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Performance and emissions analysis on diesel engine fuelled with cashew nut shell biodiesel and pentanol blends

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Abstract−We studied the impact of blending pentanol, a next generation biofuel, with cashew nut shell biodiesel on its performance and emissions characteristics in a constant speed compression ignition engine. Our main objective was to reduce CO, HC, NO_X and smoke emission when fueled with neat cashew nut shell biodiesel and the pentanol blends. Cashew nut shell oil is a byproduct from cashew nut industry. Since it is nonedible, it can be used as a promising alternative. Conventional transesterification process was used to convert the cashew nut shell oil into cashew nut shell biodiesel. Pentanol with 98.4% purity was used as an oxygenated additive. The experiment involved three test fuels: neat cashew nut shell biodiesel (C100), Pentanol blended with cashew nut shell biodiesel by 10% volume (C90P10) and Pentanol blended with cashew nut shell biodiesel by 20% volume (C80P20). The feasibility of using neat biofuel (without adding diesel) was also investigated. Experimental work concluded that the test fuels used in this study does not require any modification in engines. In addition, the combustion of fuels was smooth and there was no physical and visible damage in the engine components when fueled with cashew nut shell biodiesel and the pentanol blends. By adding 10% and 20% of pentanol to cashew nut shell biodiesel, significant reduction in CO, HC, NO_X and smoke emission was observed. In addition, brake thermal efficiency increased marginally with slight reduction in brake specific fuel consumption.

Keywords: Pentanol, Cashew Nut Shell, Biodiesel, Performance, Emissions

INTRODUCTION

Depleting petroleum resources and increasing environmental issues leads to the search for environmental friendly renewable fuels. Further, the dangerous crisis that the world faces of late is environmental pollution [1,2]. Automobiles are the major contributor to the greenhouse emissions. The diesel engine plays a key role in transport, industry and power owing to its fuel economy and sturdiness. But unfortunately, it emits more nitrogen oxide, sulfur oxide, carbon monoxide emissions when fueled with fossil fuel. An alternate fuel has to be developed to replace the usage of fossil fuel to reduce the drawbacks associated with it [3,4].

Biodiesel derived from animal fats, vegetable oil and food waste is renewable and is established as an alternative fuel. Biodiesel consists of long chain alkyl esters. Chemically, biodiesel is made of lipids reacting with alcohol [5,6]. The main benefits of biodiesel are that it can be used in the existing diesel engine with no major modifications. The concept of using biodiesel as an alternate fuel is an active area of research. Biodiesel is used in compression ignition engines by blending it with petroleum diesel. Though biodiesel has many built-in advantages, the major troubles with it are higher viscosity and density, lower calorific value, higher NO_X emissions [7,8].

To reduce the drawbacks of neat biodiesel, various alcohols such as methanol, ethanol, butanol, pentanol and hexanol are added as an oxygenated additive. Addition of alcohol in biodiesel reduces the emissions associated with it. Alcohols can be added by many techniques, namely, fumigation, dual fuel injection, blending with biodiesel, and emulsion of biodiesel into alcohol [9,10]. Addition of alcohol in liquid fuels has gained interest in recent times. Main researchers have proved that adding alcohol to liquid fuels reduces the emissions [11,12]. It is also experimentally proved that the alcohol can be blended to diesel and biodiesel up to a range of 30% without any modification in existing compression engine. Chen et al. blended butanol in diesel fuel and found a reduction in NO_X and smoke emissions, stating effective mixing of fuel with air as a reason [13,14]. Various experimental works reported that the addition of alcohol reduces the viscosity of fuel and increases the mixing rate of fuel with air and aids improved combustion [15].

