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Feasibility of blending karanja vegetable oil in petro-diesel and utilization in a direct injection diesel engine

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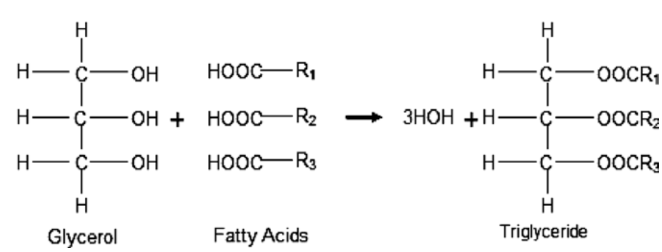
ABSTRACT

Karanja (*Pongamia pinnata*) oil, a non-edible high viscosity (27.84 cSt at 40 °C) straight vegetable oil, was blended with conventional diesel in various proportions to evaluate the performance and emission characteristics of a single cylinder direct injection constant speed diesel engine. Diesel and karanja oil fuel blends (5%, 10%, 15%, and 20%) were used to conduct short-term engine performance and emission tests at varying loads (0%, 20%, 40%, 60%, 80%, and 100%). Tests were carried out over the entire range of engine operation and engine performance parameters such as fuel consumption, thermal efficiency, exhaust gas temperature, and exhaust emissions (smoke, CO, CO_2, HC, NO_x, and O_2) were recorded. The brake specific energy consumption (BSEC), brake thermal efficiency (BTE), and exhaust emissions were evaluated to determine the optimum fuel blend. Higher BSEC was observed at full load for neat petro-diesel. A fuel blend of 10% karanja oil (KVO10) showed higher BTE at a 60% load. Similarly, the overall emission characteristics were found to be best for the case of KVO10 over the entire range of engine operation.

1. Introduction

The Earth's limited reserves of fossil fuel have been a matter of global concern as these are under threat of depletion due to over-exploitation. Deteriorating environmental conditions have become an issue of ever increasing world-wide public concern. Currently, the combustion of fossil fuels is the dominant global source of CO_2 emissions. There are efforts around the globe to protect the environment from further deterioration. These factors have led to an innovative global search for renewable sources of energy. Consequently, some alternatives, particularly renewable energy options have been discovered and explored. Several feasible technologies in the area of solar, wind, and biomass have been discovered, tested, perfected, and are increasing in popularity. Although majority of the renewable energy technologies are more eco-friendly than conventional energy options, their adoption is very slow because of various factors such as economic constraints, lack of supply, and technical know-how of users, etc. Further the use of these technologies is still limited primarily to stationary operations, mainly due to technological limitations and poor economics.

Straight vegetable oils (SVOs) have been tested in diesel engines. The relatively high viscosities (11–17 times higher than diesel) of these oils cause problems such as coking of the injectors, oil ring sticking, and thickening of the lubricating oil. This high viscosity results from the high molar masses of the oils and the presence of unsaturated fatty acids. At high temperatures there can be certain problems due to polymerization of unsaturated fatty acids. This occurs when cross-linking starts to occur between molecules, causing the formation of very large agglomerations and consequent gumming. Commercial diesel chemical composition is the mixture of alkanes, alkenes, alkynes, and small traces of sulphur. Diesel has more number of double bonds than vegetable oils. If we study the structure of a typical triglyceride (vegetable oil), there are only three double bonds as shown below.



The use of SVOs as a fuel for compression ignition engines is restricted by certain unfavorable properties, particularly their viscosity. The higher viscosities of SVOs cause poor fuel atomization, which leads to incomplete fuel combustion and carbon deposition on the injector and valve seat, resulting in serious engine fouling. When direct injection engines are run with SVOs, injectors become choked after a few hours. This choking also leads to poor fuel

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atomization and incomplete combustion. Due to incomplete combustion, partially burnt vegetable oil runs down the cylinder walls and dilutes the lubricating oil.

