine. This implies that more fuel (butanol blended) is needed to get same performance as that of gasoline. As the load is gradually increased, fuel consumption reduces gradually. The trends of SFC are similar in both the engines with all three fuels. At maximum load, fuel consumption increases in both the engines with all three fuels. This is because the carburetor is designed to choke at maximum load, and to overcome the load, more fuel is put into the air stream. When compared to gasoline in base engine, SFC is higher by 1.48% and 0.94% at lower and maximum loads when fueled with GNB10 in base engine. Increase in engine load alters the mass of fuel which affects the air–fuel ratio characteristics considerably on both uncoated and coated engine head. In contrast to these increments, SFC for all test fuels decreases in coated condition. The positive effect of increased in-cylinder temperatures, due to heat insulation, the SFC decreases for all test fuels in coated condition.

4.4. Brake thermal efficiency

Comparison of brake thermal efficiency (BTE) of both the engines with gasoline GBN10 and GBN15 is shown in Fig. 6(a and b). Increase in break thermal efficiency is observed with all three fuels in both the base and the coated engines with increase in load. Gasoline in ceramic coated engine showed 3.8% rise in break thermal efficiency at lower loads and peaks to 6% at maximum load when compared to gasoline in base engine. With GNB10 blend fuel at initial load, a marginal rise of 0.7% in thermal efficiency was observed in base engine, while with ceramic coated engine with same fuel, engine showed

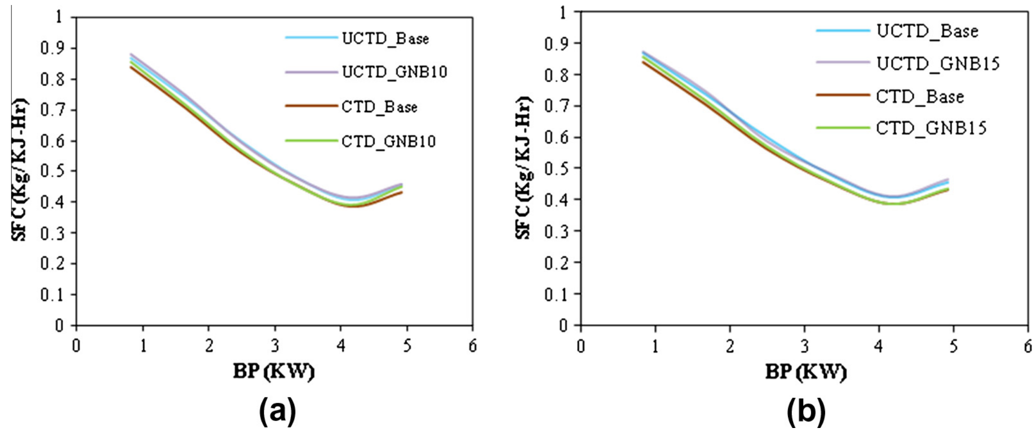


Figure 5 Comparison of SFC with (a) blend GNB10 and (b) blend GNB15 to gasoline as baseline.

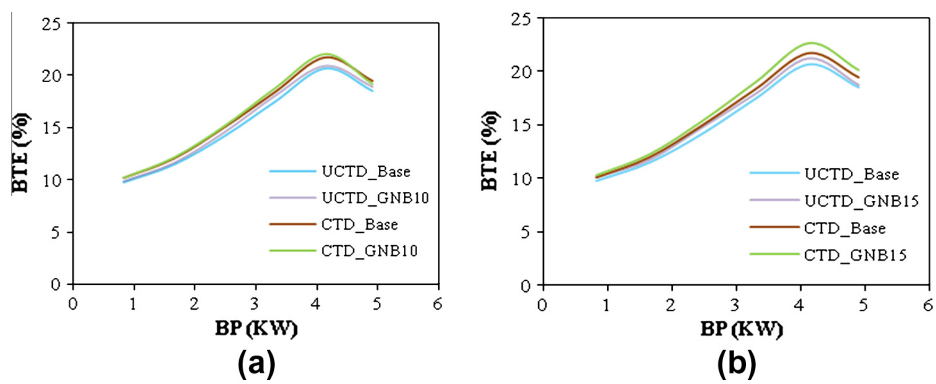


Figure 6 Comparison of BTE with (a) blend GNB10 and (b) blend GNB15 to gasoline as baseline.