In this work, pentanol was blended with cashew nut shell biodiesel at 10 and 20% by volume. Pentanol has a greater potential to get blended with diesel and biodiesel. It has five straight chain carbons with higher energy density [16]. It has superior cetane number and better stability while blending than other alcohols. Pentanol is also an excellent renewable substitute which requires lesser energy during production. Very limited work has been conducted in the literature using pentanol in diesel engine [8,9,13]. Li

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et al. [9] investigated using pentanol and diesel blends in a constant speed diesel engine. They concluded that by adding pentanol to diesel results in significant reduction in NO_X and CO emissions at low and middle loads.

Atmanli [10] studied the impact of blending pentanol in diesel by 10%, 20% and 30% by volume in a constant speed direct injection engine. He found 8% reduction in NO_X emissions by adding 30% of pentanol to diesel. In addition, particulate emissions were reduced by 11% by adding pentanol to diesel. Gonca [13] analyzed the emission characteristics of neat pentanol using pilot injection technique and found instantaneous reduction in NO_X and smoke emissions. From the very few studies we conclude that little to no work has been carried out on blending pentanol in neat biodiesel to view its effects on emission characteristics. The other possible reason for selecting pentanol as an alcohol is the following: Pentanol is a 5-carbon straight-chain alcohol that has greater potential as a blending component with diesel fuel owing to its higher energy density, higher cetane number, better blend stability and less hygroscopic nature when compared to other widely-studied lower alcohols like ethanol, methanol and even butanol. In addition, pentanol consumes less energy for production owing to its long carbon chains. The latent heat of vaporization, density and viscosity of pentanol is also close to diesel fuel compared to other alcohols [14].

Hence in this work, three test fuels—Neat cashew nut shell biodiesel (C100), Pentanol blended with cashew nut shell biodiesel by 10% volume (C90P10) and Pentanol blended with cashew nut shell biodiesel by 20% volume (C80P20)—were fueled in a constant speed compression ignition engine. The performance and emission characteristics of all the test fuels were investigated and compared with the baseline diesel.

EXPERIMENTAL MATERIALS AND METHODS

1. Cashew Nut Shell Oil

Cashew nut shell oil is a soft honeycomb structure which contains dark reddish brown viscous liquid. Cashew nut, the fruit yielded from cashew tree [15], consists of three shells: epicarp, endocarp and Mmesocarp. The mesocarp consists of natural resin which contains cashew nut shell oil. Cashew nuts are a possible feedstock commercially used for biodiesel production and other uses. The major producing countries of cashew are Tanzania, India, Mozambique, Sri Lanka, Kenya, Madagascar, Thailand, Malaysia, Indonesia, Nigeria, Senegal, Malawi, and Angola. The cashew nut is a high value edible nut that yields two oils: one of these, found between the seed coat and the nuts, is called the cashew nut shell liquid (CNSL).

Cashew nut trees yield fruit after 15 months. The nuts are harvested and dried to reduce the moisture content and manually decorticated to remove the kernel from the shell. Then the nuts are milled to reduce diameter and expose more area for higher oil extraction. The extracted cashew nut shell oil with low boiling petroleum contains 90% of anacardic acid and about 10% of cardol [16]. The demand for cashew nut shell oil is around 10,000 ton. The estimated growth rate in demand is 7% to 8% per annum [17].

2. Pentanol

Pentanol is a colorless alcohol comprised of five carbon atoms with the molecular formula of $C_5H_{11}OH$. It is one of the 8 isomers of the amyl alcohol which forms the straight chain. Pentanol is prepared from fossil fuels by means of fractional distillation. In this work, n-pentanol of 98.4% purity was procured from Thermo-Fisher chemicals.

3. Transesterification

Transesterification is the process of exchanging the organic group of ester with an organic group of an alcohol, which are catalyzed by addition of an acid or base catalyst. Transesterification is performed to convert the cashew nut shell oil into cashew nut shell biodiesel. For transesterification, methanol and potassium hydroxide are mixed at a proportion of 250 ml and 150 ml, respectively. The mixture obtained is called a methoxide. In the second step the methoxide mixture is mixed with 500 ml of cashew nut shell oil. The mixture is then heated to 65 °C for 60 minutes. The mixture is kept undisturbed for the separation of glycerol and cashew nut shell biodiesel. As a result, two layers are formed. The upper layer is a pure cashew nut shell biodiesel and the lower layer is a glycerol. A heavy lower layer is removed by gravity separation method. The properties of cashew nut shell biodiesel were calculated by adapting the ASTM standards and are listed in Table 1.

