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Performance and emission studies on an agriculture engine on neat Jatropha oil †

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Abstract

Diesel engines have proven their utility in the transportation, agriculture, and power sectors in India. They are also potential sources of decentralized energy generation for rural electrification. Concerns on the long-term availability of petroleum diesel and the stringent environmental norms have mandated the search for a renewable alternative to diesel fuel to address these problems. Vegetable oils have been considered good alternatives to diesel in the past couple of years. However, there are many issues related to the use of vegetable oils in diesel engine. Jatropha curcas has been promoted in India as a sustainable substitute to diesel fuel. This study aims to develop a dual fuel engine test rig for evaluating the potential suitability of Jatropha oil as diesel fuel and for determining the performance and emission characteristics of an engine with Jatropha oil. The experimental results suggest that engine performance using Jatropha oil is slightly inferior to that of diesel fuel. The thermal efficiency of the engine was lower, while the brake-specific fuel consumption was higher with Jatropha oil compared with diesel fuel. The levels of nitrogen oxides (NOx) from Jatropha oil during the entire duration of the experiment were lower than those of diesel fuel. The reduction of NOx was found to be an important characteristic of Jatropha oil as NOx emission is the most harmful gaseous emission from engines; as such, its reduction is always the goal of engine researchers and makers. During the entire experiment, carbon monoxide (CO), hydrocarbon (HC), and carbon dioxide (CO_2) emissions in the case of using Jatropha oil were higher than when diesel fuel was used. The higher density and viscosity of Jatropha oil causes lower thermal efficiency and higher brake-specific fuel consumption. The performance and emission characteristics found in this study are significant for the study of replacing diesel fuel from fossils with Jatropha oil in rural India, where the availability of diesel has always been a problem.

Keywords: Biofuel; Jatropha oil; Transesterification; Triglycerides

1. Introduction

Energy is the building block of socio-economic development in any country. India is rich in coal and is abundantly endowed with renewable energy in the form of solar, wind, hydro, and bio-energy. However, the country's hydrocarbon reserve is only 0.8 billion tons, accounting for a mere 0.5% of the world's reserve. India accounted for 10.88% of the total primary energy consumption in the Asia Pacific region and 3.83% of the world's primary consumption in 2008 [1]. Diesel engines used in heavy trucks, city transport buses, locomotives, electric generators, farm equipment, underground mine equipment, and so on [2, 3] play a very important role in India's economy, but they also significantly contribute to the pollution in the country.

India is an agricultural country, where oil and electricity are the two major energy sources used in the agriculture sector. The number of electric and diesel irrigation pumps in the country has increased from 1.6 million in 1970–1971 to the current 21 million [4]. However, the growing concerns on the long-term availability of diesel and its environmental disadvantage have necessitated the search for a renewable alternative to diesel fuel. Biofuel can provide a feasible solution to these problems; known liquid biofuels are fuels derived from alcohol and vegetable oils. However, modification, handling and transportation, ease of production, and investment cost are some of the important parameters that should be considered before using an alternative fuel in an existing diesel engine. The modification required in the engine design should be very minor to minimize the investment in engine modification.

Among the wide variety of biofuels, vegetable oil is considered a promising fuel as many of its kind can be used directly as diesel fuel on a short-term or emergency basis. However, the physical and chemical differences between unmodified vegetable oils and the conventional diesel fuel work against their long-term use. In 1916, using the first diesel engine imported to Argentina, Gutierrez tested castor oil as an alternative fuel. In 1944, again in Argentina, De Vedia described the

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duration runs with blends of vegetable oils−including sunflower, linseed, groundnut, cottonseed, and turnip [5]−and diesel fuel. The vegetable oils have comparable energy density, cetane number, heat of vaporization, and stoichiometric air fuel ratio with those of mineral diesel fuel [6]. With the recent increase in petroleum prices and the uncertainties about the availability of petroleum, there is renewed interest in the use of vegetable oil fuels for diesel engines [7].

