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Experimental evaluation of C.I. engine performance using diesel blended with Jatropha biodiesel

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Abstract
Costlier and depleting fossil fuels are prompting researchers to use edible as well as non-edible vegetable oils as promising alternative to petro-diesel. The higher viscosity of vegetable oils leads to problem in pumping, atomization and spray characteristics. The improper mixing of vegetable oils with air leads to incomplete combustion. The best way to use vegetable oils as fuel in compression ignition (CI) engines is to convert it into biodiesel. Biodiesel is a methyl or ethyl ester of fatty acids made from vegetable oils (both edible and non-edible) and animal fat. The main feedstock for biodiesel production can be non-edible oil obtained from *Jatropha curcas* plant. *Jatropha curcas* plant can be cultivated on different terrains in India under extreme climatic conditions. Biodiesel can be used in its pure form or as a blend with petro-diesel in different proportions. It is being used in CI engines because it has properties similar to petro-diesel. The aim of this paper is to analyze suitability of petro-diesel blended with biodiesel in varying proportions in CI engines. For this purpose, a stationary single-cylinder four-stroke CI engine was tested with diesel blended with Jatropha biodiesel in 0%, 5%, 20%, 50%, 80% and 100%. Comparative measures of specific fuel consumption (SFC), brake thermal efficiency, smoke opacity, HC, CO_2, CO, O_2, NO_X have been presented and discussed. Engine performance in terms of comparable brake thermal efficiency and SFC with lower emissions (HC, CO_2, CO) was observed with B20 fuel compared to petro-diesel. Volumetric efficiency showed almost no variation for all the blends. Important observations related to noise and vibrations during testing have also been discussed.

Keywords: Biodiesel; CI; Ester; Jatropha curcas; SFC.

1. Introduction

The petroleum fuels fulfill our energy needs in industrial development, transportation, agriculture sector and many other basic requirements. These fuel reserves are fast depleting due to excessive usage. Besides combating the limited availability of crude oil, researchers are also dealing with other associated serious problems with petroleum fuel such as increase in pollutant emissions like: CO_2, HC, NO_x, SO_x and many other [1]. These pollutants cause diseases of the respiratory/nervous system, skin infection and acid rain phenomenon also occurs due to these emitted pollutants. One of the very important issues catching the attention of researchers worldwide is rise in green house gases (GHGs) emissions levels due the usage of petroleum fuels. In last few years volatility in the pricing of petroleum and its products has

seriously affected the political-economic scenario of nations around the whole world. Hence, the need to search alternative to petroleum fuels is inevitable.

India imports more than seventy percent of its crude oil requirement. Almost forty percent of all the quantity of petroleum products consumed in India is diesel. As evident from the Figure 1, petro-diesel consumption is showing an increasing trend.

Sector wise petro-diesel consumption in India shown in Figure 2 indicates that automobile sector comprising of commercial and passenger vehicles is the largest consumer followed by industry and agriculture.

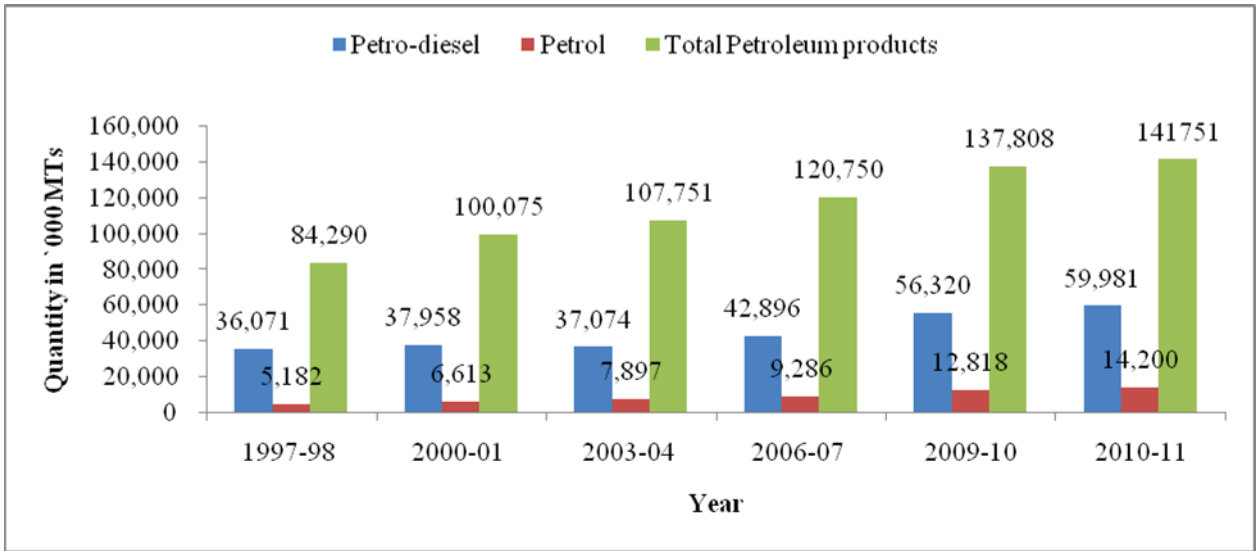

Figure 1. Consumption of petro-diesel, petrol and total petroleum products in India [2]

Recent sales trend of automobiles in India clearly indicates increasing dominance of petro-diesel vehicles as compared to petrol vehicles. Mileage and price differential relative to petrol vehicles is the major factor leading to increased sales trend petro-diesel vehicles in India. Moreover latest CI engines being used in Indian automobiles have less operational noise, vibrations and maintenance issues as compared to their primitives.

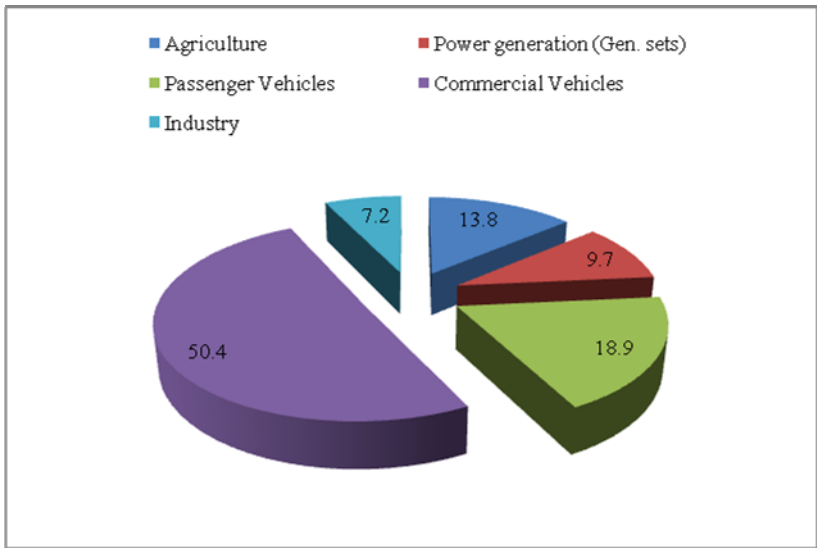

Figure 2. Sectorwise petro-diesel consumption in India [3]

Self-sustainable energy sources are likely to hold the key to economic development of India in future. India should not look towards a certain group of countries to meet its ever growing petroleum needs but

it is mandatory to seriously implement bioenergy development programs as a part of environmental sustainability in the form of clean development mechanism (CDM) [4]. The much required green energy revolution would provide India an opportunity to change its standing from a fuel-importing nation to one that generates clean and affordable energy [5]. Hence researchers are looking for techno-economically alternatives to petro-diesel.