4. Engine Setup

We used a single cylinder, four stroke air cooled diesel engine. The engine was equipped with a rated power of 4.2 kW. Compression ratio of the engine was 17.5 : 1. Engine had a bore diameter of 87.5 mm and a stroke length of about 110 mm. Speed of the engine was maintained constant at the rate of 1,300 rpm. The specification of engine is listed in Table 2. AVL 444 di gas analyzer was used

Table 1. Properties of tested fuels

Properties	C100	C90P10	C80P20	Pentanol	Diesel	Method
Density @ 18 °C (gm/cc)	0.8829	0.8662	0.8482	0.8148	0.8200	ASTM D4052
Kinematic Viscosity @ 35 °C (mm^2/s)	4.30	3.97	3.76	2.89	2.5	ASTM D445
Calorific Value (kJ/kg)	38108	38567	38812	32160	42957	ASTM D240
Latent heat of vaporization (kJ/kg)	685.1	541.2	448.6	308.5	256	-
Cetane Index (CI)	52	54	56	20	47	ASTM D976
Flash point in °C	140	137	136	49	50	ASTM D93
C (% wt)	77.2	77.6	76	68.18	-	ASTM D5291
H (% wt)	11.4	11.4	11	13.64	-	ASTM D5291
O (% wt)	11.4	11	13	18.18	-	-

Table 2. Specification of experimental setup

Make	Kirloskar
Stroke	4
Cylinder	Single
Rated power	4.2 KW
Rated speed	1800 rpm
Bore diameter (D)	87.5 mm
Stroke (L)	110 mm
Compression ratio	17 : 1

Table 3. Gas analyzer and smoke meter accuracy details

Model of gas analyzer	AVL 444 di gas analyzer range	
Pollutant	Range	Accuracy
CO	0-10%	0.01%
HC	0-20000	±10 ppm
NOx	0-5000 ppm	±10 ppm
Smoke	AVL 437 Smoke meter	0.01%

Table 4. Uncertainty of calculated parameters

Emissions and performance parameters	Uncertainty	
Emissions	Absolute (ppm)	Relative (%)
CO	±0.004	±6
HC	±0.89	±3
NOx	±2	±0.1
Smoke	±0.03	±4
Performance	Absolute	Relative
BTE	±0.01%	±1
BSFC	±0.02 (kg/h)	±2%

to measure the pollutants in the exhaust gas. AVL 437 Smoke meter was used to measure the smoke opacity of exhaust gas. Technical specification of gas analyzer and smoke meter is listed in Table 3. Calculations for uncertainty for BTE, BSFC, CO, HC, NO_X and smoke emission were calculated by the technique suggested by Moffat [18]. Table 4 illustrates the uncertainty of calculated parameters.

5. Test Fuels and Testing Conditions

We tested four fuels: neat cashew nut shell biodiesel (C100), 90% of cashew nut shell biodiesel and 10% of pentanol on volume basis (C90P10), 80% of cashew nut shell biodiesel and 20% of pentanol (C80P20) on volume basis and neat diesel for fuel properties, adapting the standards of ASTM. The properties of each sample are shown in the Table 3. Also found was that by blending pentanol with biodiesel resulted in no separation of phases and found miscible even after 72 hours. To obtain homogeneity, the blends were mixed vigorously using ultrasound apparatus just prior to the fueling. The experimental work was conducted in ambient conditions and the speed of the engine was maintained at 1,800 rpm. Experiments were repeated three times and the average of these values was taken for further analysis.