Oil can be extracted from a variety of plants and oilseeds. Under the Indian condition, only such plant sources can be considered which is essentially non-edible oil and can be grown on a large scale on wastelands. Moreover, some plants and seeds in the country have high medicinal value; as such, considering the use of oil from these plants as diesel engine fuel may not be a viable and wise option. With all the above options, trees or crops in India that can be considered as substitute for diesel fuel are the following [8]:

- Jatropha curcas or Ratanjot
- Pongamia pinnata or Karanja
- Calophyllum inophyllum or Nagchampa
- Hevea brasiliensis or Rubber seeds
- Calotropis gigantia or Ark
- Euphorbia tirucalli or Sher
- Boswellia ovalifololata
- Orizya sativa or Rice bran oil

Among these potential plant alternatives, Jatropha curcas has the highest potential for use as diesel fuel. A hectare of Jatropha plantation with 4,400 plants per hectare under rainfed conditions can yield about 1,500 L of oil [8]. The residue oil cake after the extraction of oil from Jatropha can then be used as organic fertilizers. An acre of Jatropha plantation is estimated to produce oil sufficient to meet the energy requirement of a family of five, while the remaining oil cake when used as fertilizer could cater to an acre of land. Jatropha can be grown in any wasteland with less irrigation, giving it a distinct advantage for consideration as the prime feedstock under India's environment conditions. As Jatropha oil is considered an impending substitute to diesel fuel in the agriculture sector, the present study was undertaken to evaluate the potential suitability of Jatropha oil in an agriculture diesel engine. The objectives of this study are as follows:

(1) Determination of the important physico-chemical properties of Jatropha oil
(2) Development of a dual fuel experimental diesel engine test rig
(3) Conducting exhaustive experiments on the test rig to evaluate the performance and emission characteristics of Jatropha oil and compare them with the baseline results of diesel

2. Vegetable oils as diesel fuel

Petroleum-based diesel fuels have different chemical structures compared with vegetable oils. The former contain only carbon and hydrogen atoms arranged in normal (straight chain) or branched chain structures, and aromatic configurations. The normal structure is preferred for better ignition quality. Diesel fuel can contain both saturated and straight or unbranched chain unsaturated hydrocarbons, but the latter are not present in large amounts, making oxidation a problem [7].

Table 1. Tests and limits for fuel properties [7].

Test	ASTM test	ASTM limits
Kinematic viscosity, mm^2/s	D 445	1.9–4.1
Distillation temperature, °C (90% volume recovered)	D 86	282–338
Cloud point, °C	D 2500	*
Pour point, °C	D 97	4.4-5.5°C
Flash point, °C	D 93	52° C min
Water and sediment, % vol	D 1796	0.05% max
Carbon residue at 10% residue	D 524	0.35% max
Ash by weight, %	D 482	0.01% max
Sulphur by weight, %	D 129	0.5% max
Copper strip corrosion	D 130	3 max
Cetane number	D 613	40 min

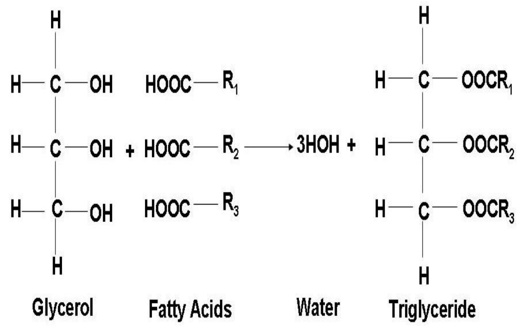

Fig. 1. Chemical structure of vegetable oils.

Table 1 lists the ASTM limiting requirement for No. 2 diesel fuel and the standard ASTM test for measuring each corresponding fuel property.

Vegetable oils consist of about 97% triglycerides; the remaining 3% accounts for diglycerides, monoglycerides, and three fatty acids, with the accompanying fat mostly removed through refining [9]. Structurally, a triglyceride is a reaction product of a molecule of glycerol with three fatty acid molecules, yielding three molecules of water and one molecule of triglyceride, as shown in Fig. 1 [10].