Despite the above-mentioned limitations of SVOs, it could be possible to use them for certain low-end applications, such as energizing the single cylinder diesel engines which are widely used in rural/agricultural applications. However, this would call for an additional fuel supply, since starting and stopping of the engine has to be done on diesel only to avoid deposition of neat oil on various engine parts, which would affect cold starting and performance of the engine. Also, the exhaust heat of the engine could be utilized to reduce the viscosity of the intake oil through an appropriate heat exchange device. Experiments conducted at various institutes have concluded that engines running on neat SVOs with the integration of above-mentioned additional sub-systems could perform effectively for around 250 h [1]. Thus, it may be possible to work out an optimum maintenance schedule suitable for engines running on SVOs. However, the additional sub-systems seriously hamper the feasibility of SVO-based engine systems for rural areas, as they require elaborate care in running the engine. This calls for exploring various blending ratios of SVOs in mineral diesel such that an unmodified engine can be run without hampering its performance.

It is reported in [1] that compared to commercial diesel fuel, vegetable oils are much more viscous, and reactive to excess oxygen, and have higher cloud points. The viscosities of vegetable oils were found to range from 10 to 20 times greater than that of diesel fuel. Increased carbon chain length and a reduced number of double bonds were associated with increased oil viscosity, cetane rating and gross heat content. It was found that, except for castor oil, there was little difference between the gross heat content of any of the vegetable oils. Heat contents were approximately 88% of that of diesel. Transesterification of vegetable oil to its methyl ester reduces its molecular weight and viscosity and increases its cetane number [2]. The current status of vegetable oils as a possible substitute for diesel fuel has been reviewed [3]. The most predominant oil bearing crops considered as fuel substitutes are sunflower, safflower, soybean, cotton, winter rape, canola, and peanut. Transesterification, oil processing, storage, filtration, and engine test aspects have been further discussed.

The performance of a direct injection, three-cylinder, 2600 series Ford tractor engine with 1:3 (v/v) blends of soybean oil and sunflower oil with diesel fuel for 200 h were evaluated [4]. It was concluded after the 200 h test that as far as power output, thermal efficiency, and lubricating oil data were concerned, the 1:3(v/v) blends of soybean oil and sunflower oil with diesel fuel performed satisfactorily. However, when the general condition of the combustion chamber and fuel injectors after 200 h of operation were considered, the performance was not satisfactory. All combustion chamber parts and injector tips were coated with carbon deposits. Rao and Goapalkrishnan [5] evaluated the performance of a diesel engine with vegetable oils and methyl esters of karanja oil, soybean oil, sunflower oil, and neem oil. The brake thermal efficiency (BTE) of the engine was reported to be less with vegetable oils and methyl esters of different vegetable oils as compared to diesel. The exhaust smoke intensity was also found to be more with vegetable oils and their methyl esters compared to diesel fuel. It was observed that the combustion delay for all the vegetable oils used was higher than that of diesel by 1–2 degrees CA at full load and the highest ignition delay was observed with neem. However, the ignition delay was shorter for the methyl esters compared to vegetable oils.

It has also been reported [6] that the transesterification process has been used world-wide as an effective means of bio-diesel production and viscosity reduction for vegetable oils. It is the process of converting a triglyceride with an alcohol in the presence of a catalyst to produce glycerol and fatty acid esters. Temperature, catalyst type, concentration ratio of alcohol to fuel, and stirring rate influence the transesterification process to a great extent. The observed major differences between [7] diesel fuel and vegetable oil that vegetable oil possesses significantly higher viscosities, moderately high densities, lower heating values, the rise in the stochiometric air–fuel ratio due to the presence of molecular oxygen, and the possibility of thermal cracking at the temperatures encountered by the fuel spray in naturally aspirated diesel engines (in the case of vegetable oil). These differences contributing to poor atomization, coking tendencies, carbon deposits, and wear were generally experienced and adversely affected the durability of the engine.

The high viscosities of vegetable oils cause problems in the injection process leading to an increase in smoke levels, and the low volatility of the vegetable oils results in oil sticking to the injector or cylinder walls, causing deposit formation which interferes with the combustion process [8]. Bari et al. [9] conducted short-term performance tests using crude palm oil (CPO) as a fuel for a diesel engine and CPO showed to be a suitable substitute for diesel fuel. However, prolonged use of CPO as a fuel caused the engine performance to deteriorate. After 500 h of cumulative running with CPO, maximum power was reduced by about 20% and the minimum brake specific fuel consumption (BSFC) was increased by about 26%. Examination of the different parts after the engine was dismantled revealed heavy carbon deposits in the combustion chamber; traces of wear on the piston rings; the plunger and the delivery valve of the injection pump; slight scuffing of the cylinder liner; and uneven spray from the nozzles. Tests revealed that the main reason for engine performance deterioration was 'valve sticking', caused by carbon deposits on the valve seats and stems. This resulted in leakage during the compression and power strokes and a reduced effective compression ratio, which subsequently affected the power and fuel economy.