India being agriculture based economy, with more than sixty percent of population still living in rural areas, locally grown biodiesel can be a viable source of meeting their energy needs on a reasonable cost.

Among various alternatives to diesel, Government of India (GoI) has identified jatropha, a non-edible oil bearing tree capable of producing oil that is easily convertible in to biodiesel with properties almost similar to diesel [6]. *Jatropha curcas* plant is a drought-resistant, perennial plant living up to 50 years and has the capability to grow on marginal soils. It requires very little irrigation and grows in all types of soils, thus making Jatropha a more sustainable choice than other vegetable oils. In the longer run economic sustainability of jatropha biodiesel will definitely prove to be the best bet for India as far as economic viability of biodiesel w. r. t. diesel is concerned [7].

Production of jatropha biodiesel would also result in reclamation of degraded/waste land, help in supplementing the ever increasing energy demand in line with the requirements of higher targeted growth rate and may also fulfill other social objectives such as: additional employment generation and participation of marginal laborers without threatening the food security with a sustainable ecosystem. An integrated approach realizing the monetary benefits of CDM is required to be implemented with proper co-ordination amongst the various governmental and nongovernmental organizations to achieve the targeted production of jatropha biodiesel [8].

Biodiesel, a methyl or ethyl ester (ME or EE) of fatty acids made from vegetable oils (both edible and non-edible) and animal fat is looked upon as potential supplement/alternative to petro-diesel. Biodiesel can be used in its pure form or as a blend with petro-diesel in different proportions. It is being used in diesel engines because it has properties similar to petro-diesel as shown in Table 1. Important properties of both diesel and jatropha biodiesel (JME) like: density, viscosity, cetane number, calorific value and carbon content are comparable. Moreover JME has negligible sulfur content, reducing the chances of SO_x emissions which cause acid rains. Better self-lubrication property of biodiesel is also attributed to the lesser sulfur content, which causes reduced wear & tear of engine and its components. Biodegradability of ME due to its oxidation leads to lesser damage to flora and fauna in case of accidental spillage. Inbuilt oxygen content helps in ensuring proper combustion and lesser release of carbon monoxide (CO).

Table 1. Properties of diesel and Jatropha biodiesel [9]

Property	Diesel	Jatropha biodiesel
Density (kg/m^3) at 15 ˚C	840 $\pm$ 1.732	879
Kinematic viscosity at 40 ˚C (cSt)	2.44 $\pm$ 0.27	4.84
Cetane Number	48-56	51 - 52
Pour point (˚C)	6 $\pm$ 1	+3
Flash point (˚C)	71$\pm$ 3	191
Conradson carbon residue (%, w/w)	0.1 $\pm$ 0.0	0.01
Ash content (%, w/w)	0.01 $\pm$ 0.0	0.013
Calorific value (MJ/kg)	45.34	38.5
Sulfur (%, w/w)	0.25	<0.001
Carbon (%, w/w)	86.83	77.1
Hydrogen (%, w/w)	12.72	11.81
Oxygen (%, w/w)	1.19	10.97

The objective of this study is to explore performance of petro-diesel (B0) blended with JME (B100) in 5% (B5), 20% (B20), 50% (B50) and 80% (B80) by volume in direct injection CI engine used extensively for agricultural applications under varying load conditions. It is mandatory to experimentally validate suitable blends to be used as fuel in the engines in future with better performance, lesser emissions and optimum level of noise and vibrations.

2. Experiment and experimental set-up

Constant speed (1500 rpm) short-term engine performance (STEP) tests were conducted on a 3.7 kW single cylinder, naturally aspirated, four-stroke Kirloskar engine at varying load. The fuel used in the engine was B0, B5, B20, B50 and B100. The major specifications of the Kirloskar engine are presented in Table 2. The engine was coupled to a hydraulic dynamometer for application of load and opening the water inlet valve increased the load and vice-versa.

Table 2. Kirloskar Engine Specifications

Parameters	Value
BHP	5
Speed	1500 rpm
No. of cylinder	1
Compression ratio	16.5:1
Bore	80 mm
Stroke	110 mm
SFC	245 g/kWhr
Method of loading	Hydraulic dynamometer
Orifice diameter	20 mm
Arm length of hydraulic dynamometer	320 mm

Experimental setup as shown in Figure 3 was used for performance and emissions analysis. In this study following operational parameters were focused upon while analyzing the performance of an engine like: specific fuel consumption (the ratio of amount of fuel consumed in kg/hr to power output in kW), volumetric efficiency (breathing ability of an engine) and brake thermal efficiency (the ratio of brake power to heat input).

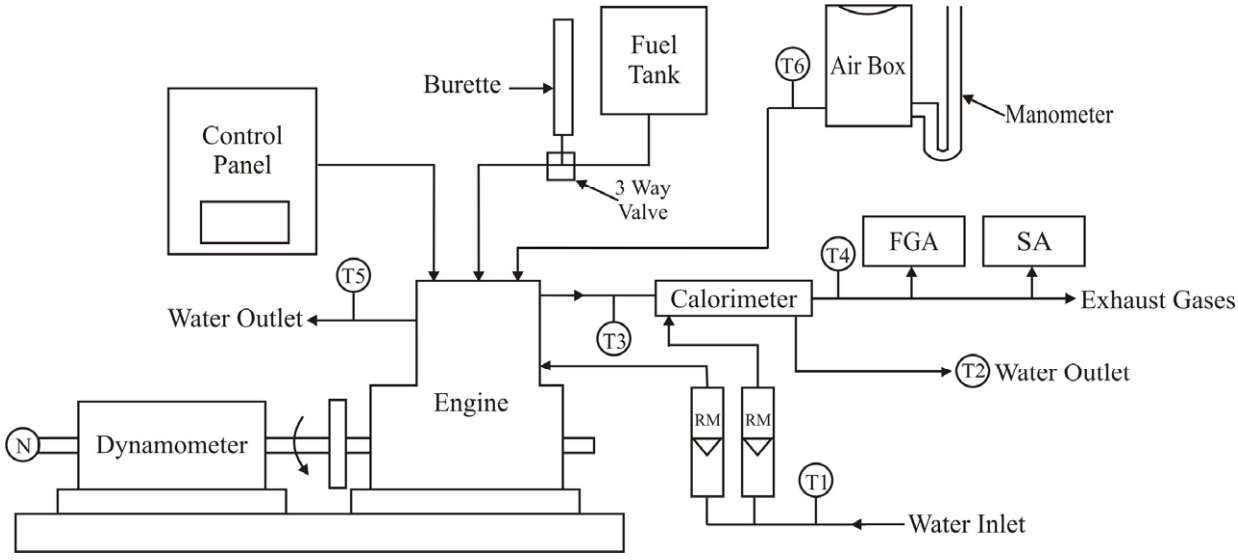

Figure 3. Experimental setup of single cylinder four stroke diesel engine with hydraulic dynamometer