R, R', and R'' are the alkyl groups of different carbon chain lengths (varying between 12 and 18) and -COO- is a carboxyl group. Vegetable oils have different chemical structures, as shown in Fig. 2 [11].

The large size of vegetable oil molecules (typically three or more times larger than hydrocarbon fuel molecules) and the presence of oxygen in the molecules suggest that some fuel properties of vegetable oils are significantly different from those of hydrocarbon fuels [7]. The characteristics of a variety of available vegetable oils fall within a narrow band and are closer to those of diesel oil. The kinematic viscosity of

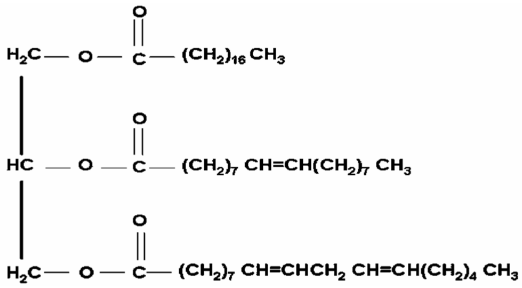

Fig. 2. Structure of a typical triglyceride molecule.

vegetable oils varies in the range of 30-40 cSt at 38ºC. The high viscosity is due to their larger molecular mass and chemical structure. Vegetable oils have high molecular weights of 600-900, which are three or more times higher than that of diesel fuel. The flash point of vegetable oils is also very high (above 200ºC). Their heating value is at the range of 39-40 MJ/kg, comparatively lower than that of diesel fuels (about 45 MJ/kg). This is because the presence of chemically bonded oxygen in vegetable oils lowers the heating value by about 10%. The cetane number is in the range of 32-40, while the iodine value ranges from 0-200, depending on unsaturation. The cloud and pour point of vegetable oils is higher than that of diesel fuel [11, 12].

It is clear that the use of vegetable oils as fuels for diesel engines depends on their physical and chemical properties, their combustion characteristics, the type of engine used, and the conditions of operation. Although the properties vary from one type of oil to another, this general comparison with the diesel fuel is valid for all [13]. The use of vegetable oils "as is" for fueling diesel engines is not impossible. However, the following difficulties might be experienced, as what was encountered during the utilization of vegetable oil [14, 15]:

- The increased viscosity of the neat vegetable oils leads to poor atomization and incomplete combustion with an unmodified fuel injection system.
- Clogging of the fuel system
- Polymerization during storage
- Blow-by, which causes the polymerization of the lubricating oil
- Thickening and gelling of the lubricating oil as a result of contamination by the vegetable oil
- Oil ring sticking
- Carbon deposits around the nozzle orifice, the upper piston ring grooves, and around the piston rings
- Progression of combustion
- Implementation, particularly under low temperature conditions

3. Definition of the problem

Many researchers have reported encountering difficulties with the use of vegetable oil in diesel engine. These difficulties are mainly attributed to the high viscosity of vegetable oils. Jatropha is a sustainable source of diesel alternative in India.

Table 2. Specifications of the diesel engine.

Parameters	Value
Model	DAF 8
Rated brake power (bhp/kW)	8/5.9
Rated speed (rpm)	1500
Number of cylinder	One
Bore x stroke (mm)	95 x 110
Compression ratio	17.5:1
Cooling system	Air cooled (radial cooled)
Lubrication system	Forced feed
Cubic capacity	0.78 liter
Inlet valve open (Degree)	4.5 bTDC
Inlet valve closed (Degree)	35.5 aBDC
Exhaust valve open (Degree)	35.5 bBDC
Exhaust valve closed (Degree)	4.5 aTDC
Fuel injection timing (Degree)	26 bTDC

However, the issue about its high viscosity must first be resolved before it can be used for diesel engine in a long-term basis. Due to its high viscosity, two strategies can be employed when using Jatropha oil as fuel for diesel engines. The first is to modify the engine to adapt to the fuel, while the second is to process the fuel to adapt to the engine. The adaptation of Jatropha oil to the diesel engine can be done by using neat Jatropha oil through a dual tank approach, blending Jatropha oil with diesel, and producing methyl esters through the transesterification process, which can be used directly instead of diesel or dual fuelling with diesel. However, exploring the possibility of using neat Jatropha oil in a dual fuel tank mode before experimenting with other techniques is essential because such techniques require expertise and equipment difficult for a rural community to adopt. Therefore, a dual tank approach in evaluating the initial feasibility was used in this study.