India has vast amounts of wasteland that government agencies and other non-government organizations are using for cultivation of non-edible oil seeds, fire, and fuel wood species for economic as well as environmental benefits. Among the non-edible oil species, karanja, neem, Jatropha, and Mahua are the prominent trees. The non-edible oil is being used in the soap and pharmaceutical industries, but due to the dark colour and odour of karanja oil, it is less preferable compared to other non-edible oil species. Hence, karanja oil can be obtained easily for engine applications.

This experimental investigation, carried out in the "Engines and Unconventional Fuels Laboratory" of the Indian Institute of Technology, Delhi, aims to identify key characteristics of karanja oil blends that affect the performance of engines running on these fuels. After identifying performance and emission parameters, the fuel obtained by blending karanja vegetable oil (KVO) with mineral diesel in a pre-defined percentage was characterized and its performance and emission characteristics were compared vis-à-vis petro-diesel. The experiments were conducted on a single-cylinder constant speed (1500 rpm) diesel engine having compression ratio 17.5, as widely used in rural/agricultural applications. The fuels studied were mineral diesel and blends of KVO with mineral diesel.

2. Experimental techniques

In order to achieve the objectives outlined above, we reviewed the available literature to determine the current status of understanding on the subject, and identify important issues related to this experiment. The literature review also helped in identifying the specific activities to be carried out. To analyze the suitability of the fuel blends, it was necessary to identify properties of the fuels as well as various performance and emission parameters of the engine. The following methodology was adopted for experimental investigations.

2.1. Karanja vegetable oil (KVO) characterization

The physico-chemical properties of karanja oil, neat petro-diesel, KVO 5 (5% v/v of KVO in diesel), KVO 10, KVO 15, and KVO 20 were determined. The properties were measured as per ASTM standard procedures and the results are discussed in Section 3.1. The density of the liquid fuel was determined by pyknometer. This is an accurate method for the determination of the density of a liquid. The kinematic viscosity of the test fuels was determined at various temperatures by using a constant temperature bath viscometer and a stopwatch. This apparatus works by measuring the time for gravity flow of a fixed volume of a test fuel through a specified jet made through a piece of agate. A bomb calorimeter was used to measure the amount of heat generated when a known amount of matter was burnt in a sealed chamber in an atmosphere of pure oxygen gas. It is a simple and inexpensive yet accurate method for determination of heat of combustion, i.e., calorific value. Pensky Marten's flash point apparatus was used to the determine flash and fire points. Flash point measures the response of the sample to heat and flame under controlled laboratory conditions. It is only one of a number of properties which must be considered in assessing the overall flammability of a material. The cloud and pour points of the fuel oil sample were determined by a pour and cloud point apparatus. This apparatus was equipped with a refrigeration bath that can be operated from above room temperature to below −30 °C.

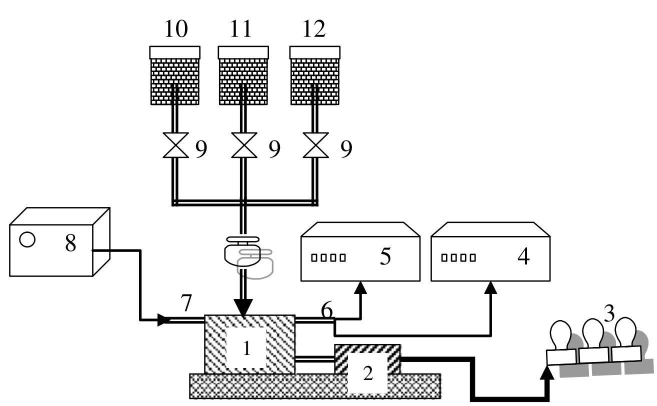
2.2. Performance testing

Short-term engine performance tests were carried out on a small size water-cooled diesel engine (Table 1) with neat diesel oil, KVO 5, KVO 10, KVO 15, and KVO 20. The objective of such a study was to compare the suitability of these fuels for engine applications. Engine systems equipped with experimental technologies (Fig. 1) to evaluate performance parameters such as brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC), brake mean effective pressure (BMEP), brake thermal efficiency (BTE), and volumetric efficiency.