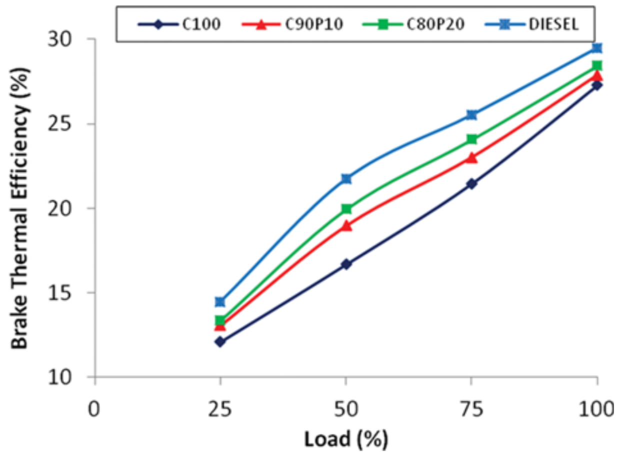

Fig. 1. Variation of brake thermal efficiency with load.

RESULTS AND DISCUSSION

The results on the above-mentioned experiments were discussed on the basis of their performance and emission characteristics for different proportions of cashew nut shell biodiesel with pentanol.

1. Brake Thermal Efficiency (BTE)

BTE defines the amount of useful energy obtained by burning a fuel. Change in BTE with load for C100, C90P10, C80P20 and diesel is shown in Fig. 1. It is observed that the efficiency of C100, C90P10, and C80P20 is lesser than diesel at all loads. This is due to inferior heating value of cashew nut shell and pentanol blends [19]. It is also obvious that the efficiency of all fuels increases with load. With increase in load the fuel supplied to maintain power is more, which sequentially results in higher BTE.

It is also prominent that BTE for cashew nut shell and pentanol blends (C90P10 and C80P20) increases with increase in pentanol content. BTE for C90P10 and C80P20 is higher than C100 by 0.61 and 1.17%, respectively, at full load conditions. This is due to higher energy density of pentanol, which improves the combustion rate and result in higher BTE [20]. Further, the viscosity of C90P10 and C80P20 is lower than C100. Due to lower viscosity, the atomization and vaporization of fuel is enhanced and leads to higher

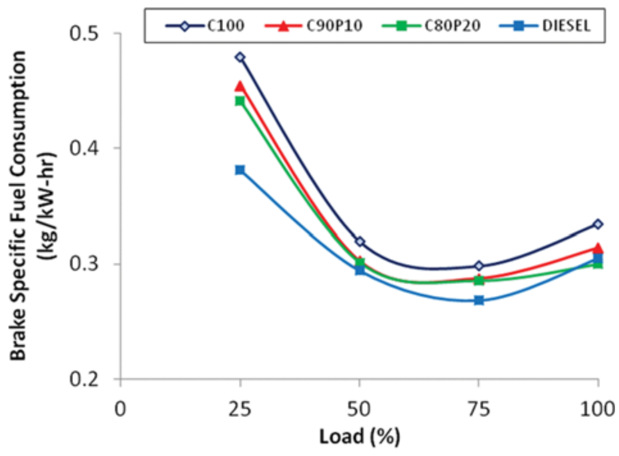

Fig. 2. Variation of BSFC with load.

BTE. BTE at full load conditions for C100, C90P10, C80P20 and Diesel was 27.27%, 27.88%, 28.44 and 29.48% respectively.

2. Brake Specific Fuel Consumption (BSFC)

BSFC confers the quantity of fuel required to produce a unit of power output. Fig. 2 shows the change in BSFC with load for C100, C90P10, C80P20 and diesel. BSFC increases with load for all the fuels. At higher load conditions the requirement of fuel to sustain the steady power output is on the higher side, which causes higher BSFC with loads [19]. BSFC for diesel is least among all test fuels. This is in consequence of higher calorific value leading to lesser requirement of fuel [20].