4. Experimental setup

A Kirloskar engine (DAF 8) was selected due to the large-scale utilization of such engines in the agriculture sector. The detailed specifications of the test engine are summarized in Table 2.

The main components of the experimental setup are two fuel tanks (diesel and Jatropha oil), fuel consumption measuring unit, electrical loading arrangement, voltmeter, ammeter, rpm meter, and temperature indicator. AVL 437 smoke meter and AVL Di Gas analyzer were used for emission measurement. The engine was started using diesel for at least 30 min; once the engine had warmed up, it was then switched over to Jatropha oil. For the switching of the engine from diesel to Jatropha oil, a two-way valve was provided on the control panel. Both fuels from the two tanks can be separately fed to the engine through this valve. One end of the valve is connected to the Jatropha oil, while the other is connected to the

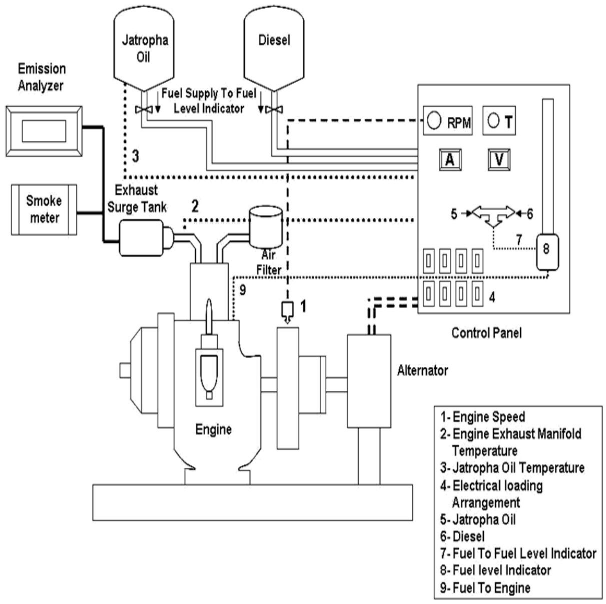

Fig. 3. Schematic diagram of the experimental setup.

diesel. Fuel from the valve enters into the engine through this fuel measuring unit, which enables the volumetric flow of the fuel to be measured easily. The fuel from the fuel measuring unit then enters into the fuel filter before entering the engine.

The schematic diagram of the experimental setup and all the instrumentations is shown in Fig. 3.

The engine test was carried out in accordance with the methods of testing for internal combustion engines set by the Bureau of Indian Standards (IS: 10000). The main parameters desired from the engine are the following: power produced by the engines, engine speeds (rpm), fuel consumption, exhaust temperature, and speed of the engine.

5. Experimental procedure

The engine was started at no load by pressing the exhaust valve with the decompression lever; it was released suddenly when the engine was hand cranked at sufficient speed. After adjusting the feed control to enable the engine to achieve the rated speed of 1,500 rpm, it was allowed to run (about 30 min) until the steady state condition was reached. With the fuel measuring unit and stop watch, the time elapsed for the consumption of 10, 20 and 30 cc of fuel was measured and averaged. Fuel consumption, rpm, exhaust temperature, smoke density, carbon monoxide (CO), nitrogen oxide (NO_X), hydrocarbon (HC), carbon dioxide CO_2, and power output were also measured. Fuel leakages from the injector were measured using a small measuring cylinder. The engine was loaded gradually, keeping the speed within the permissible range, and observations on the different parameters were recorded. Short-term performance tests were also carried out on the engine with diesel to generate the base line data; subsequently, neat Jatropha oil was used to evaluate its potential suitability as fuel. The engine was always started with the use of diesel as fuel; after running for 30 min, the engine was then switched over to Jatropha oil. Before turning off the engine, Jatropha oil was replaced again with diesel oil. The engine was allowed to run on diesel oil until all Jatropha oil in the fuel filter and pipe line was consumed.