The dynamometer used to load the engine was comprised of a shunt wound AC generator and a load bank. Pressure in the inlet manifold was measured by a normal U-tube manometer. Airflow was measured by means of a viscous flow meter. Thermocouples were installed to monitor gas temperatures at the inlet and outlet ducts as well as the cylinder wall temperatures. The fuel system

Table 1
Physico-chemical properties of test fuels

Properties	Fuel blend					
	Diesel	KVO 100 (neat KVO)	KVO 5	KVO 10	KVO 15	KVO 20
Density (kg/m^3)	850	913	859	867	873	878
CV (kJ/kg)	44,019	37,304	43,681	43,349	43,019	42,688
Viscosity (cSt) at 40 °C	2.87	27.84	4.33	5.79	7.03	8.92
Flash point (°C)	76	205	84	93	102	114
Fire point (°C)	82	209	89	99	110	123
Cloud point (°C)	6.5	13.2	7.3	8.1	9.4	10.2
Pour point (°C)	3.1	6.4	3.6	3.9	4.2	4.4



1. Single cylinder 4-stroke diesel engine, 6 kW	7. Intake manifold
2. Alternator	8. Air drum
3. Lamp load	9. Control valve
4. Gas Analyzer	10. Fuel Tank for neat diesel
5. Smokemeter	11. Fuel Tank for blends of diesel and KVO
6. Exhaust manifold	12. Fuel Tank for neat KVO

Fig. 1. Schematic diagram of experimental set up for engine test rig.

was modified by adding an additional filter and a three-way, hand operated, two position directional control valve which allowed rapid switching between the diesel fuel used as a standard and the test fuels. Fuel was fed to the injector pump under gravity and the volumetric flow rate was measured with a 50 cm^3-graduated burette and stopwatch. The speed was also checked with an infrared-type digital tachometer. The experiments were carried out using test fuel blends at different engine load conditions from 0% to 100% in approximate steps of 20%.

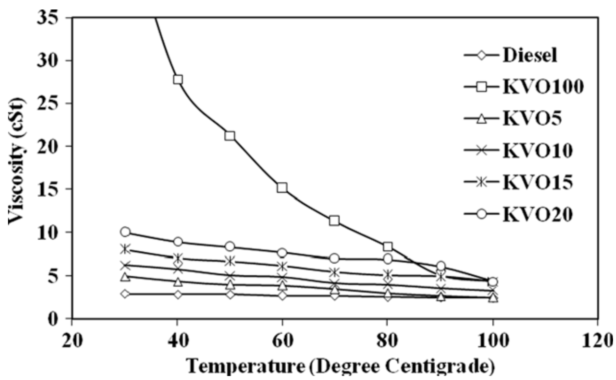


Fig. 2. Effect of temperature on viscosity of karanja oil and its blends with diesel.

To evaluate the performance parameters, some observations like engine shaft speed, generator output, fuel consumption rate, airflow rate, temperature of engine cooling water, and engine exhaust gases were measured. The performance parameters were calculated from the fundamental relations between these measurements while varying the load on the engine from 0% to 100% in approximate steps of 20%.

2.3. Emission testing

Engine emissions like carbon monoxide, carbon dioxide, nitrogen oxides, oxygen, smoke, and unburned hydrocarbon were measured with an AVL five gas analyser and a smoke-meter. The sensor of the analyser was exposed to the engine exhaust and the observations were recorded. The measured emissions were analyzed and interpreted graphically as shown in Fig. 5–8.

