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Improving the poor properties of methyl ester with pyrolysis oil and fossil diesel – An experimental investigation on PSZ ceramic coated engine with the addition of GO nanoparticles

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The aim of this work is to assess the effect of graphene oxide (GO) nanoparticles on performance and emission characteristics of a ceramic coated diesel engine fuelled with ternary blends of pyrolysis oil-methyl ester-diesel. Tyre pyrolysis oil and hemp oil methyl ester (biodiesel) have been produced and PBD20 (10%pyrolysis oil + 10%biodiesel + 80% diesel) blend has been prepared for engine analysis. This work also evaluate the performance and emission characteristics of the engine operated with PBD20 with different dosage of GO in both conventional and partially stabilized zirconia (PSZ) coated engines. Initially, base diesel, 20% blend and 20% blend with different GO dosage level are tested in a standard engine and later, the same fuels are tested in a ceramic coated engine under varying load conditions from 0 to 100%. The performance parameters such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), emission parameters such as carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx) are all measured. The results showed that the engine is able to run on blends of tyre pyrolysis oil and hemp oil at different loads, showing similar performance to diesel. From the research, it is noted that PBD20 with 50 ppm GO in a coated engine showed 4.41% higher performance than diesel operated in a standard engine. The BSFC of the engine running on the same blend showed similar trend to diesel. The emission of CO and HC are reduced by 40% and 25.58%, respectively, when the engine operated using PBD20GO50 in coated engine.

Keywords: Ceramic coating, IC engine, Nanoadditives, Performance characteristics, Ternary blend

Introduction

Energy is the most important and vitalone for the developing country's economy. The quick development of industrialization and the transportation segment for the past two decades has resulted in an increase in the depletion of fossil fuels[1]. With respect to this perspective, the researchers working on internal combustion (IC) engines give attention to the invention and application of biodiesel as a direct alternative fuel for fossil fuel or as a blend option in order to improve its overall performance. Biodiesel is a possible substitute for diesel fuel consisting of long-chain fatty acid esters that can be used directly for IC engines without any alterations. Biodiesel has become the most important product associated with environmental concern. It is well identified that the emissions caused by fossil fuels have a serious impact on all living organisms. Biodiesels are renewable products that can be produced mostly through transesterification reactions[2]. Among the variety of available edible oils, there are many different types of non-edible feedstock that are available for biodiesel production, including jatropha curcas oil, neem oil, eucalyptus oil, fish oil, waste cooking oil and animal oil[3].

Utilization of biodiesel for IC engines has some limitations, including lower fuel economy, higher NOx emissions and cold starting issues. The higher cetane number, higher oxygen elements, higher dense and viscosity are the key reason for the inferior performance of the biodiesel in IC engines. These drawbacks with biodiesel can be mitigated by employing a few relatively novel technologies, such as the inclusion of nano-additives and the use of hybrid fuel[4]. Fuel additives are chemical elements that are blended directly with diesel and other alternative fuels to improve their properties. These additives can help with oxidation stability, corrosion resistance, storage and deposit. The additives are divided into several categories based on oxygen-rich, nano-based, water, tocopherol and polymers. The nano-based additives in fuels serve as a catalyst for better combustion. The increased heat generated within the chamber due to nano additives increases the BTE with reduced fuel consumption. In addition to that, the nanoparticles can reduce harmful gases. In accordance with the large surface air-to-volume ratio, good thermophysical behaviour and higher thermal conductivity of nanoadditives, it was found that adding nano materials efficiently prevents agglomeration during blending and improves engine efficiency.

In view of the advancement in nanotechnology over the last two decades, many researchers have concentrated their efforts on improving the combustion behaviour, performance parameters with reduced emissions by incorporating nanoparticles into the fuel. Copper, silicon, cerium, barium, cobalt and graphene oxides are the most frequently used fuel additives. It was found that a large number of investigations were done primarily with different types of biodiesel under various proportions. Only few literatures described the use of biodiesel with nanoparticles to reduce harmful emissions. Ghanbari *et al*. examined the combustion properties of an engine operated with a biodiesel blend including carbon nanotubes and Ag nano-additives[5]. The study illustrated greater in-cylinder peak pressure than diesel. Adzmi *et al*.explored the impact of silica (SiO_2) with palm biodiesel. With the addition of SiO_2, the engine showed a 43% increased brake power (BP), 25% decreased in CO, and 4.48% drop in NOx[6]. Gavhane *et al*.explored the influence of ZnO nanoadditives mixed with soybean biofuel and investigated the combustion parameters[7]. The study showed improved BTE, higher heat release rate and mean gas temperature by 23.2 %, 19.45 % and 2.4 % respectively. According to this study, the CO, HC, CO_2, and smoke formations were reduced by 28.21%, 32.23%, 21.66% and 22.5%, respectively. Adding cerium oxide (CeO_2) to biodiesel also promoted higher BTE and lower emissions. According to Perumal and Ilangkumaran, combining copper oxide (CuO) with 20% pongamia biodiesel with diesel resulted in 4.01% higher BTE, 1.0% lower BSFC, 12.8% lower smoke, and 9.8% lower NOx emissions[8]. By combining two distinct nanoparticles, SiO_2 and MgO, Özgür *et al*. evaluated the effect of nanoparticles with biodiesel. To achieve distinct blends, these nanoparticles were mixed with biodiesel at various dosages of 25 and 50 ppm. In this study, the addition of these two nanoparticles with rapeseed methyl ester reduced the concentration of NOx and CO with improved BTE[9].