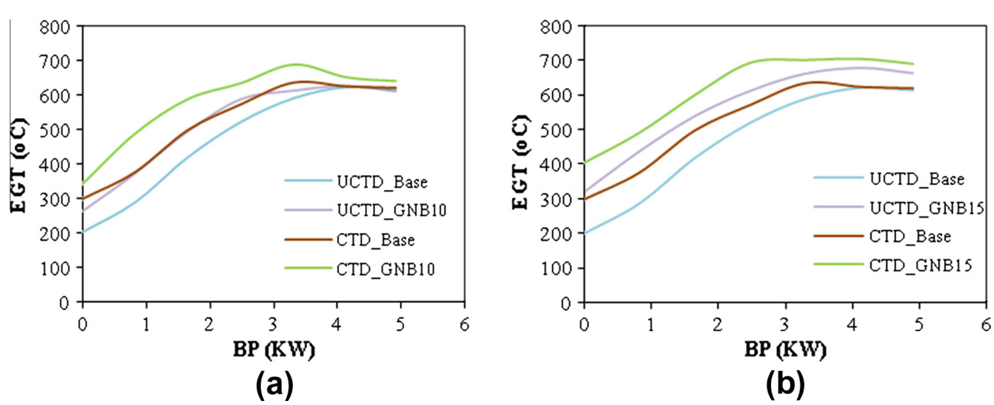


Figure 7 Comparison of EGT with (a) blend GNB10 and (b) blend GNB15 to gasoline as baseline.

3.9% increase at lower load. When compared to gasoline in base engine, GNB10 fuel blend showed a maximum increase in efficiency by 3.2% in base engine and 7.4% in ceramic coated engine at 85% of the maximum load. The differential change in thermal efficiency of the engine when operated with GBN10 and GBN15 was marginal in both the base and the ceramic coated engines.

4.5. Exhaust gas temperature

Comparison of exhaust gas temperature (EGT) of both the engines when operated with all three fuels is shown in Fig. 7(a and b). Results indicate an increase in exhaust temperature in ceramic coated engine when operated with both GBN10 and GNB15 fuel. The lower heating value of n-butanol which

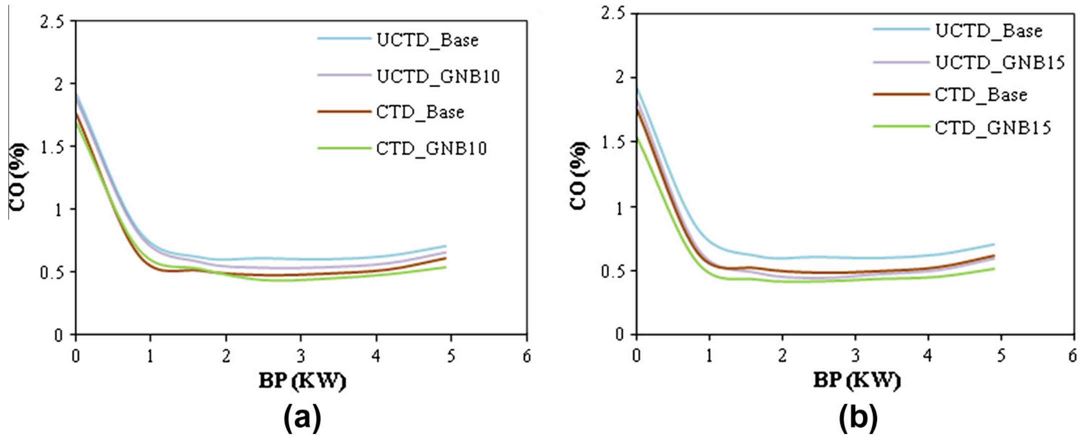


Figure 8 Comparison of CO with (a) blend GNB10 and (b) blend GNB15 to gasoline as baseline.