3. Results and discussion

The results obtained from the comprehensive experimental investigations are analyzed and described below. They include physico-chemical properties of the mineral diesel, neat KVO and

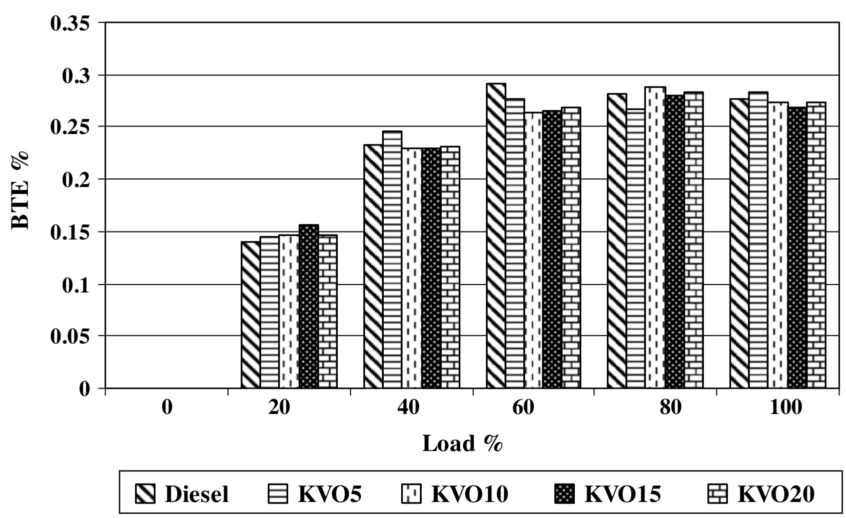


Fig. 3. Comparative plot of brake thermal efficiency vs. % load.

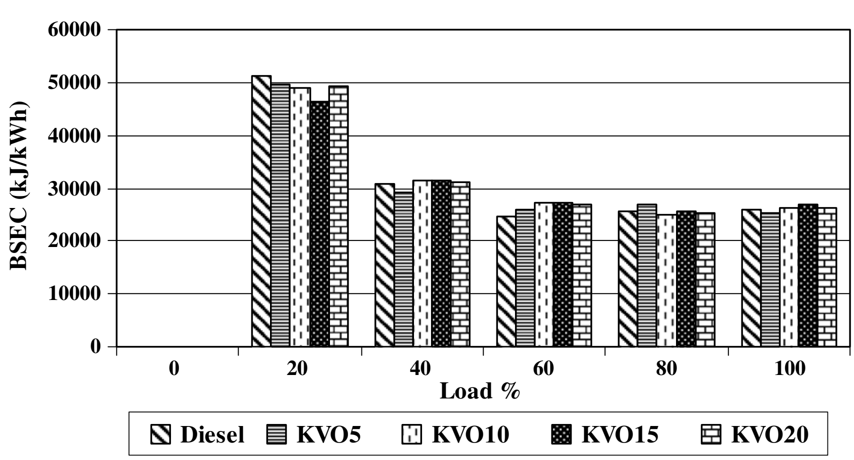


Fig. 4. Comparative plot of brake specific energy consumption vs. % load.

their blends in 5% steps of KVO up to KVO 20. Engine performance and emission characteristics operating with these different fuels were also analyzed and described for further investigation.

3.1. Fuel properties

The physico-chemical properties of the karanja oil, neat petro-diesel, KVO 5, KVO 10, KVO 15, and KVO 20 were determined and the results are shown in Table 1. From the table it can be seen that the chemical characteristics of neat karanja oil were found to be as follows: kinematic viscosity of 27.84 cSt at 40 °C (which is around 10 times more than that of diesel), flash point of 205 °C, cloud point of 13.2 °C, pour point of 6.4 °C, and acid value of 5.06 mg KOH/gm. The KVO was taken directly for blending with mineral diesel without any chemical modifications such as neutralization or degumming in these experiments.

The kinematic viscosity of karanja oil reduced considerably with increases in temperature to 100 °C as shown in Fig. 2. The viscosity of the KVO 100 changes significantly with temperature due to the poor thermal stability and presence of less number of double bond. The bond length also changes with temperature for organic structure. In case of diesel fuel, the thermal stability is better than vegetable oil due to absence of oxygen in diesel. Therefore, the viscosity remains constant at high temperature for diesel fuel. The kinematic viscosity of fuel blends with 5%, 10%, 15%, 20% and neat karanja oil was 2.49, 3.31, 4.35, 4.36 and 4.37, respectively, at 100 °C. The viscosity values were 1.84, 2.48, 2.68, 4.56 and 23.47 cSt, higher than that of fuel blends at 40 °C, respectively. This indicates the significant effect of temperature on the viscosity of karanja oil with diesel. The kinematic viscosity of 5% karanja oil with diesel and neat karanja oil at 90 °C and 100 °C was within the limits for diesel.