Pyrolysis oil obtained from lignocellulosic biomass, plastics and waste tyres are a potential fuel for IC engines. Pyrolysis oil from lignocellulosic biomass has a lower heating value than the pyrolysis oil produced from plastics and tyres[10]. According to Umeki *et al*. pyrolysis oil/diesel blends displayed characteristics that allowed for their use as fuel[11]. Raguraman *et al*. utilized waste polystyrene pyrolysis oil for IC engine operation and found higher BTE with lower fuel consumption up to a 10% blend with fossil diesel[12]. Plastic pyrolysis oil produced from pyrolysis of mixed plastics was used by Kalargaris *et al*. for IC engine operation. According to the results, the engine produced same power output with plastic oil at high loads, but at lower loads, stability problems are caused by the longer ignition delay[13]. Consistent with Hurdogan *et al*. adding 10% pyrolysis oil to diesel did not have an adverse effect on the torque and power output of engines[14]. Martinez *et al*. evaluated a CI engine with fuel containing 5% tyre pyrolysis oil[15]. The authors found that at low loads, the engine operated with blended fuel had somewhat greater BSFC and lower BTE, but at higher loads, they found no differences.

The study conducted by various researchers on nano metal additives with alternative fuels showed increased performance and reduced emissions. Many studies have also exposed a significant decrement in NOx with biodiesel and nano additives. This work is novel in terms of the selection of fuel for the IC engines. On ceramic coated engines, there was no literature on the usage of a ternary blend of pyrolysis oil, biodiesel and diesel with GO nanoparticles. The objective of this work is to give comprehensiveness on the effect of performance and emission characteristics of the diesel engines.

Experimental Section

Production of tyre pyrolysis oil

Tyre pyrolysis oil for this work was obtained by pyrolyzing waste tyres. The oil was collected by maintaining the reactor at 450°C. The trials were repeated as necessary under the same operating circumstances to extract an adequate amount of oil for this investigation. The reactor receives the necessary amount of heat using a 2000 W electric heater, which is measured by an autotransformer that also regulates the heat supply. Condensable volatiles were transformed into oil by passing through a water-cooled condenser maintained at 5°C. For each run, around 100 g of tyre were loaded into the fixed bed reactor. At the end of each experimental run, the amount of solid and oil fractions was weighted to estimate their yield percentage. The basic properties of the produced pyrolysis oil are shown in Table 1. From the table, it can be seen that the tyre pyrolysis oil has a density that is noticeably higher than diesel and has a lower cetane number. These characteristics indicate that tyre pyrolysis oil, without upgrading, is mostly employed in marine engines instead of road transportation applications, which require significantly higher standards. On this basis, the task for this work was focused on power generation in a stationary internal combustion engine. The pyrolysis oil having similar properties is also used by Kalargaris *et al*. for the production of power[13].

Production of biodiesel

The biodiesel was produced from hemp seed oil. Hemp seed oil was obtained from the physical pressing process of hemp seeds. Transesterification is an efficient technique since it produces a higher quantity of biodiesel. The produced pyrolysis oil and biodiesel are mixed with diesel to make a B20 blend. The basic properties of the source oil and its blend are also revealed in Table 1.