AVL make exhaust and flue gas analyzer were used to determine the percentage of smoke opacity, HC, CO_2, CO, O_2 and NO_X in the exhaust with the range mentioned in Table 3. For every blend, the engine was started and after it attains stable condition, important parameters related to its performance were recorded. The engine was operated at the speed of 1500 ± 10 rpm. The engine was then tested at 13.33%, 20%, 40%, 60%, 80% and 100% load. As per the test rig specifications, at rated power, i.e. at full load (100%), the hydraulic dynamometer is to be loaded with 7.5 kg load for given arm length. The engine at the above mentioned loads was tested on all the fuel blends discussed above. For each load condition, the experiment was repeated three times.

Table 3. Parameters measured by Gas analyzer

Measured Quality	Measuring Range
CO	0… 10 % vol
CO_2	0… 20 % vol
HC	0… 20000 ppm
NO_x	0… 5000 ppm
O_2	0… 22 % vol

3. Literature review

Few studies have reported higher thermal efficiencies, lower BSFC and higher exhaust temperatures for all blends of biodiesel compared to mineral diesel [10]. But in some other studies the higher BSFC and lower exhaust temperature have been reported [11]. The need for monitoring the non-regulated air toxic aromatic, polyaromatic and carbonyl compounds while using biodiesel is also emphasized [12]. The use of biodiesel leads to loss in engine power mainly due to the reduction in heating value and high density and viscosity of biodiesel compared to diesel [12, 13, 18]. Use of biodiesel reduces carbon deposit and wears of the key engine parts, compared with diesel due to lower soot formation, higher oxygen content, lower aromatic compounds and the inherent lubricity of biodiesel [12]. CO emissions reduce when using biodiesel due to the higher oxygen content and the lower carbon to hydrogen ratio in biodiesel compared to diesel. HC emissions reduces when biodiesel is fueled instead of diesel mainly due to the higher oxygen content of biodiesel, but the advance in injection and combustion of biodiesel also favor the lower HC emissions [12, 17]. It is believed that the CO_2 emission reduces for biodiesel as a result of the low carbon to hydrocarbons ratio, and researcher showed that the CO_2 emission increases or keeps similar because of more effective combustion [12].

The BTE of biodiesel and its blends are slightly lower than that of diesel at low engine loads, and almost same at high engine loads. The oxygen content in the biodiesel results in better combustion and increases the combustion chamber temperature, which leads to higher NO_x emissions, especially at high engine loads [13, 16]. HC emissions of biodiesel and its blendes are lower from diesel fuel. It is also observed that there is a significant reduction in CO and smoke emissions at high engine loads [13, 16, 17]. Excess oxygen contents of biodiesel causes earlier initiation of combustion for biodiesel and its blends than for diesel. The peak pressure rise rate and peak heat release rate of biodiesel are higher than those of diesel fuel at low engine loads, but inversely at high engine loads [13].

It was observed that any diesel engine can be operated with 20% blend of degummed vegetable oil as a prime mover for the agriculture purposes without any modification of engine. Jatropha is promising to yield good performance and emissions at high loads in all respects [14].

Tests on esters of soyabean, jatropha and honge resulted in a slightly reduced thermal efficiency and increased smoke, HC and CO levels compared to the standard diesel oil. Relatively higher viscosity, poor atomization and lower volatility of biodiesels compared to diesel oil are responsible for this trend. The existing engine could be operated on the esters tested without any major modification [15].

Higher density, viscosity and molecular weight make it difficult to atomize the biodiesel at low temperature at the engine low loads causing more CO emissions. The main reason for the lower CO emissions at high loads from the combustion of the biodiesel is the inbuilt oxygen content which makes the combustion of biodiesel more complete when the engine works at high loads. At the engine high loads, HC emissions from the combustion of the biodiesels are all less than that of diesel possibly due to the higher viscosity and higher molecular weight of the chinese pistache biodiesel leading to difficulties to evaporate at low temperatures at engine low loads [16].

Brake specific fuel consumptions for all the biodiesel blends with diesel increases with blends and decreases with speed [17, 18]. The best brake specific fuel consumption improvement is observed with JB20. Biodiesel proportion of more than 20% in the blend tends to decrease BSFC. However, there is a slight increase in CO, NO_x and combine HC and NO_x [17].

For pure biodiesel, the maximum torque is reached at higher speed; this fact might be related to an increase of the flame velocity observed with biodiesel. By reducing the injection advance, it is possible to optimize combustion, improving performances especially at low and medium speed, lower HC and CO emission with respect to nominal injection advance operation, by reducing the injection angle, power and torque are increased up to almost pure diesel oil levels while SFC is reduced. NO_X are reduced over the entire speed range due to lower average temperatures [18].

It has been demonstrated that increase in compression ratio associated with increase in injection pressure improves the performance of the engine measured in terms of BSFC and BTHE. The highest performance is delivered by the engine at 250 bar injection pressure and compression ratio of 18 at which BSFC improves by 10% and BTHE improves by 8.9%. With regard to emission aspects, increase in compression ratio leads to increase in emission of HC and exhaust temperature whereas Smoke and CO emission reduces. NO_x emissions are found to remain unaffected at higher injection pressure. The higher injection pressure helps in keeping the emissions of HC, NO_x and Smoke at a lower level while increasing the CO and temperature of exhaust [19].
Reviewed literature presents varying trends for emissions during engine operation but no effort is made to discuss other operational issues like: injector fouling, filter choking, noise and vibrations during engine operation on JME blended with diesel. Hence it becomes utmost important to analyze these issues as well along with experimentally validating the best possible JME blend for the engine performance.

4. Results and discussions

The Brake specific fuel consumption (BSFC) was calculated by fuel consumption divided by the rated power output of the engine. Figure 4 shows that variation of BSFC with load. SFC is showing an increasing trend for B80 and B100 for higher loadings. For B0 to B50 fuel consumption is decreasing with respect to increase in loading. Higher SFC can be attributed to the lower calorific value of biodiesel than that of diesel and poor atomization of blended JME with petro-diesel to its higher viscosity and density. Lowest BSFC is observed for B0 (254.5 g/kW hr) than B5 (268.4 g/kW hr) and B20 (278.5 g/kW hr) at 13.33% load. As a blended fuel B20 has marginally higher BSFC than B0. Highest BSFC is observed for B100 (597.5 g/kW hr) at 13.33% load. B80 and B100 fuel were found to give lowest BSFC at 60% load implying that the impact of higher viscosity and density is minimal.