3.2. Performance studies

Short-term engine tests were conducted using specified blends with diesel in order to study their effect on engine performance parameters at various loads of 20%, 40%, 60%, 80%, and 100%. Based on the fundamental definitions, calculations were made and the CI engine performance parameters such as BSFC, BSEC, BMEP, BTE,

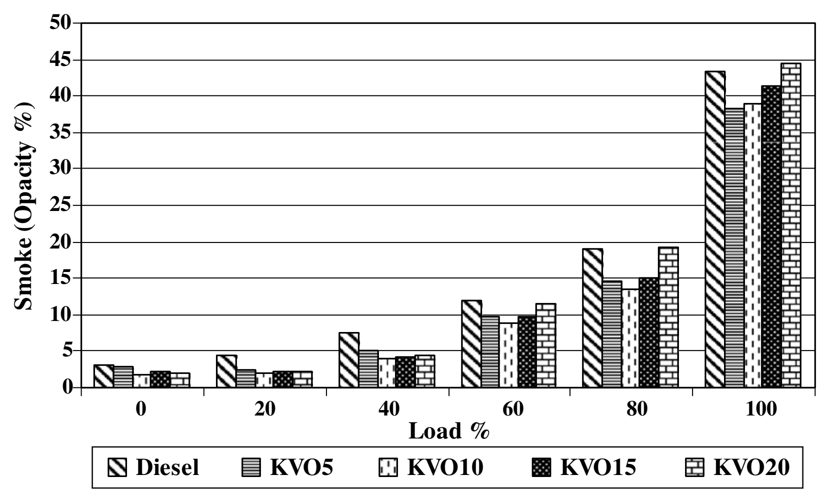


Fig. 5. Smoke (opacity%) at different loads.

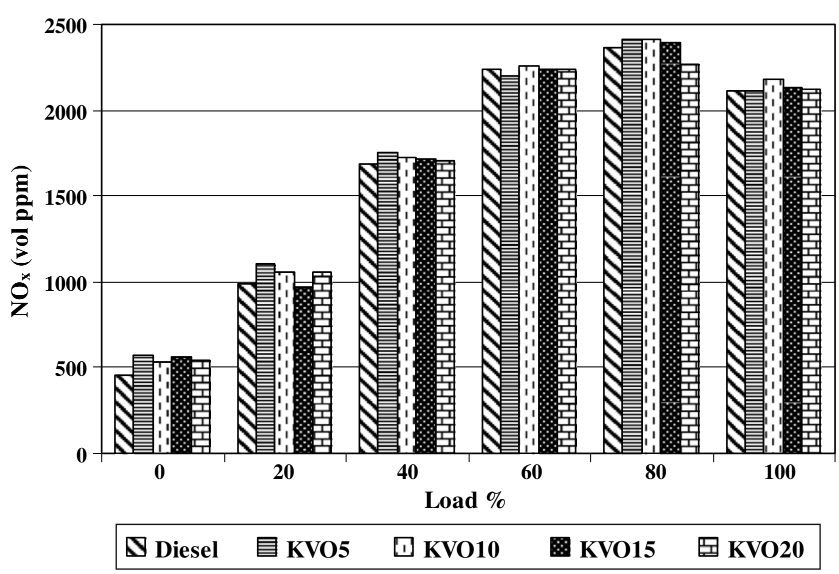


Fig. 6. NO_x emission at different loads.

and volumetric efficiency for petroleum based diesel, KVO5, KVO10, KVO15, and KVO20 were recorded. These are analyzed and represented graphically in Figs. 3 and 4.