Preparation of nanofuel

To prepare the blended fuel with nano additives, the process is performed with an ultrasonic approach. Initially, the required amount of GO is weighed and well mixed into the base fuel before use. An ultrasonic shaker is used to continually stir the mixture for 30 minutes to achieve a uniform suspension. The dispersion phenomena of the nanoadditive are enhanced by the use of a sonication bath. The ultrasonicator can be used to regulate particle sedimentation by enhancing the dispersion property of the particles. The same method is employed to produce nanofluids with varying levels of GO in the solution. After 3 h, the produced nanofluids are visually checked to determine their stability. Before conducting the experiments in the engine, the prepared nanofluids are tested to ensure that there is no particle settlement in the fluid. The same method is followed to prepare biodiesel with different dosages of GO such as 50 ppm, 75 ppm, 100 ppm. In this wok, the GO nanoparticles were mixed only with B20 blends and tested in the engine. Prior to conducting the experiments with nanoparticles, the trial experiments were conducted with various blends of B20, B40, B60, B80 and B100. The trial study exhibited B20 with better characteristics. The B20 fuel with nanoparticle additive was tested to ensure that it met all applicable statutory standards. Table 2 lists the blend types and Table 3 displays some recent work on biodiesel with nanoparticles. In addition to that, Table 4 displays the required characteristics of the fuels.

Engine set up

The experimental study, operated with B20 fuel with different dosages of GO has been carried out on a Kirloskar-made diesel engine. This engine is frequently utilized for agricultural and industrial applications. Fig. 1 depicts the overall structure of the experimental set-up and its technical details are summarized in Table 5. The setup is fully equipped with different measuring devices to measure engine speed, torque, fuel and air consumption, temperatures,

Table 2 — Blend type

Content	Blend name
0% pyrolysis oil + 0% hemp oil biodiesel + 100% diesel	D
10% pyrolysis oil + 10% hemp oil biodiesel + 80% diesel	PBD20
PBDB20 + 25 ppm GO	PBD20GO25
PBDB20 + 50 ppm GO	PBD20GO50
PBDB20 + 75 ppm GO	PBD20GO75
PBDB20 + 100 ppm GO	PBD20GO100

Table 1 — Properties of hemp oil and biodiesel

Properties	Tyre pyrolysis oil	Hemp oil biodiesel	B20	Diesel
Density (g/cm^3)	0.926	0.886	0.859	0.850
Heating value (MJ/kg)	42.31	42.92	43.08	43.6
Kinematic viscosity (mm^2/s)	2.73	4.76	4.11	3.9
Flash point (°C)	69	78	60	57
Cetane number	49	52	50	50

Table 3 — Recent works on biodiesel with nanoparticles

Nanoparticle	Dosage level (ppm)	Source of biodiesel	Performance parameters		Emission parameters				Reference
			BTE	BSFC	CO	HC	NOx	Smoke	
Al_2O_3	40	*Calophylluminophyllum* oil	▲	▼	6.09%▼	12.24%▼	7.76%▼	6.2%▼	[16]
TiO_2	25 to 100	Tamanu oil	#	#	▼	▼	▼	#	[17]
CeO_2 and CNT	25 to 100	Castor oil-ethanol	#	#	22.2%▲	7.2%▼	#	47.6%▼	[18]
CuO_2	50	*Botryococcusbraunii* algae oil	▲	▼	#	#	#	#	[19]
GO	20 to 60	Dairy scum oil	11.56%▲	8.34%▼	#	21.68%▼	#	24.88%▼	[20]
TiO_2	50 to 100	Orange peel oil	1.6%▲	3.0%▼	▼	▼	▲	▼	[21]
CeO_2 -WCNT	90	Waste cooking oil	#	▼	38.8%▼	71.4%▼	18.9%▼	#	[22]
Al_2O_3 and CNT	30 to 60	Tamarind seed oil	▲	▼	▼	▼	▲	▼	[23]
MWCNT	50	Jatropha oil	#	#	55%▼	50%▼	45%▼	#	[24]
CeO_2 , ZrO_2 and TiO_2	25	*Garcinia gummi-gutta* oil	#	#	▼	▼	▲	▼	[25]
SiO_2 and TiO_2	50 to 100	Algae oil	▲	▲	▲	▲	#	#	[26]
GO	30 to 90	*Oenothera lamarckian* oil	▲	#	▼	▼	▲	#	[27]
TiO_2 and ZnO	50 to 100	*Calophyllumino phyllum* oil	▲	▼	▼	▼	▼	▼	[28]
TiO_2	300	Neem oil	▲	▼	▼	▼	▲	▼	[29]
Al_2O_3	10 to 30	Jatropha oil	7.8%▲	4.93%▼	11.2%▼	5.69%▼	9.39%▼	#	[30]
Al_2O_3	90	Honge oil	10.5%▲	11.6%▼	42%▼	#	#	#	[31]
CuO_2	60	*Neochlorisoleo abundans* oil	▲	▼	#	#	#	#	[32]
Al_2O_3 and TiO_2	50 to 100	Waste cooking oil	▲	▲	▼	▼	▼	#	[33]