Table 3. Physico-chemical properties of diesel and Jatropha oil.

Property	Mineral diesel	Jatropha oil
Density (kg/m^3)	830	918
API gravity	37.15	22.81
Kinematic viscosity at 40° C (cSt)	2.5	37
Cloud point (°C)	–12	9
Pour point (°C)	–17	4
Flash point (°C)	70	238
Calorific value (kJ/kg)	42,200	37,500
Carbon residue (%, w/w)	0.05%	0.8
Ash content (%w/w)	0.01	0.04
Carbon (%,w/w)	86.71	77.21
Hydrogen (%,w/w)	12.98	10.25
Nitrogen (ppm)	5	3
Oxygen (%,w/w)	0.31	12.52
Sulfur (ppm)	340	8

6. Result and discussion

The important physico-chemical properties of Jatropha oil were determined and are presented in Table 3.

The variation of the brake thermal efficiency (BTE) of the engine with Jatropha curcas oil and diesel is shown in Fig. 4(a). With increasing brake power, the BTEs of vegetable oils and diesel also increased; however, they tended to decrease when further increase in brake power was observed. The BTEs of the Jatropha curcas oil are lower than those of diesel fuel throughout the entire range, possibly due to the lower calorific value and the high viscosity of Jatropha oil compared with diesel fuel. The results obtained are not consistent with the better thermal efficiency obtained by Pramnik et al. [16]. The maximum thermal efficiency achieved was 28.51% for diesel and 25.53% for Jatropha oil.

The brake-specific fuel consumptions (BSFC) were also higher in the case of Jatropha curcas oil than in diesel fuel, as evident in Fig. 4(b). This is mainly due to the combined effects of the relative fuel density, viscosity, and heating value of the blends. The higher density of Jatropha oil led to more discharging of fuel for the same displacement of the plunger in the fuel injection pump, thereby increasing the specific fuel consumption. The results of the test show that the brake-specific consumption of Jatropha oil when used in an unmodified diesel engine is high, which is in line with the result obtained by Pramnik et al. [16], which indicate higher BSFC.

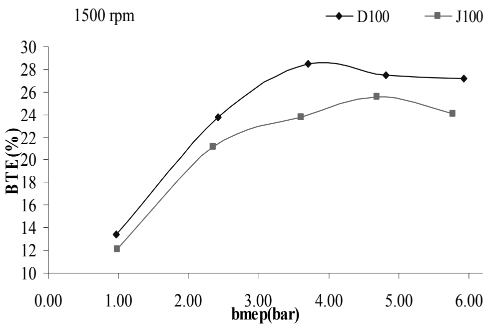

Fig. 4(a). Effect of bmep on BTE with D100 and J100 fuels.

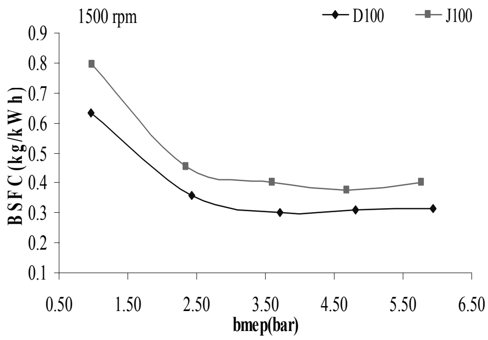

Fig. 4(b). Effect of bmep on BSFC with D100 and J100 fuels.

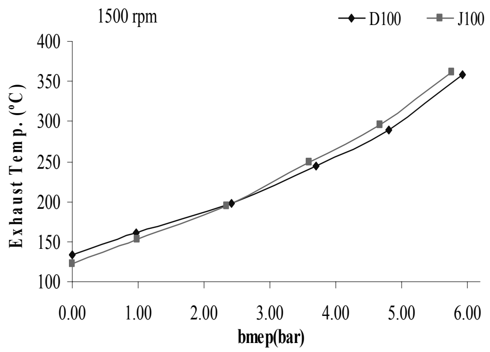

Fig. 4(c). Effect of bmep on exhaust temperature with D100 and J100 fuels.