The trends of BTE for KVO blends improved slightly, especially at lower loads as compared to neat petroleum based diesel fuel, as shown in Fig. 3. This could possibly be due to better combustion and the additional lubricity of KVO. The BTE curve in case of KVO10 was higher at full load as compared to mineral diesel. BTE was reduced at higher loads for all other blends as compared to mineral diesel. This may be due to the poor combustion of blended fuel because of the high viscosity of blended KVO with mineral diesel.

When corresponding observations of BSFC at different loads were interpreted graphically, the trends of the BSFC increased slightly for all blends as compared to neat petro-diesel. This may be due to the low calorific value of KVO and its blends with mineral diesel. However, BSFC is not a very reliable parameter to compare fuel blends as the calorific value and the density of the blends follow a slightly different trend. Hence BSEC is a more reliable parameter for comparison. Therefore, this parameter is also used in this study to compare volumetric consumption of all of the test fuels. It was observed that BSEC was slightly higher for neat diesel at lower loads and remained the same at higher loads for KVO5, KVO10, KVO15, and KVO20 (Fig. 4). Higher BSEC for diesel fuel is due to the higher calorific value of diesel.

3.3. Emission studies

The engine emissions were measured with an AVL-5 gas analyser (for NO_x, HC, CO, CO_2, and O_2) and a smoke-meter. The measured emissions are shown graphically in Figs. 5–8. The smoke was significantly reduced for all blends as compared to neat petroleum based diesel fuel (Fig. 5). This was due to the complete and stable combustion of the blend, which contained a greater number of oxygen atoms. The opacity was least for the case of KVO10 at up to a 80% load and hence this blend is recommended for long-term application in diesel engines.

For diesel fuel, the most important pollutants are smoke and NO_x, hence the optimum KVO concentration is also subject to evaluation for NO_x emissions. From the NO_x curves presented in Fig. 6, two important observations were made. First, NO_x emissions were a direct function of engine loading. This was expected because with increasing load the temperature of the combustion chamber in-

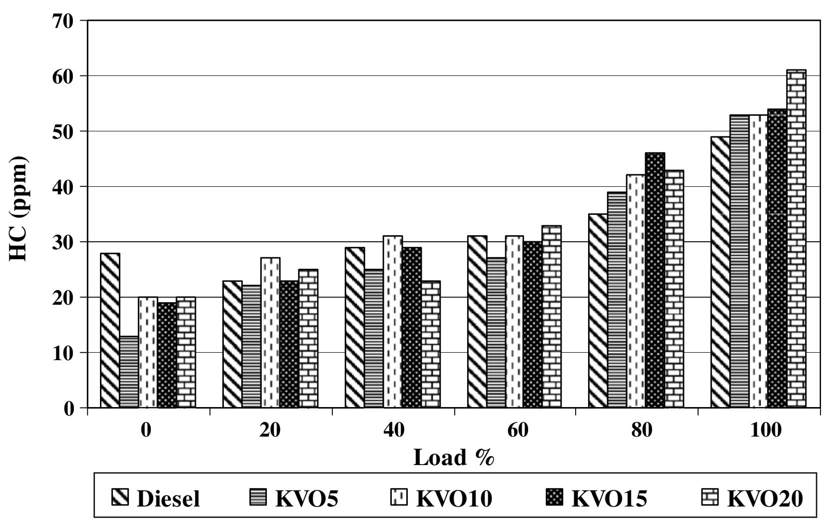


Fig. 7. Emission of unburnt hydrocarbons at different loads.