BSFC for C90P10 and C80P20 at full load is inferior to C100 by 0.0732 kg/kWh and 0.1038 kg/kWh, respectively. BSFC decreases with increase in pentanol content, owing to reduction in viscosity of fuel with addition of pentanol [13]. Fuel with lesser viscosity aids the combustion as it mixes effectively with air in the cylinder during combustion. In addition, the energy density of fuel mixtures increases with addition of pentanol, which subsequently reduces BSFC for C90P10 and C80P20 at all loads. BSFC at full load conditions for C100, C90P10, C80P20 and diesel is 1.431 kg/kWh, 1.358 kg/kWh, 1.327 kg/kWh and 1.248 kg/kWh, respectively.

3. Carbon Monoxide [CO]

Carbon monoxide is a colorless and odorless poisonous gas formed due to incomplete burning of fuels. Change in carbon monoxide emissions with load for C100, C90P10, C80P20 and diesel is shown in Fig. 3. CO emissions from biofuels are relatively less than diesel at all load. This is due to ample availability of oxygen in cashew shell biodiesel, pentanol and its blends. It is also found that the CO emission reduces with increase in pentanol content. By adding 100 and 200 ml of pentanol to cashew nut shell biodiesel, 11.1% and 12.3% of CO emissions is reduced. The likely reason for reduced CO emissions for C90P10, C80P20 is the improved combustion rate. Pentanol acts as additional oxygen buffer which stores and releases during combustion. The other possible reason for reduction of CO emissions is owing to reduced viscosity of C90P10, C80P20. Fuel with lesser viscosity aids better evaporation of fuel with air and results in improved combustion and lesser CO emissions. This result is in conformation with the experimental work done by [21]. CO emissions at full load conditions for C100, C90P10, C80P20 and Diesel are 3.618 g/kWh, 2.063 g/kWh, 1.821 g/kWh and 3.774 g/kWh, respectively.

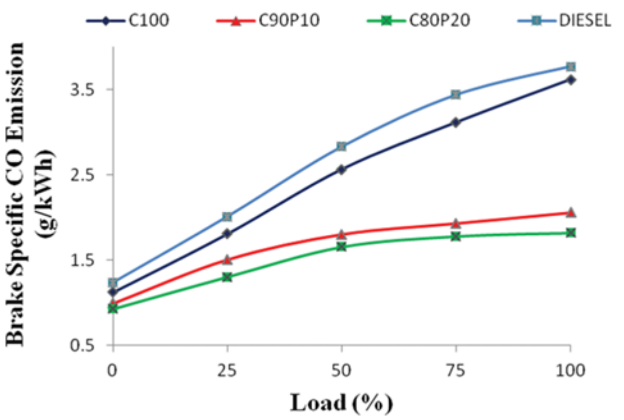

Fig. 3. Variation of CO with load.

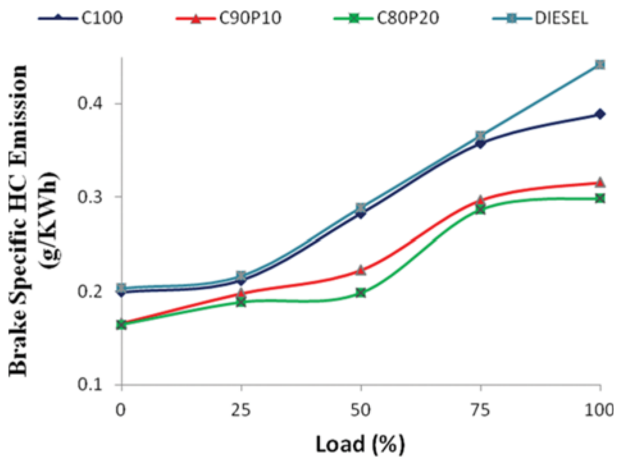

Fig. 4. Variation of HC with load.