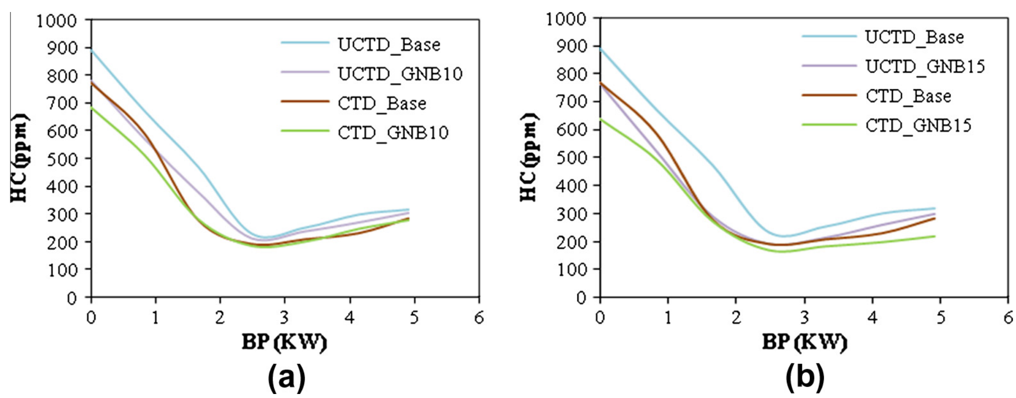


Figure 9 Comparison of HC with (a) blend GNB10 and (b) blend GNB15 to gasoline as baseline.

is closer to gasoline and improved volumetric efficiency due higher latent heat of vaporization of butanol (gasoline – 349 kJ/kg, butanol – 584 kJ/kg) and the adiabatic conditions created by ceramic coating (the quantity of heat blocked by coating is transferred to the exhaust gas) has lead to such increased exhaust gas temperature. Ceramic coated engine head with GNB15 blend registers slightly higher exhaust temperature than GNB10 blended fuel.

4.6. Carbon monoxide emission

Carbon monoxide is the intermediate product that is formed during combustion of hydrocarbon fuels. Some of the reasons for formation of CO are incomplete combustion and poor air–fuel management. The presence of oxygen plays a major factor in CO emissions in SI engine. Comparison of carbon monoxide (CO) emission from engine exhaust with n-butanol and gasoline fuel blends for both uncoated & coated engine with respect to gasoline in base engine is shown in Fig. 8(a and b). N-butanol consists of 21.6% oxygen atoms by weight. Addition of butanol to gasoline aids in producing a proper combustible mixture. Coated engine head tested with gasoline high decrease in CO levels. Better performance is indicated by using GNB10 and GNB15 fuel blends for coated engine head. Further decrease in CO level was attained as the engine load was increased.

The decrease in CO emission in the coated engine head as compared to the uncoated engine head may be explained by an increase in combustion temperature as a result of the decrease in heat losses going to cooling, and outside, due to ceramic coating. Heat transfer affects engine performance, efficiency, and emissions. The coating attributes reductions to insulation of the engine head, increases in wall temperature and thus contributes positively to combustion efficiency. Local conditions specifying temperature, mixture ratio, and amount of oxygen, affect combustion and make the combustion continuous in petrol engines. Thus, the results clearly indicate that the ceramic coating improves local conditions.

4.7. Hydro carbon emission

The unburned hydrocarbon emission from the engine is mainly due to completely unburned or only partially burned fuel. The amount of unburned hydrocarbon depends on the engine operating conditions and fuel properties. Fig. 9(a and b) has shown the unburned hydrocarbon emission by uncoated gasoline, coated gasoline and uncoated and coated n-butanol gasoline blends for different load conditions. All the experiments have shown the decreasing trend of unburned hydrocarbon emission level as the BP increases. This trend is due to increased temperature and pressure at high load conditions leading to better combustion. It is observed that conventional engine is emitting