#Not reported

Table 4 — Fuel properties

Properties	PBD20	PBD20GO25	PBD20GO50	PBD20GO75	PBD20GO100
Density (g/cm^3)	0.859	0.841	0.843	0.864	0..865
Heating value (MJ/kg)	43.08	43.12	43.14	43.22	43.34
Kinematic viscosity (mm^2/s)	4.11	4.15	4.15	4.17	4.17
Flash point (°C)	60	62	62	63	64
Cetane number	50	51	51	51.2	51.5

Fig. 1 — Experimental set-up

and pressures. Primarily, the engine ran on clean diesel. For each experiment, a thorough inspection of the engine was performed to make sure that no fuel or oil had leaked and after reaching steady state environment, the analyses was done. The analysis was done in three stages overall. On an uncoated engine, the first phase of operation involves using base diesel and its ternary mixtures. In the second phase, the readings were noted on the engine when it was operated with nanofuel. The third stage of the readings was noted on coated engine with diesel, biofuel and nanofuel. At 20% load intervals, the load for the engine was changed from 0 to 100% to conduct the testing. The concentrations of the emitted gases are analyzed by an AVL DI gas analyzer. All the readings were collected from the engine at 1500 rpm for a certain period of time without adding load.

Table 5 — Specifications of the test engine

Items	Specification
Make	Kirloskar TV1
Type	Four stroke, compression ignition
Power	5.2 kW
Number of cylinder	1
Compression ratio	17.5:1
Injection pressure (bar)	210
Bore (mm)	87.5
Stroke (mm)	110
Displacement (cm^3)	661
Cooling	Water
Orifice diameter	20 mm
Fuel	Diesel and biodiesel blend
Start of injection	23° bTDC
Loading type	Eddy current dynamometer
Gas analyzer	AVL DiGas

Coating preparation

Plasma spraying is used to apply a coating on the piston. When compared to alternative coating methods, this technique is straightforward and less expensive. PSZ was selected as a ceramic material for this study since it is widely used for high-temperature applications. With the use of the plasma spray technique, 350 µm thickness of coated material (PSZ) was applied. Before ceramic coating, 150 µm NiCrAl was applied to the substrate as a bond coat. The surfaces are subjected to a 6 µm grit blasting process to increase bonding strength. Overall, the thickness of the coating was maintained as 500 µm. Prior to coating, a micro-machining procedure was carried out to preserve the same compression ratio as that of a conventional diesel engine. Fig. 2 displays the ceramic coated piston used in the coated engine. Some recent studies on coated engines operated with diesel and biodiesel are projected in Table 6.

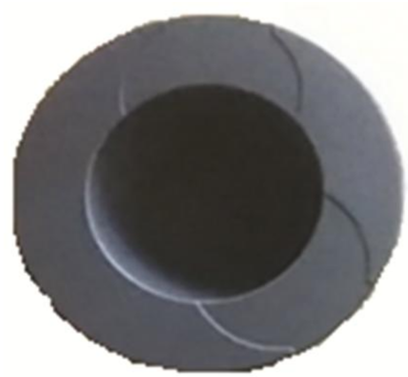

Fig. 2 — Ceramic coated piston

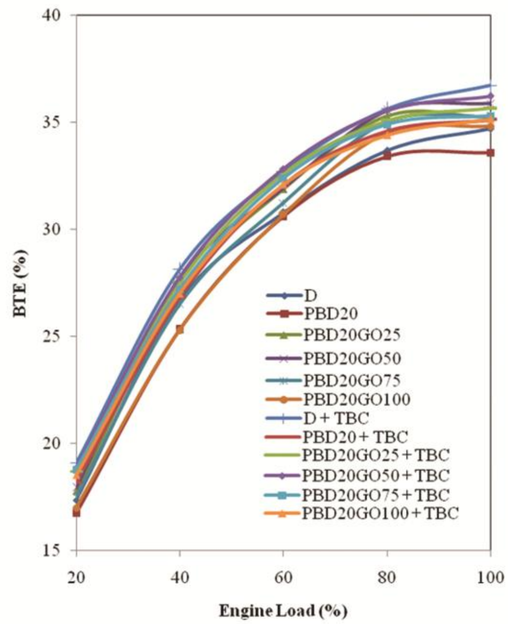

Fig. 3 — Variation of brake thermal efficiency with engine load for different tested fuel