4. Hydrocarbons [HC]

Change in hydrocarbon emissions with load for C100, C90P10, C80P20 and diesel is shown in Fig. 4. HC emissions from biodiesel and its pentanol blends are significantly lower than diesel at all load. This is due to the presence of excess oxygen in the fuel. Further, this is also due to the higher cetane number of C100 and pentanol blends, which results in the reduction of emissions of hydrocarbons. Moreover, the higher temperature of the fuel causes less condensation of hydrocarbons, which improves the rate of combustion and reduces the formation of unburned hydrocarbons [22].

It is also inferred that the HC emission increases with load for all the fuels. At higher load the mixture is too rich to meet out the power, which in turn results in higher HC emission [23]. The HC emission drops considerably at all loads with addition of pentanol. Increasing the pentanol content further reduces the HC emission of C100. This is due to reduced viscosity of cashew nut shell biodiesel with addition of pentanol. The viscosity of C90P10 and C80P20 is reduced by 3.6% and 4.8% when compared to C100. Thus, the mixing rate of fuel with air in the cylinder is significantly improved. This results in improved combustion and lesser HC emission. Further, the vaporization of pentanol is faster, which in turn increases the mixing rate of fuel and air. HC emissions at full load conditions for C100, C90P10, C80P20 and diesel are 0.389 g/kWh, 0.316 g/kWh, 0.299 g/kWh and 0.442 g/kWh, respectively.

5. Oxides of Nitrogen [NO_X]

When nitrogen and oxygen in the cylinder are exposed to higher elevated temperature, NO_X are formed. Formation of NO_X is directly proportional to the temperature present in the combustion chamber. NO_X can be lowered by reducing the combustion temperature. Change in NO_X emissions with respect to load for C100, C90P10, C80P20 and diesel is shown in Fig. 5. It is observed that the NO_X emission is higher for C100, C90P10, and C80P20 than diesel at all load. This is due to higher oxygen content in the biodiesel and pentanol blends, which promotes combustion and increases the combustion chamber temperature [23].

NO_X emissions increase with load for all test fuels. It is evident that at higher load, the temperature of combustion chamber will be higher, which results in increases in NO_X emissions [24]. In

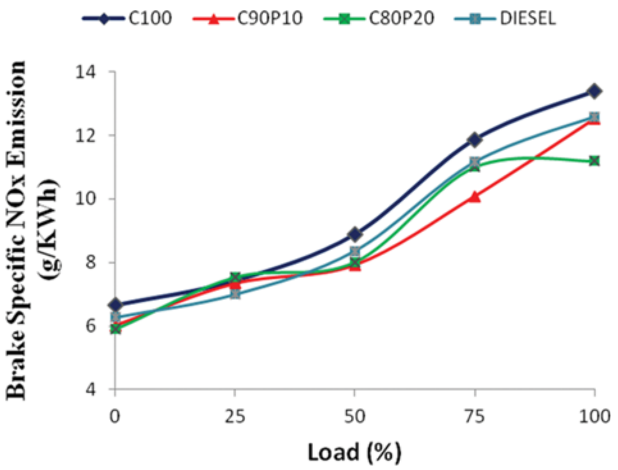

Fig. 5. Variation of NO_X with load.

addition, this is due to the rich fuel mixture supplied at high load condition. By adding 10 and 20% (volume basis) of pentanol to cashew nut shell biodiesel, the NO_X emissions are reduced by 6.1% and 7.7%. This is due to lower cylinder temperature because of lower calorific value and higher latent heat of vaporization of pentanol in Cashew nut shell biodiesel. In addition, it is also due to reduction in viscosity of cashew nut shell biodiesel by incorporating pentanol. Lower viscosity of cashew nut shell biodiesel and pentanol blends improves the rate of mixing of air and fuel, leading to improved combustion and reducing the temperature in the combustion chamber [25]. This result is in conformation with the experimental work done by [20]. NO_X emissions at full load conditions for C100, C90P10, C80P20 and diesel are 13.378 g/kWh, 12.517 g/kWh, 11.193 g/kWh and 12.588 g/kWh, respectively.