Fig. 4(c) shows that the exhaust gas temperature increases with the increase in brake power in all cases. The highest value of exhaust gas temperature of 362°C was observed with Jatropha oil, whereas the corresponding value with diesel was only at 359°C. This is due to the poor combustion characteristics of the Jatropha curcas oil because of its high viscosity. The higher exhaust temperature with Jatropha oil is indicative of the lower thermal efficiencies of the engine. At lower thermal efficiency, less of the energy input in the fuel is converted to work, thereby increasing exhaust temperature.

The NO_X emissions, shown in Fig. 4(d), increase along with the increasing engine load due to the higher combustion temperature. This proves that the most important factor for the emissions of NO_X is the combustion temperature in the engine cylinder and the local stoichiometry of the mixture. Within the

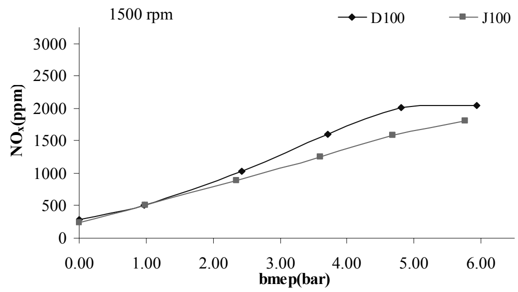

Fig. 4(d). Effect of bmep on NO_x with D100 and J100 fuels.

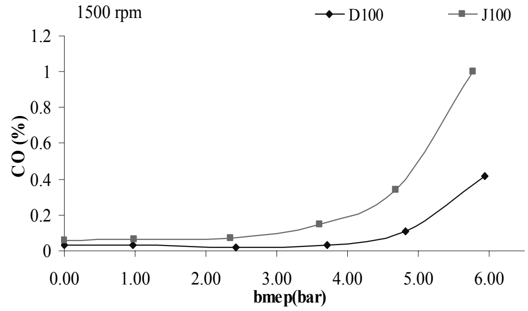

Fig. 4(e). Effect of bmep on CO with D100 and J100 fuels.

range of tests, the NO_X emissions from Jatropha oil are lower than that of diesel fuel. NO_X emissions were reduced from 2,046 ppm to 1,813 ppm at full load, possibly due to the smaller calorific value of vegetable oils. This is the most important emission characteristic of plant oil as the NO_X emission is the most harmful gaseous emission from engines; therefore, its reduction has always been the goal of engine researchers and makers. This emission character of NO_X for plant oil is very useful in the application of plant oil to diesel engines as a kind of alternative fuel for petroleum-based ordinary diesel fuel. The results obtained from the experiment clearly show that using plant oil in diesel engine reduces NO_X emissions, which is in accordance with what was posited by Wang et al. [17].

Within the experimental range, the CO emission from Jatropha oil is higher than neat diesel fuel, as seen in Fig. 4(e). This is possible due to the high viscosity of vegetable oils; the higher the viscosity, the more difficult it is to atomize vegetable oils. This resulted in locally rich mixtures in the engine. Consequently, more CO was generated during the combustion due to the lack of locally available oxygen. The results are in accordance with those obtained by Agarwal et al. [18].

The CO_2 emissions are shown in Fig. 4(f). In the range of the whole engine load, the CO_2 emissions of diesel fuel are higher than that of the other fuels because vegetable oil contains oxygen element. The carbon content is relatively lower in the same volume of fuel consumed at the same engine load, and consequently, the CO_2 emissions from the vegetable oil and its blends are lower. The result shows that CO_2 emissions slightly increase when using plant oil, which is in line with the findings of Agarwal et al. [18].