Engine analysis

Performance characteristics

Brake thermal efficiency

Fig. 3 compares the BTE of the engines produced by diesel and other fuels under different loading conditions. As can be observed, biodiesel-operated engines produced lower power than neat diesel. The BTE of the PBD20 biodiesel under full load conditions is 33.58%, which is 3.95% lower than diesel. The lower power output with biodiesel is owing to the lower energy content and higher density. The reduction in BTE is also linked with the consumption of more fuel for the operation since the plunger in the injector pump discharges more biodiesel related to diesel. The output power is significantly increased by adding GO nanoparticles to biodiesel. Nanoparticles show a better effect on engine power with full loads compared to partial loadings. At 100% load conditions, the BTE with PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100 is 35.24%, 35.88%, 35.27% and 34.82%, respectively. The increased power output by utilizing GO nanoparticles suggests improved fuel combustion and energy conversion[52]. The GO particle used for this work precludes carbon and iron deposition and boosts power. In addition to that, adding nanoparticles shortens the ignition delay and combustion duration, which increases peak cylinder pressure[53]. On the aforementioned fuels, the BTE was tested on a ceramic coated engine, which indicated a higher BTE than a standard engine. The BTE of the

Table 6 — Recent works on ceramic coated engines

Coating material	Coating thickness (μm)	Source of biodiesel	Performance parameters		Emission parameters				Reference
			BTE	BSFC	CO	HC	NOx	Smoke	
Y_2O_3-ZrO_2	350	Sunflower oil	▲	▲	#	#	#	#	[34]
TiO_2	500	Pongamia oil	▲	10%▼	▼	▼	15%▲	#	[35]
PSZ	500	Palm oil	1.5%▲	▼	#	▼	▲	45.74%▼	[36]
ZrO_2-MgO-Al_2O_3	400	Fried oil and cotton seed oil	▲	▼	▼	▼	▲	▼	[37]
PSZ	500	Jatropha oil	▲	▼	#	#	▲	▼	[38]
PSZ	400	Rice bran oil	▲	▼	#	▼	▲	▼	[39]
Mo-NiAl	250	Cotton seed oil	#	6%▼	18%▼	#	4.5%▲	8%▼	[40]
Al_2O_3–TiO_2	250	Corn oil	5%▲	4.6%▼	#	15%▼	8.8%▲	8.3%▼	[41]
PSZ	500	Mohr oil	7%▲	▼	#	#	▲	11%▼	[42]
Al_2O_3	200	Rice bran oil and mahua oil	11.4%▲	10.9%▼	▲	▲	▼	▼	[43]
MgO–ZrO_2	350	Canola oil	1.7%▲	8%▼	▼	24%▼	7.3%▲	8.2%▼	[44]
PSZ	500	Jatropha oil	▼	#	#	#	▲	#	[45]
Fly ash	200	Rice bran oil and pongamia oil	6.8%▲	16.8%▼	#	47%▼	10.8%▲	43.2%▼	[46]
YSZ	350	Sunflower oil	6.5%▲	9%▼	#	#	#	#	[47]
PSZ	400	Honge oil	0.5%▲	#	▼	▼	#	▼	[48]
PSZ-Al_2O_3	#	Hongeoil and cotton seed oil	▲	▼	#	▼	▲	▼	[49]
ZrO_2	#	Cottonseed oil and sunflower oil	▲	▼	▼	▼	▲	▼	[50]
Al_2TiO_5	#	Pongamiaoil and neem oil	11.9%▲	13.9%▼	#	▼	▲	▼	[51]

#Not reported

coated engine operated with diesel, PBD20, PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100 is 36.72%, 35.12%, 35.64%, 36.22%, 35.30% and 35.15%, respectively. From the results, it can be perceived that the neat diesel operated in a coated engine showed higher BTE and that for biodiesel combination, PBD20GO50 in a coated engine showed a higher BTE of 4.41%. Due to coating, the loss of heat can be restricted, which delivers more power output. It asserts that the coating on the engine parts functions effectively to compensate for heat loss. Heat energy is typically converted completely into useful work output in the coated piston[54].