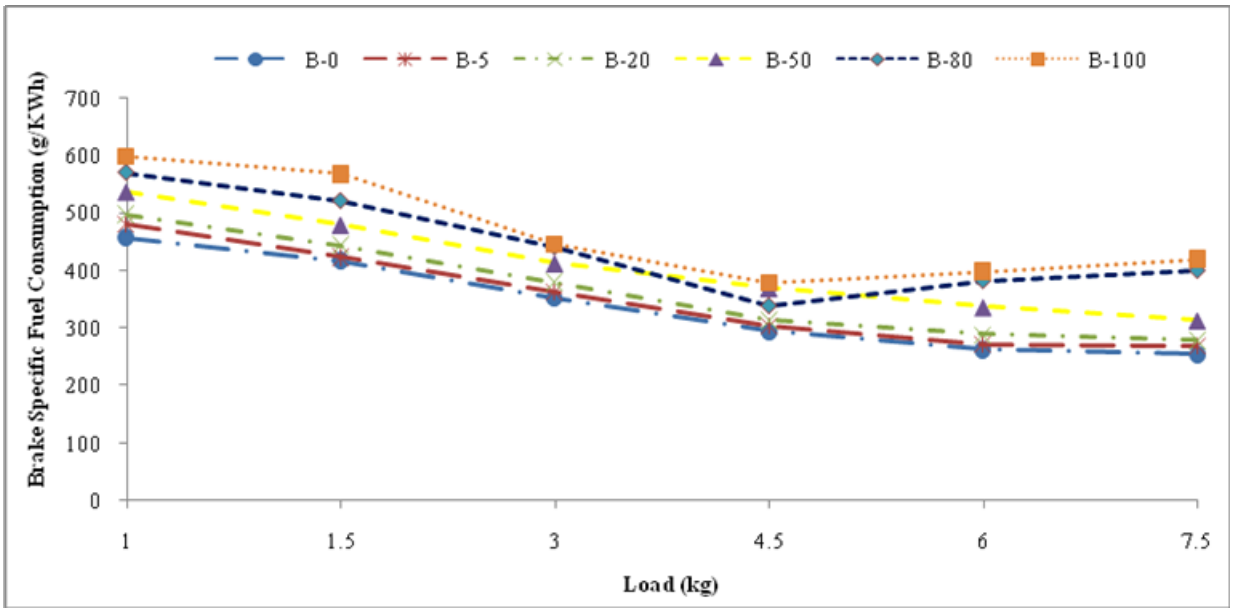

Figure 4. BSFC vs load

Figure 5 shows that variation of brake thermal efficiency with load. The BTE of the engine was observed to increase with increase in the load and was found maximum for B-0 (32.05%) at 100 % of load. This implies that the engine running on B0 fuel has good full load efficiency. For B5 (30.56%) and B20 (30.01%) BTE was lower as compared to that of B0 at 100% load due to lower calorific value, higher viscosity and density. For higher blends B50 and above, full load BTE is lower as compared to that of B0. This could also be attributed to the high mass flow rate of fuel inside the engine cylinder on account of larger density of JME as compared to diesel. Lower volatility, high viscosity and density of B50, B80 and B100 cause poor atomization and combustion and hence lower efficiency. Poor atomization leads to improper nuclei formation for initiation of combustion. Moreover larger density and viscosity of B50 and above blends leads to utilization of more amount of heat energy for initiation and completion of combustion thus leading to lower thermal efficiency.

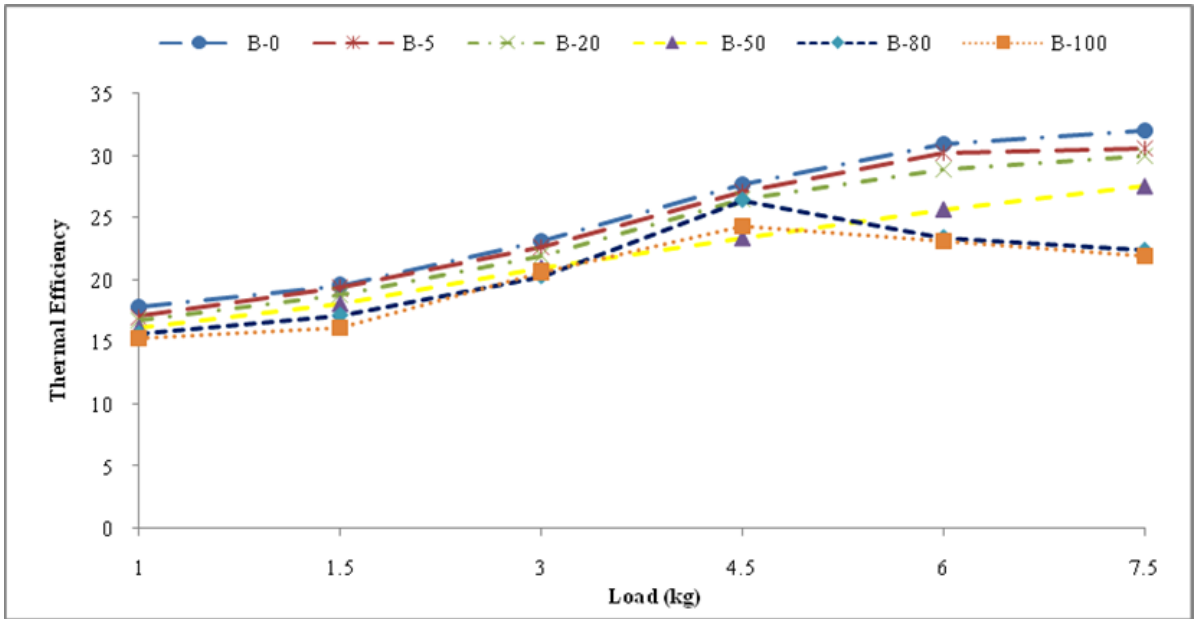

Figure 5. Thermal efficiency vs load

Hydrocarbon (HC) emissions at varying load on different blends are shown in Figure 6. Lowest value of HC emissions at 17-21 ppm is observed for B50. Highest value of HC emissions is observed for B0 (65 ppm) at 100% load. HC emissions for B20 are in the range of 24-32 ppm. Lower HC emissions are very strong criteria favouring the usage of blended diesel in place of pure diesel. Cetane number of JME being higher than diesel, leads to a shorter delay period and results in better combustion resulting in lower HC emission. Also the intrinsic oxygen present in the fuel B5 to B100 was responsible for the reduction in HC emission. Since a long time diesel is known to emit large amount of soot particles which may cause serious respiratory disorders in human beings. B20 depicts lower HC emissions even at higher loading. Slightly higher HC emissions are observed at higher loading for B80 and B100 primarily due to higher viscosity and density causes improper Air/Fuel ratio resulting in improper combustion. Lower HC emissions may lessen the wear of key engine parts, compared with diesel. It is attributed to the lower soot formation, and the inherent lubricity of biodiesel. The higher oxygen content and lower aromatic compounds also reduces HC emissions.