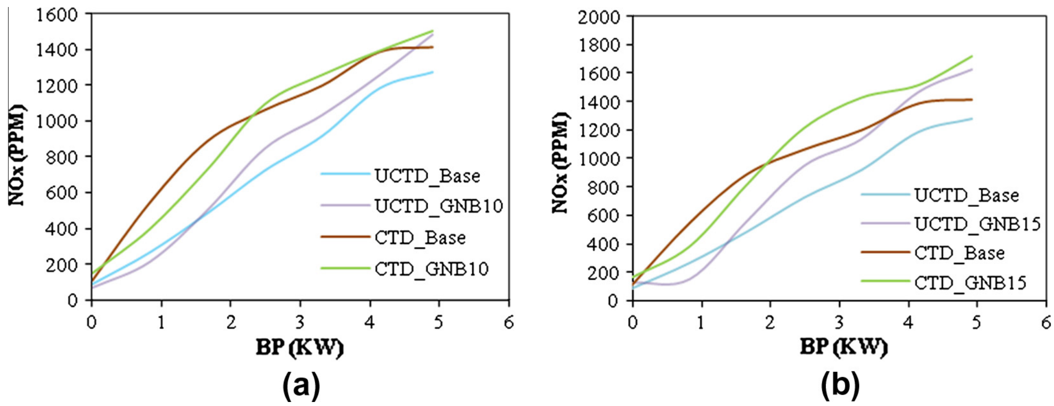


Figure 10 Comparison of NO_x with (a) blend GNB10 and (b) blend GNB15 to gasoline as baseline.

unburned hydrocarbon at higher level when compared to LHR and LHR with n-butanol blends. This is due to lower operating temperature in conventional engine as compared to coated engine. Moreover, engine operated with n-butanol–gasoline blends has shown lower HC emissions as compared to pure gasoline. Low energy content of n-butanol and presence of oxygen atom contributes as the prime factors for the decrease in HC emissions with blends. Butanol can provide more oxygen for the combustion process. Since the HC emissions are resulted due to incomplete combustion, when butanol is added, HC emissions decreases significantly.

4.8. NO_x emission

The NO_x forms by oxidation of atmospheric nitrogen at sufficient high temperatures. An increase in after-combustion temperature causes an increase in NO_x emission. All factors facilitating and accelerating the reaction between oxygen and nitrogen increase NO_x formation. Thus, the main factor in NO_x formation is temperature. However, engine load, combustion chamber content, combustion chamber homogeneity, and mixture density in the combustion chamber are also factors.

Fig. 10(a and b) indicates that NO_x levels were lower in uncoated engine, while they were higher in low heat rejection engine at different operating conditions with n-butanol gasoline blends when compared with gasoline operation on uncoated engine at all loads. The NO_x increase for all the test fuels used in the coated head may be a result of an increase in after-combustion and combustion chamber temperature due to the coating. Increase in combustion temperatures with the faster combustion and improved heat release rates in LHR engine caused higher NO_x levels. NO_x levels increased in n-butanol gasoline blends operation when compared to pure gasoline operation on uncoated engine. This was due to increase in ignition delay with n-butanol blends and increase in gas temperatures in LHR engine.

5. Conclusions

The study of the effect of thermal barrier coatings applied to cylinder head, inlet and outlet valves on performance and emission characteristics of a SI engine fueled with n-butanol and gasoline blend leads to the following conclusions:

Combustion process in the ceramic coated engine is advanced as compared to the uncoated engine.
The peak cylinder pressure of coated engine is higher than the baseline engine.
With increase in proportion of n-butanol in the blends for both the coated and base engine, HC emissions are significantly reduced.
The CO decreases for all the test fuels in the coated engine compared with uncoated head.
NO_x emission increased for blends in coated engine compared with uncoated head due to the adiabatic conditions.
The increase in NO_x emission for all the test fuels in coated head engine occurred due to the higher gas temperatures.
The SFC decreases for all the test fuels in coated engine compared with uncoated base engine. This can be considered that the rising combustion temperature as a result of the coating of combustion chamber components provides a positive effect on SFC
Because of the heat, which would be lost to atmosphere through cooling system, exhaust gas temperature increased.
In coated cylinder head engine due to the reduction in SFC, the brake thermal efficiency was increased.
The applied ceramic coating protects the combustion chamber components from negative effects such as irregular thermal tension and thermal shock.

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