Brake specific fuel consumption

Fig. 4 shows the BSFC versus load. For all tested fuels, BSFC is found to be marginally greater than diesel. The BSFC for fuels increases along with the increased load. It might be due to friction and heat transmission because the combustion chamber was substantially larger at low engine load. Additionally, as the load increases, the power output also increases, leading to lower fuel consumption. Compared to

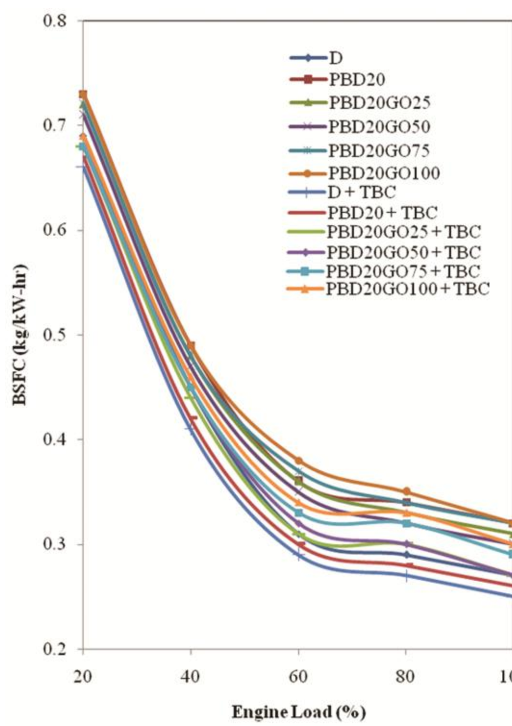

Fig. 4 — Variation of brake specific fuel consumption with engine load for different tested fuel

diesel, raw blended fuel consumed more fuel for all loading conditions. For uncoated engines, the value of BSFC for diesel and PBD20 is 0.27 kg/kW-h and 0.32 kg/kW-h, respectively. Compared to diesel, the engine consumed 15.63% higher fuel to produce equal power output. The lower energy value and greater density of the biofuel is the main reason for higher fuel consumption[55]. When compared to B20, it is seen that the BSFC of biodiesel blended with GO declined. For uncoated engines, the BSFC for PBD20GO25, PBD20GO50, PBD20GO75, and PBD20GO100 fuel is 0.31 kg/kW-h, 0.3 kg/kW-hr, 0.32 kg/kW-h, and 0.32 kg/kW-h, respectively. This is explained by the inhibition of thermal dissociation and higher combustion in the premixed combustion stage[56]. The nanoparticles in the biodiesel serve as an oxygen donor and likely result in complete combustion. Among the various dosage levels, the addition of 50 ppm GO with 20% blended biodiesel resulted in the lowest BSFC. The rate of combustion of GO blended biodiesel was higher due to micro-explosion and secondary atomization. Under ceramic coated conditions, the BSFC profile was stepped down due to enhanced fuel burning. In a coated engine, the BSFC for PBD20, PBD20GO25, PBD20GO50, PBD20GO75, and PBD20GO100 fuel is 0.26 kg/kW-h, 0.27 kg/kW-h, 0.29 kg/kW-h, and 0.30 kg/kW-h, respectively. Focusing on the coated engine, due to the heat-trapping ability of PSZ, BSFC of the nano biodiesel reclined nearer to the diesel. The higher combustion chamber temperature increased the conservation of energy[57]. The improved atomization of PBD20GO50 and the higher chamber temperature leads to complete combustion.

Emission characteristics

CO emissions

Fig. 5 illustrates the CO emissions versus engine load. The deviation in CO emissions is minimum at lower load and higher at higher load. CO is an intermediary product that is developed during incomplete combustion. It was also obvious to state that CO concentration increases as engine load increases. It seems logical that as engine load increases, the oxygen level in the chamber decreases[58]. As seen in Figure, the CO emission dropped as the proportion of test fuels containing pyrolysis oil and biodiesel. In conventional engine, the emission of CO for diesel and PBD20 is 0.25% and 0.21%, respectively. The biodiesel has higher oxygen content, allowing for more efficient combustion and, thus, a reduction in CO formation. CO is oxidized during the combustion process if enough oxygen molecules are present and the temperature is appropriate. The CO emission is further reduced with the addition of nanoparticles with biofuel. Engine operated by biodiesel with GO, the CO fractions are decreased due to the enhancement in the combustion persuaded by catalytic activity of GO, which improves the transformation of CO into CO_2 (Ref.59). It is evident that when the engine is operated with PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100 in a conventional engine, the CO emissions are 0.19%, 0.16%, 0.18% and 0.2%, respectively. The extreme reduction of CO emissions is recorded with the addition of 50 ppm GO with PBD20. Compared to diesel, PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100 in conventional engine showed 24%, 36%, 28% and 20% of reduction in CO emissions. The combination of these fuels operated in a ceramic coated engine resulted in a further reduction in CO formation. The higher temperature in the cylinder caused by the ceramic coating increases the oxidation of CO into CO_2, just like in diffusion combustion, indicating enhanced combustion[59]. In coated engine, the CO emission for PBD20, PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100 fuel is 0.20%, 0.17%, 0.15%, 0.16% and 0.17%, respectively. The CO emission is much lower for PBD20GO50 (40%) compared to diesel operated in conventional engine. Consequently, CO emissions