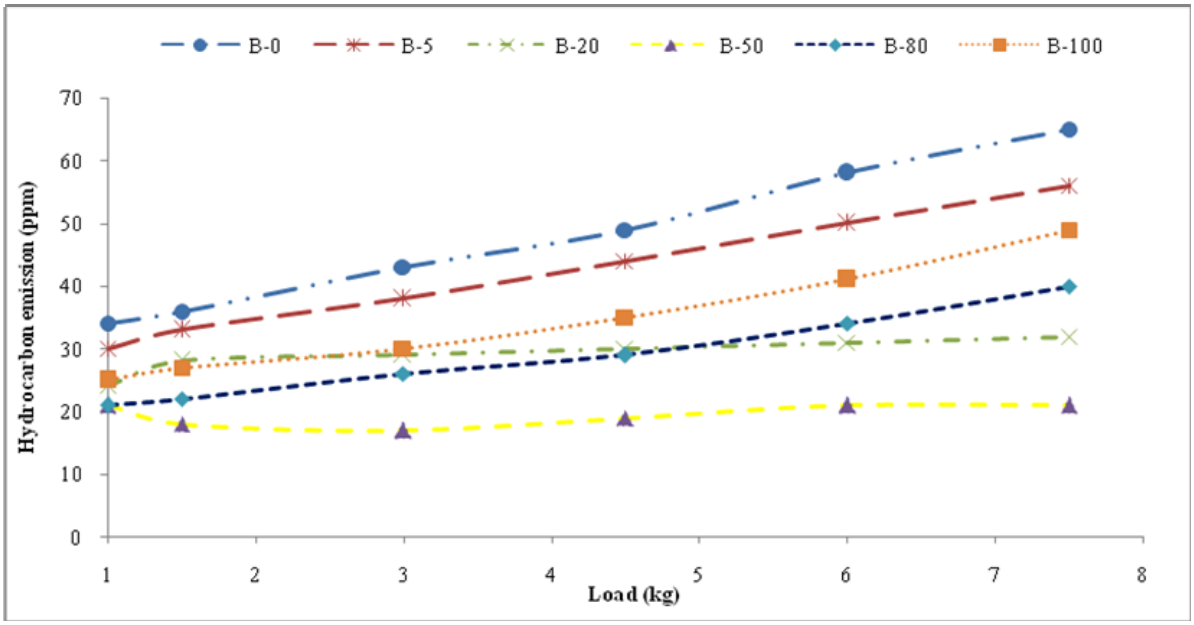

Figure 6. Hydrocarbon emission vs load

The variation of oxides of nitrogen (NO_x) emission for different blends is indicated in Figure 7. The NO_x emission for all the fuels tested resulted in an increasing trend with respect to load. NO_x emissions are higher for B-5, B-20, B-50, B80 and B100 as compared to B-0. NO_x emission depends upon the maximum combustion temperature. Higher combustion temperature of blends is the main reason for increasing NO_x. The lowest combustion temperature is for B-0. Therefore, total heat developed is comparatively low and lowest emission in NO_x is observed for B-0. The reason could be the higher average flue gas temperature at higher load conditions. The amount of fuel injected increases with the engine load in order to maintain the power output and hence the amount of heat release and the exhaust gas temperature rise with increase in load. Suitable NO_x reducing catalyst are being developed which can take care of this issue.

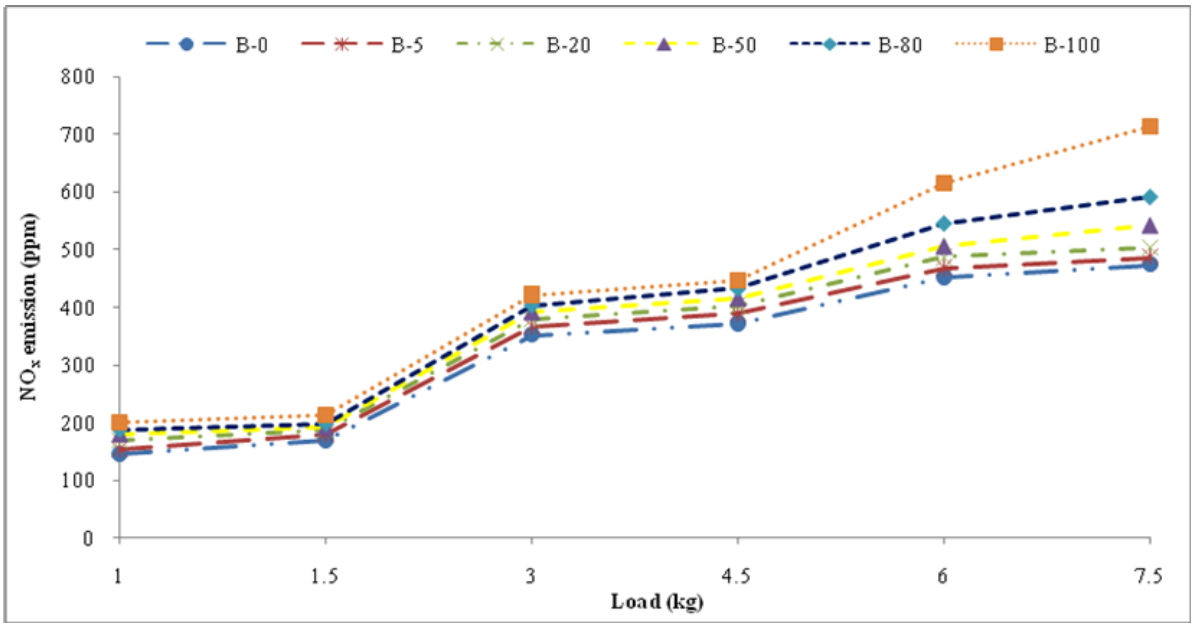

Figure 7. NOx emission vs load

The variation of exhaust gas temperature for various blends with respect to the load is indicated in Figure 8. The exhaust gas temperature for all the fuels tested increases with increase in the load. The amount of fuel injected increases with the engine load in order to maintain the power output and hence the heat release rate and the exhaust gas temperature rise with increase in load. Exhaust gas temperature is an indicative of the quality of combustion in the combustion chamber. Exhaust temperatures for B0 were in the range of 143°C to 441°C. At all loads, B100 was found to have the highest temperature of 561°C and the temperatures for the different blends showed a upward trend with increasing concentration of JME in the blends. This is due to the increased heat release rate owing to higher SFC. The increased exhaust gas temperature may heat the combustion chamber also thus putting extra load on engine cooling and lubrication system. This may enhance the requirement of coolant and lubricating oil in the engine. Increased combustion chamber temperature may itself cause detonation of injected fuel. Thus more field trials are required in hot areas in order to establish validity of JME blends with petro-diesel.

Figure 9 shows variation of smoke opacity with different blends at different loads. Smoke opacity increases with clogged, worn, mismatched injectors, misadjusted injection timing, clogged or worn fuel filters and restricted air filters. During experimental work Injector fouling took place while operating CI engine using diesel blended with JME. Excessive gum deposits were observed around injector which might have fouled the injector. Injection timing needs readjustment while using different fuel in the engine. Smoke opacity showed an increasing trend for diesel blended with biodiesel. B20 showed lower opacity compared to B50, B80 and B100 fuel. It is due to heavier molecular structure and higher viscosity; atomization becomes poor and this leads to higher smoke emission.