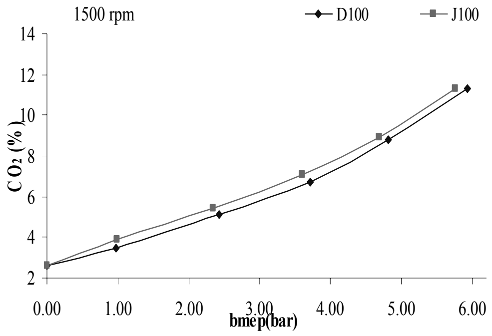

Fig. 4(f). Effect of bmep on CO_2 with D100 and J100 fuels.

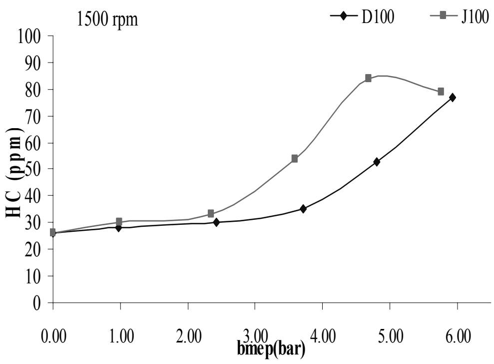

Fig. 4(g). Effect of bmep on HC with D100 and J100 fuels.

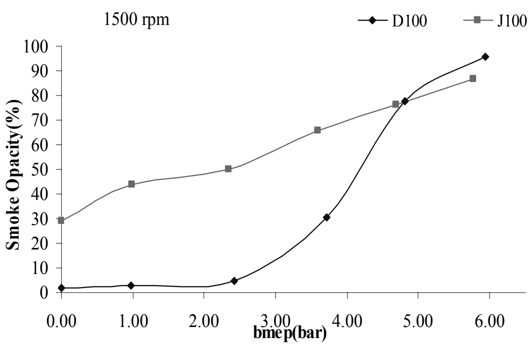

Fig. 4(h). Effect of bmep on smoke opacity with D100 and J100 fuels.

The value of unburned HC emission from the diesel engine in the case of straight vegetable oil is higher than that of diesel fuel, as seen in Fig. 4(g). HC emissions are lower at partial loads but tend to increase at higher loads for both fuels. This is due to the lack of oxygen, which is caused by engine operation at a higher equivalence ratio.

Fig. 4(h) shows the comparison of the smoke opacity of both fuels at different engine loads. In most of the ranges of the experiment, the smoke opacity from Jatropha oil is higher than that from diesel fuel due to the high viscosity of vegetable oils, which results in incomplete combustion and more smoke formation.

7. Conclusions

This study was conducted on an unmodified diesel engine, which was converted to run on a dual mode operation. The results of the experiment showed that the performance of the engine on Jatropha oil was slightly inferior to that on diesel fuel. The thermal efficiency of the engine was lower, while the brake-specific fuel consumption was higher on Jatropha oil than on diesel. The levels of NO_X from Jatropha oil during the entire experiment were lower than those from diesel fuel. CO, HC, and CO_2) emissions from Jatropha oil were higher than from diesel fuel during the entire process of the experiment. High viscosity, density, and level of unsaturation seemed to be the main reasons for the lower thermal efficiency and the increase in some of the gaseous emissions.

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Naveen Kumar completed his Bachelor of Mechanical Engineering degree from D.E.I., Agra, in 1984, his Master of Technology at IIT Delhi in 1990, and his Ph.D. from the University of Delhi. Dr. Kumar has over 19 years of experience in the industry, teaching, and research, including more than 13 years of teaching at the Delhi Technological University (formerly Delhi College of Engineering), where he is currently a professor in Mechanical Engineering. His specialization is in internal combustion engines and alternative fuels. His research interests include the development of various biofuels and their utilization in decentralized power systems. His work on biodiesel is highly valued internationally. Dr. Kumar has extensively traveled abroad and has interacted with various universities and industries in both developed and developing countries.

Haeng Muk Cho earned his Bachelor of Science degree in Mechanical Engineering from the Youngnam University in Korea. He completed his Master's degree in Environment Engineering in Yonsei University and his Ph.D. in the Hanyan University, Korea. Dr. Cho is currently a professor in Kongju National University, Korea. His research interest is internal combustion engines and emissions.