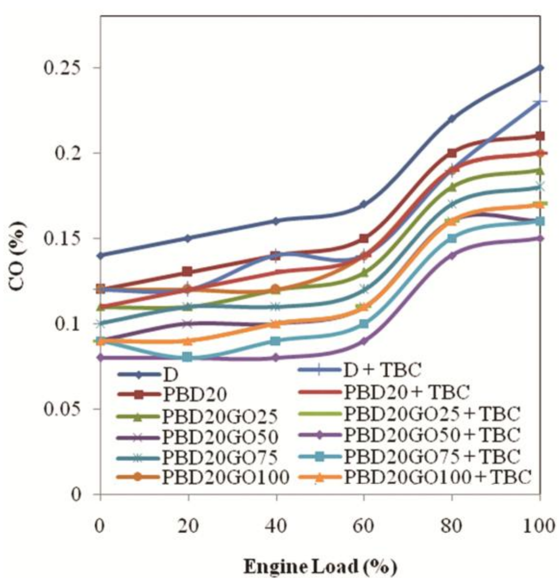

Fig. 5 — Variation of CO emissions with engine load for different tested fuel

from the ceramic coated engine were decreased to a low level under all load circumstances.

HC emissions

Fig. 6 demonstrates the HC emissions of the coated and uncoated engines operated with different fuels. HC emissions for all tested fuels increased and there has been a substantial decline in HC emissions for biofuel compared to diesel. The cause of HC emission for biofuel is the presence of oxygen molecules. The air inside the cylinder causes the fuel to evaporate, hence it burns fully. Additionally, it was known that the air fuel ratio for biofuel improved with the addition of load[60]. This finding also suggests that there was a substantial reduction in HC by adding nanoparticles to biodiesel. The decrease in HC emissions is the result of the usage of oxygenated additives, which encourage complete combustion. When the engine is operated with diesel, PBD20, PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100, the emission of HC is 43 ppm, 38 ppm, 37 ppm, 33 ppm, 34 ppm and 35 ppm, respectively. Adding 50 ppm GO reduced HC by 23.26% when compared to diesel. The HC emissions show an additional benefit when the fuel is used in coated engine. As a result of the shorter quenching distance and lower flammability limit related to coated engine combustion, Engines with coatings have a higher probability of reducing HC emissions[61]. The higher cylinder temperature in a coated engine promotes the oxidation reactions. The HC emission was considerably reduced when the biodiesel with GO nanoparticles was operated in a coated engine. In coated engine, at 100% load PBD20, PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100 emits 34 ppm, 33 ppm, 32 ppm, 33 ppm and 34 ppm HC, respectively. The blend of PBD20GO50 in coated engine showed a drop in HC emissions by 25.58% related to the diesel due to the shorter ignition delay and good atomization. In general, the reduction in HC in coated engine is attributed to improved combustion chamber temperature during afterburning stage due to lower heat rejection. The enhanced combustion process results in a more effective use of inlet air and increased oxidation.

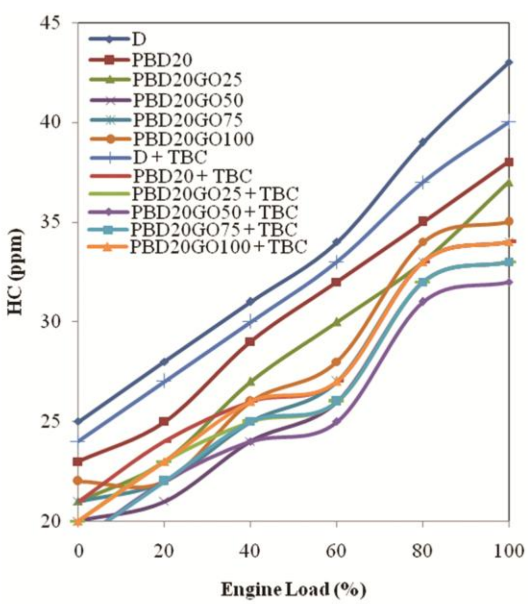

Fig. 6 — Variation of HC emissions with engine load for different tested fuel

NOx emissions

The emission of NOx is considered the most critical one for IC engines. The effect of NOx emission based on engine load on conventional and ceramic-coated engines operated with biofuel is represented in Fig. 7. All the tested fuel generates lower NOx, but with higher loads, the engine produces more NOx. As seen from the past literature, the engine operated with PBD20 produced more NOx than diesel. The emission of NOx in conventional engine operated with diesel and PBD20 is 986 ppm and 956 ppm, respectively. The 20% blended fuel produced 2.13% lower NOx than diesel. The oxygen in a fuel, combustion chamber temperature, and combustion duration are all factors that influence NOx emissions[62]. In accordance with the Zeldovich process, OH radicals are created during combustion and react with nitrogen molecules to create more