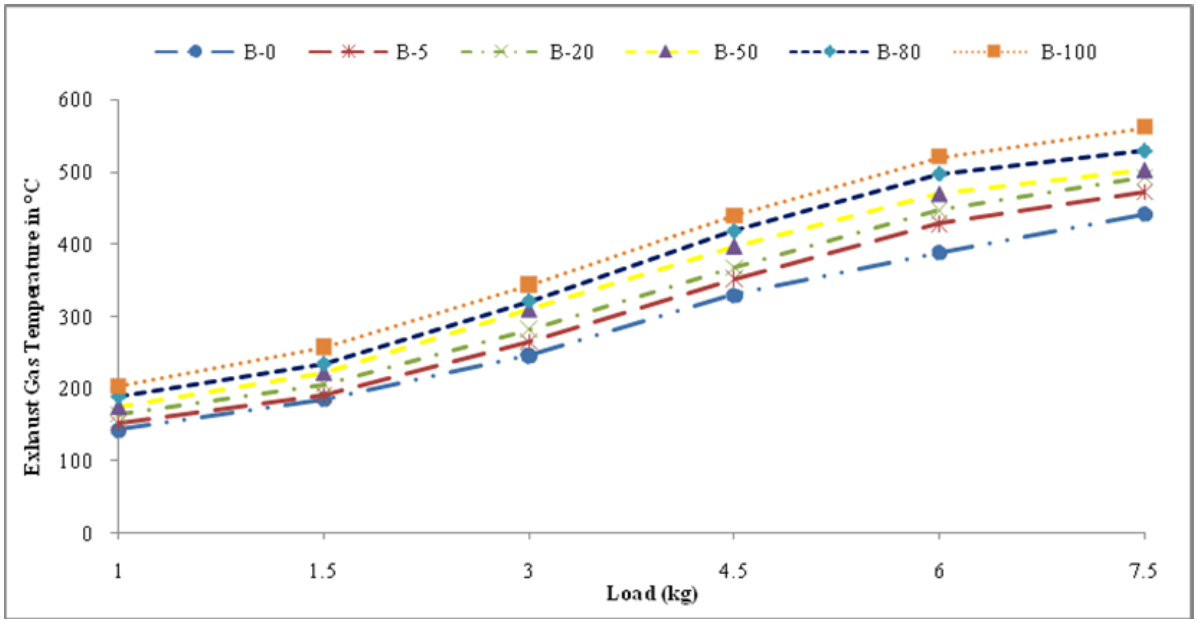

Figure 8. Exhaust gas temperature vs load

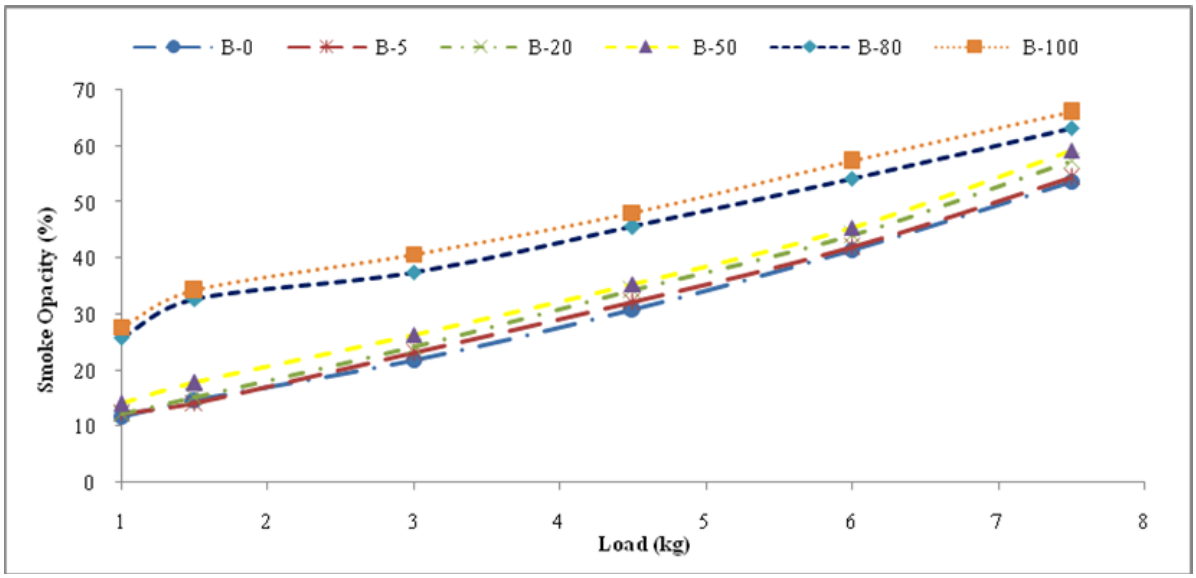

Figure 9. Smoke opacity vs load

It is interesting to note that the engine emits more CO for diesel as compared to diesel blended with JME under all loading conditions. It is seen from Figure 10 that the CO concentration is marginally present for the blend of B50 for all loading conditions and as the JME concentration in the blend increases above 50%, very marginal presence of CO is observed. At lower JME concentration, the oxygen present in the JME aids for complete combustion. Lower ignition delay due to higher cetane number also results in complete combustion. However, as the JME concentration increases, the negative effect due to high viscosity and small increase in density suppresses the complete combustion process which produces small amount of CO. At heavy loading B80 and B100 shows increase in CO emissions. This may be due to the incomplete combustion of larger quantity of fuel inducted during testing.