6. Smoke Intensity

Smoke is a collection of airborne liquid and solid particulates and gases emitted during combustion. BSU is the Bosch smoke meter unit. Smoke is measured by measurement of light absorbed (opacity) in a defined specific length of column of exhaust gas. The smoke meters employing this principle are known as light extinction type of smoke meter such as AVL smoke meters. Smoke has also been measured by filtering a fixed volume of exhaust gases

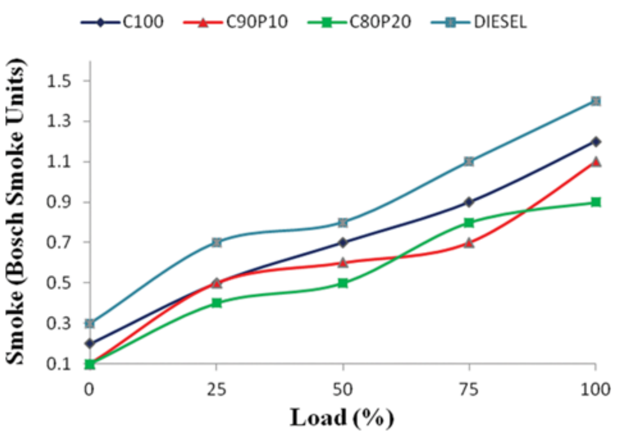

Fig. 6. Variation of Smoke with load.

through a filter paper and the smoke stain thus formed is evaluated on a grayness scale by a light reflectance meter (Bosch smoke meter). Change in smoke emissions with load for C100, C90P10, C80P20 and diesel is shown in Fig. 6. From the figure it is inferred that the smoke emission for cashew shell biodiesel and pentanol blends is less than diesel at all load. This is owing to inbuilt excess oxygen content in biofuels [26,27]. Also, the smoke emission increases linearly with increase in load for all the tested fuels at lower load and increases significantly at higher load. At higher load or loads, the quantity of fuel required to maintain a constant power output is more, which results in higher smoke emissions. Thus, it is because of the burning of additional fuel to generate higher output power at high engine loads [28,29].

By adding 10 and 20% (Volume basis) of pentanol to cashew nut shell biodiesel, the smoke emission is reduced by 3.1% and 3.4%. This is due to higher oxygen availability in pentanol, which improves the combustion rate. The other possible reason is due to the presence of oxygen atoms in pentanol which gets bonded to hydroxyl group and reduces formation of soot and Smoke emissions. Smoke emissions at full load conditions for C100, C90P10, C80P20 and diesel are 1.2, 1.1, 0.9 and 1.4 BSU, respectively.

CONCLUSION

The impact of adding pentanol to cashew nut shell biodiesel on performance and emission characteristics was compared with petroleum diesel. The following are the observations derived from this experimental work

- Cashew nut shell biodiesel can be used as a fuel without any modification in existing CI engine.
- Blending of Cashew nut shell biodiesel with pentanol resulted in no separation of phases and found miscible even after 72 hours.
- BTE for cashew nut shell (C90P10 and C80P20) increased marginally with increase in pentanol content.
- BSFC for cashew nut shell (C90P10 and C80P20) decreased significantly with inclusion of pentanol.
- CO, HC, Smoke emissions of C100 and its pentanol blends were lower than diesel at all loads.
- CO emissions for C100 dropped by 11.1% and 12.3% when blended with pentanol of 10 and 20% by volume.
- HC emissions were reduced by 3.6% and 4.8% for cashew nut shell biodiesel/Pentanol blends at all loads.
- NO_X emissions for C100 were 6.27% higher than diesel at loads. However, by appending pentanol to cashew nut shell biodiesel, NO_X emissions were reduced by 6.1% and 7.7% for at all loads.
- Smoke opacity was reduced for cashew nut shell biodiesel/Pentanol blends by 3.1% and 3.4% when compared to neat C100.

n-Pentanol is a promising additive which can be used in existing CI engine and has the ability to provide energy security as well as safety towards the environment.

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