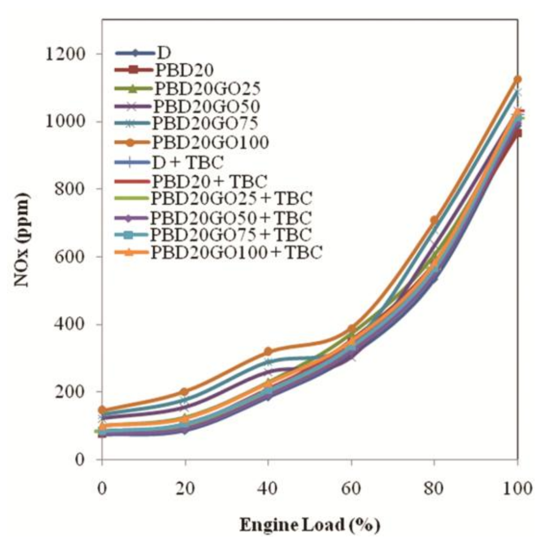

Fig. 7 — Variation of NOx emissions with engine load for different tested fuel

NOx[63]. The emission of NOx is moderately larger than that of ordinary diesel when the biodiesel is blended with GO nanoparticles. Adding GO with biodiesel increases the oxygen, improving the reactions, resulting in a higher combustion temperature, which increases the formation of NOx. At 100% load, the value of NOx emissions in conventional engine for PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100 is 1004 ppm, 1031 ppm, 1087 ppm and 1125 ppm, respectively. The inclusion of GO accelerates the completion of premixed combustion, which causes higher NOx emissions. The impact of nanoparticles strengthens combustion and prolongs the ignition delay. It was perceived that NOx increase as the dosage of GO in the biodiesel increases. This outcome could be ascribed to improved exhaust gas temperature. The nanoparticle doped biodiesel in the coated engine marginally reduced the NOx emissions. In a normal engine, NO makes up more than 90% of the NOx produced, with the remaining 10% being made up of NO_2, NO_3, and NO_4. The production of NO is 60% less when coated engines are used. At maximum load, the value of NOx emissions in the coated engine for PBD20GO25, PBD20GO50, PBD20GO75 and PBD20GO100 is 1032 ppm, 1010 ppm, 996 ppm and 1012 ppm, respectively. From the figure, it can be understood that, in a ceramic coated engine, the emissions of NOxis much like diesel fuel. The direct harmful effects of NOx are associated with respiratory diseases, the formation of ground-level ozone, and acid rain. So, the control of NOx emissions from the engine is mandatory. The emission of NOx can be further lowered in the early phases of formation by altering the engine design. Turbochargers, exhaust gas recirculation, conical-type nozzles, and toroidal-shaped combustion chambers are the most commonly recognized methods to reduce NOx emissions in diesel engines[64]. The study also recommended the above modifications in IC engines while using pyrolysis oil and biodiesel fuel in coated engines.

Conclusion

The impact of GO nanoparticles on ceramic coated diesel engine operation fuelled with a ternary blend of tyre pyrolysis oil, hemp oil biodiesel and diesel was studied. The conventional and PSZ coated diesel engines were powered with diesel, biodiesel (B20) and nano biodiesel with four different GO dosages. The use of B20 biodiesel in conventional engine decreased the BTE with increased BSFC. But the addition of GO with B20 biodiesel in a conventional engine acted as a catalyst for complete combustion. This is endorsed by the increment in BTE and the decrement in BSFC values. Furthermore, except for NOx the addition of different dosages of GO nanoparticles lowers the concentrations of CO and HC emissions. The amount of NOx increases as the temperature of the combustion chamber rises, owing to the presence of oxygenated additives in the tested fuel. The presence of 50 ppm GO in B20 biodiesel enhanced the BTE by 3.43%. With reference to diesel, the CO and HC emissions were reduced by 36% and 23.26%, respectively. Further, the NOx emission was controlled by PSZ ceramic coating in the combustion chamber parts. The use of 50 ppm GO in the coated engine increased the BTE by 4.41%. The CO and HC were further decreased by 40% and 25.58% respectively. The emission of NOx in the coated engine was observed to be similar to diesel fuel.

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