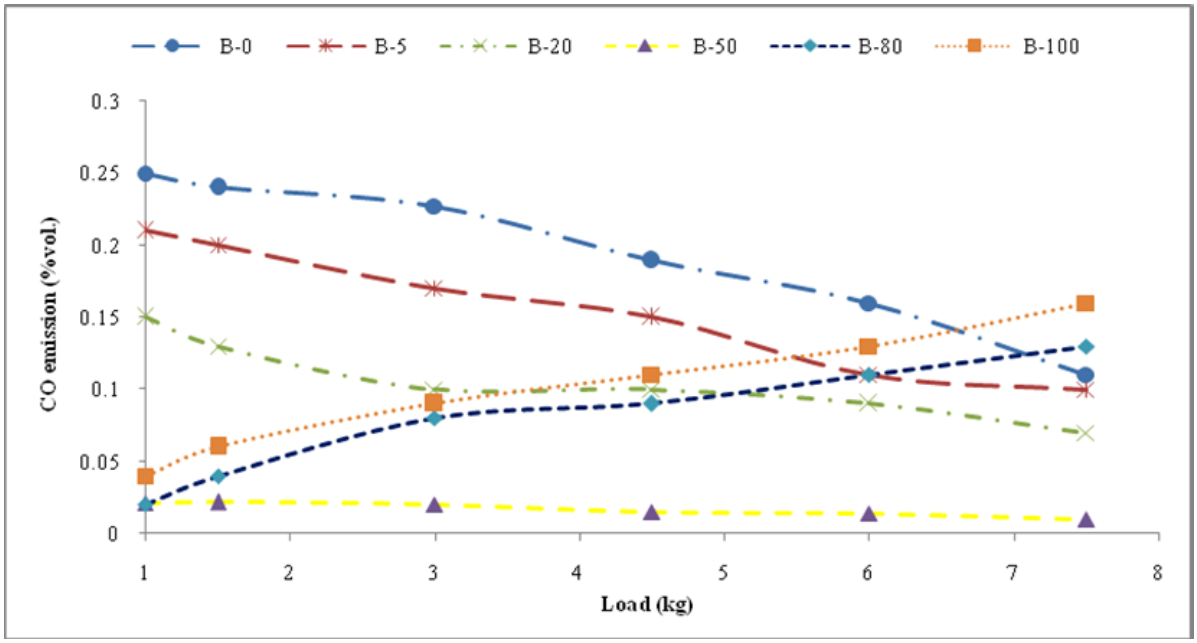

Figure 10. CO emission vs load

Figure 11 depicts the CO_2 emission of various fuels used. The CO_2 emission increased with increase in load for all blends. B20 and B50 fuel emits less amount of CO_2 in comparison with diesel. B50 emits least amount of CO_2 emissions. This is due to the fact that biodiesel in general is a low carbon fuel and has a lower elemental carbon to hydrogen ratio than diesel fuel. Using higher content JME blends, an increase in CO_2 emission was noted, which is due to the incomplete combustion as explained earlier. Though at higher loads, higher JME blends emit higher amount of CO_2, normally biodiesels themselves are considered carbon neutral because, all the CO_2 released during combustion is sequestered from the atmosphere for the growth of the vegetable oil crops.

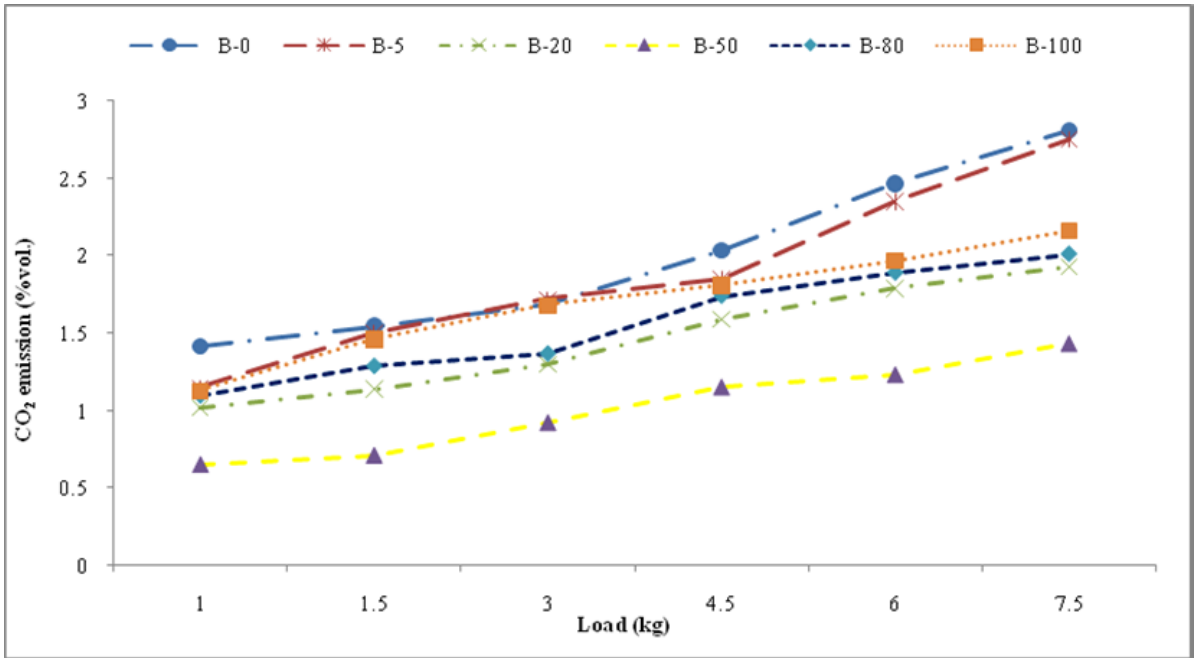

Figure 11. CO_2 emission vs load

Figure 12 shows the variation of oxygen (O_2) emission with load. The O_2 was observed to decrease with increase the load under all types of fuel. The oxygen gradually decreases with increasing diesel blended with jatropha biodiesel. At full load condition oxygen is low in B-100 as compared to that for B-5, B-20,

B-50 and B-100. Presence of oxygen in the flue gases indicates its sufficient availability for combustion of fuel. Absence of O_2 from exhaust gases implies requirement of more amount of air for fuel combustion which may eventually disturb the stoichiometric air/fuel ratio.

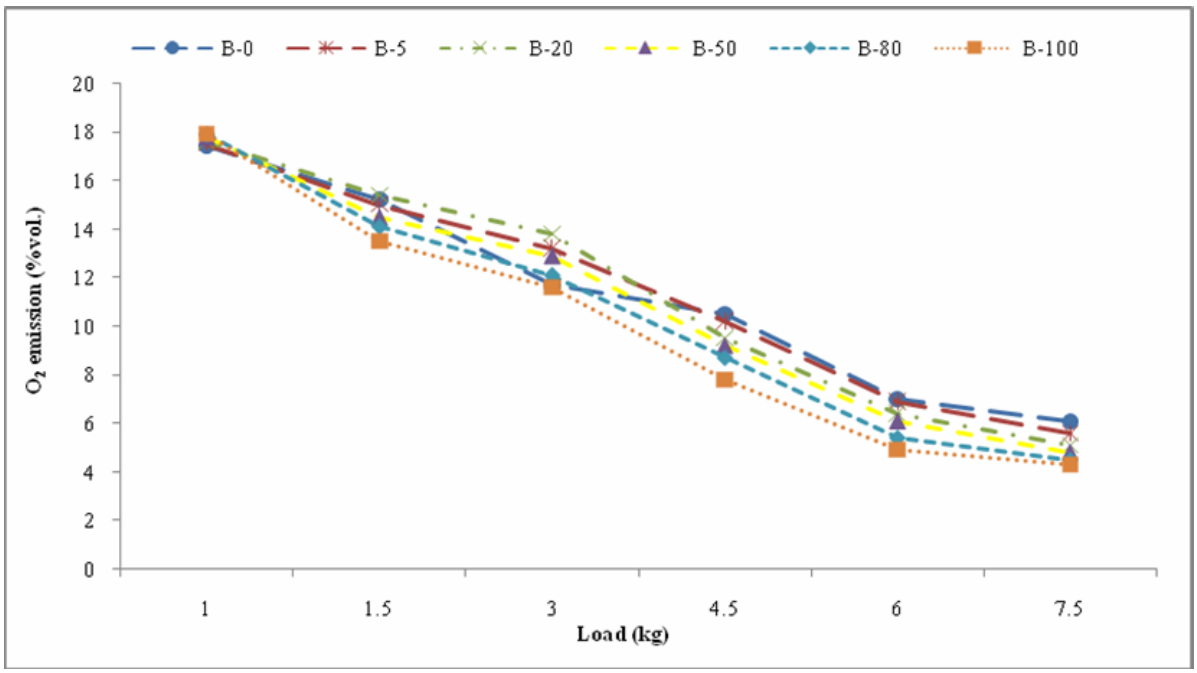

Figure 12. O_2 emission vs load

Volumetric efficiency observed for B0, B5, B20, B50, B80 and B100 fuel showed an almost similar trend as per Figure 13. Better volumetric efficiency indicates lesser deposition of carbon particles inside the engine cylinder. Even at higher loadings the value has been on higher side for all the fuels indicating availability of sufficient amount of air required for proper combustion. It is attributed to the lower soot formation and its subsequent lesser deposition inside the engine cylinder.