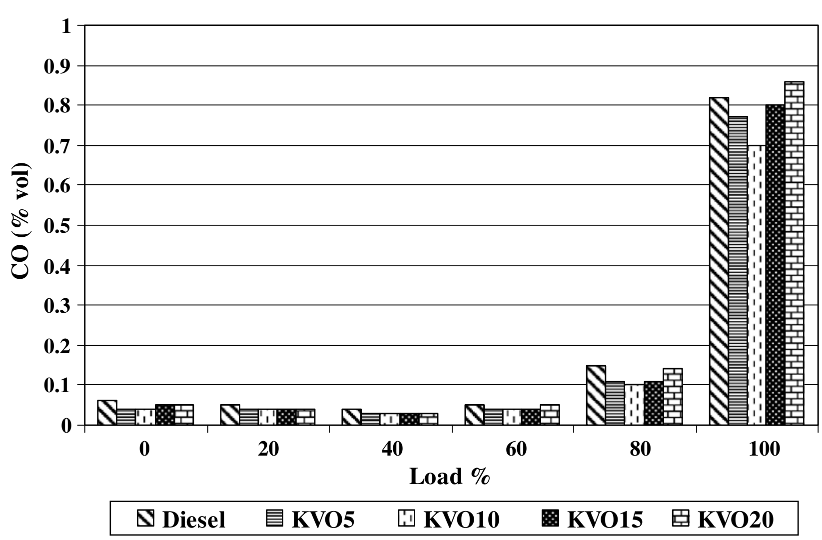


Fig. 8. Carbon monoxide emission at different loads.

creased and NO_x formation is strongly temperature dependent phenomenon. The second important observation was that NO_x emissions for the case of KVO blends were lower at 100% load. These lower NO_x emissions could be due to lower temperatures in the combustion chamber using KVO blends. This is also evidenced by lower exhaust temperatures from the KVO-fueled engine. In this study, the KVO20 blend gave around 4% lower NO_x emissions at 80% load as compared to mineral diesel. This difference could be due to less residence time and temperature in the case of KVO blends.

Unburnt hydrocarbons (UHC) are also important parameter for determining the emission behavior of the engine using these blends. It was observed from Fig. 7 that KVO10 gave relatively lower HC as compared to neat diesel up to a 70% load. However, hydrocarbon emission was higher for the case of all KVO blends as compared to mineral diesel after 70% load. This may be due to poor atomisation of the blended fuel because of higher viscosity. The KVO5 is recommended as it showed lower HC over the entire range of engine operation.

Carbon monoxide emission for KVO5, KVO10, and KVO10 were less than the diesel over the entire range of load as shown in Fig. 8. But these were slightly increased in the case of KVO20 as compared to petroleum based diesel fuel. Higher carbon monoxide emissions showed incomplete combustion in the case of KVO20. Therefore, KVO20 may not be recommended for diesel engines as far as CO emission is concerned. Greenhouse emissions, like carbon dioxide emission, showed about a 5% reduction for all blends as compared to neat petroleum based diesel fuel.

In summary, the BTE curve in case of KVO10 was higher at 60% load as compared to mineral diesel and BSEC was least for KVO10 at full load. When emission parameters were compared with diesel fuel as base line, it was observed that KVO10 had resulted relatively lower HC as compared to the neat diesel up to 70% load. The opacity% was also least in case of KVO10 up to 80% load. In case of KVO10 all the performance and emission parameters were better; except the NO_x emission. Therefore, KVO10 was taken the optimum fuel blend for this engine.

4. Conclusion

Based on exhaustive engine tests, it can be concluded that KVO10 can be adopted as an alternative fuel for existing conventional diesel engines without any major hardware modifications. Preheating of KVO is a process that brings about a change in the molecular structure of the vegetable oil molecules, thus bringing down the viscosity. The viscosity of the preheated neat karanja oil at 90 °C was found to be very close to that of petroleum diesel oil. The flash point of KVO and its blends was higher than that of diesel oil, which signifies a safe range for storage of KVO. All these tests for the characterization of KVO demonstrated that almost all the important properties of KVO were in very close agreement with diesel oil, thus making it a potential fuel for application in compression ignition engines as a partial replacement for diesel fuel.

A diesel engine can perform satisfactorily on KVO fuel without any engine hardware modifications. KVO10 was found to be the best, and it improved the thermal efficiency of the engine. Similarly, the BSEC and exhaust emissions were also reduced appreciably. Decreases in the exhaust gas temperature of a KVO-fueled engine led to an approximately 4% decrease in NO_x emissions for KVO10. The performance of the KVO-fueled engine was marginally better than the diesel-fueled engine in terms of thermal efficiency, BSEC, smoke opacity and exhaust emissions, including NO_x emission, for the entire range of operations. It was conclusively demonstrated that the self-lubricity and oxygen content of KVO played a key role in engine performance. Fuel preheating and exhaust gas recirculation is recommended for the diesel engine to be operated with optimum test fuels. Injection timing and duration may also be changed for better combustion of high viscosity vegetable oil.

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