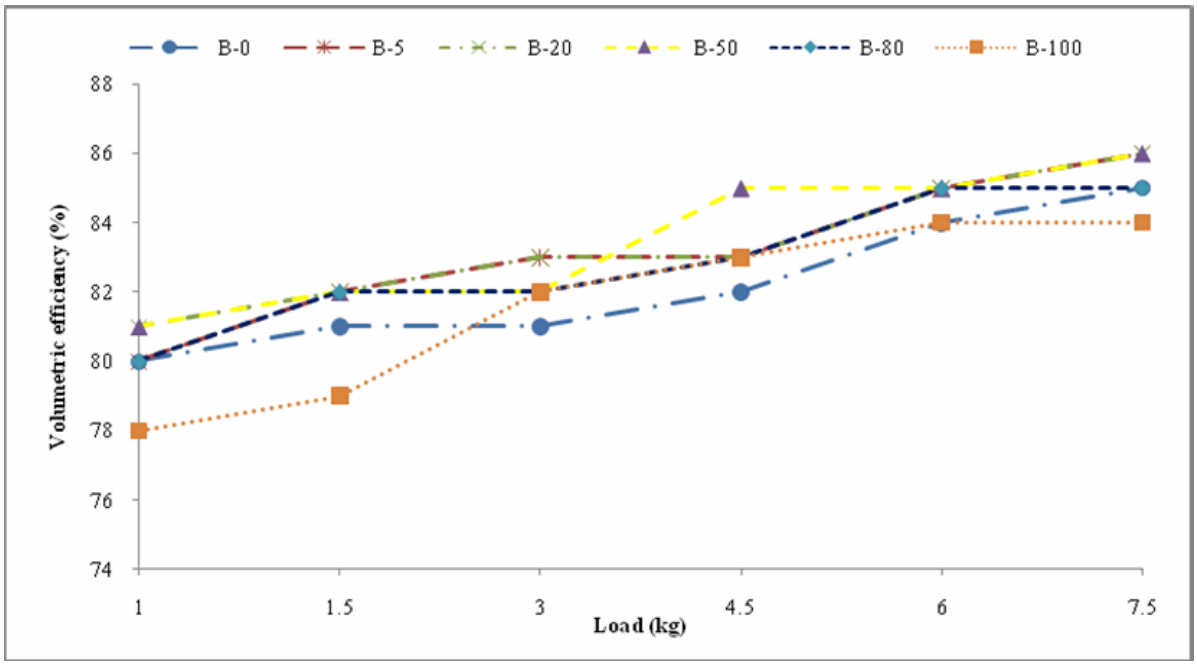

Figure 13. Volumetric efficiency vs load

5. Important miscellaneous issues

Injector fouling has been observed during testing of higher JME blends with diesel. Injector tip was frequently cleaned for proper functioning. Excessive vibrations and noise was observed while testing of B80 and B100 specifically at higher loadings 4.5 kg and above. Higher SFC and lower BTE for B80 and B100 imply lower full load efficiency. For diesel vehicles this is an important issue as they are supposed to run on higher loadings at most of the times of their usage. As a precautionary measure, fuel filter was cleaned prior to testing of B50, B80 and B100 fuels. Use of biodiesel likely reduces carbon deposit and wear of the key engine parts, compared with diesel due to the lower soot formation and inherent lubricity of biodiesel. The amount of carbonaceous residue from the hot decomposition of vegetable compounds with high molecular weight is greater than that of the diesel. This feature is crucial for a proper use of biodiesel in new advanced injection systems. Since biodiesel has detergent characteristics, it may bring in suspension fuel tank sludge that may block fuel-ways in the fuel injection system. Moreover, biodiesel is also not compatible with some plastic materials used in pipes and seals, which needs further investigation.

6. Conclusion

Presented experimental work shows higher BSFC, exhaust temperature and lower BTE with JME blended diesel. Higher exhaust temperature of JME blends can be attributed to the increased heat release rate owing to higher SFC. The increased exhaust gas temperature may heat the combustion chamber also thus putting extra load on engine cooling and lubrication system. This may enhance the requirement of coolant and lubricating oil in the engine. Increased combustion chamber temperature may itself cause detonation of injected fuel. Thus more field trials are required in hot areas in order to establish validity of JME blends with petro-diesel.

Higher BSFC for B5, B10, B20, B50 and B100 fuel is due to lower calorific value of JME as compared to diesel. Lower HC, CO_2, CO emissions during the usage of JME blended with diesel is a positive attribute related to lowering of regulated emissions. Considering stringent emission norms smoke opacity is a possible impediment to adoption of biodiesel.

Considering comparable BSFC and BTE of B20 w.r.t. diesel along with lower regulated emissions and lesser noise and vibrations observed for B20 fuel it can be concluded that maximum blending percentage of JME with diesel shall be kept as 20%.

HC emissions for biodiesel are significantly reduced, compared with diesel. The higher oxygen content, advance in injection and combustion of biodiesel and lower aromatic compounds has been regarded as the main reasons. NO_x emissions increase when using biodiesel mainly due to higher oxygen content and cetane number for biodiesel.

The further studies on the low temperature performance of biodiesel engine should be fulfilled because biodiesel presents higher viscosity than diesel, which could affect the emissions due to the different size of droplets for biodiesel and diesel without any change in fuel nozzle.

Improvement in properties and quality of biodiesel should be incorporated in the future. And the further development in additives which improve consumption of biodiesel should be needed to enhance power output and reduce emissions especially NO_x emissions. It should be done to readjust or redesign engine or/and its control systems for biodiesel, especially for optimizing ignition and injection, and EGR control to achieve a more efficient combustion and thus meet the needs of biodiesel engine.

The further studies on biodiesel engine endurance tests should be carried out to clarify the reason and mechanism of wears.

Lastly, biodiesel, especially for the blends with a small portion of biodiesel, is technically feasible as an alternative fuel in CI engines with no or minor modifications to engine. From environmental and economic perspectives, their popularity may soon grow. However, more researches and development in biodiesel resources and engine design are needed in India to make it feasible specifically in rural areas.

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