



Simulation of CI engine powered by neat vegetable oil under variable fuel inlet temperature

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Abstract

Vegetable oil was being used as fuel in earlier days when the petroleum fuel supply was quite expensive and/or difficult to obtain. Later, with the ease of availability and supply of petroleum products, vegetable oil was replaced with the diesel which reduced the dependence on vegetable oil and the entire research efforts were directed towards improving the performance of CI engine using diesel fuel and the research efforts directed towards improving the performance of CI engines using vegetable oil as fuel for CI engines were reduced to very large extent. The present work describes the simulated result of the performance of a four stroke, single cylinder, air-cooled, direct-injection compression ignition engine powered by neat jatropha oil. The preheating of the neat jatropha oil is done from 30°C to 100°C. The performance of the engine was studied for a speed range between 1500 to 4000 rpm, with the engine set at full throttle opening and hence the engine was operated under full load conditions. The parameters considered for comparing the performance of neat jatropha oil with that of diesel fuel operation, were brake specific fuel consumption, thermal efficiency, brake power, NO_x emission of the engine. The software established that i) the engine offers lower thermal efficiency when it is powered by preheated neat jatropha oil at higher speed ii) the power developed and Nox emission increase with the increase in the fuel inlet temperature iii) and the specific fuel consumption is higher than diesel fuel operation at all elevated fuel inlet temperature.

Keywords: Alternative fuel, biofuel, neat jatropha oil, diesel engine, Diesel-RK software

Introduction

Transportation fuels produced from biomass are commonly called biofuels. First-generation biofuels are mostly produced from feedstock that is also used for food products. Such biofuels are ethanol from sugar cane or corn, biodiesel from canola seeds or soybeans, and others. They are commonly produced all over the world. The second-generation biofuels, which come from non-food sources, have high potential as a renewable transportation fuel (Sulzer technical review, 2009). India being predominantly agricultural country requires major attention for the fulfillment of energy demands of a farmer. Irrigation is the bottleneck of Indian agriculture, it has to be developed on a large scale, but at the same time diesel fuel consumption must be kept to a minimum level because of the price of diesel and its scarcity. The increased use of diesel in agriculture and transportation sectors has resulted in diesel crisis (Banapurmath *et al.*, 2008).

Global ethanol production (ethanol can be used as fuel for cars) almost doubled between 2005 and 2008, increasing from 34 to 65 billion liters annually. Global production of biodiesel, starting from a much smaller base, expanded nearly fourfold in the same period. Compared with the world oil demand of around 86 million barrels (1 barrel = 159 l) per day, biofuels still constitute a small share overall. This contribution can be significantly expanded in the future, reducing emissions of greenhouse gases and increasing energy security (Sulzer Technical Review, 2009; Pugazhvidivu, 2009).

In the contest of fast depletion of petroleum reserves associated with rising vehicle population and stringent emission standards, the development of alternative energy sources has become important (Math *et al.*, 2010). Vegetable oils hold good promise as alternative fuel for diesel engines (Thiruvengadaravi *et al.*, 2009). They are biodegradable and renewable fuels. They have a reasonably high cetane number. The flash point of vegetable oils is high and hence it is safe to use them (Deepak Agarwal *et al.*, 2007). Vegetable oils typically have large molecules with carbon, hydrogen, and oxygen being present (Senthil Kumar *et al.*, 2010). They have a higher molecular mass and viscosity. Contrary to fossil fuels, vegetable oils are free from sulfur and heavy metals (Teerapong Baitiang *et al.*, 2008; Naga Prasad *et al.*, 2009). A number of vegetable oils like rapeseed oil, neem oil, palm oil, karanji oil, coconut oil, cottonseed oil, jatropha oil, etc., were tested to evaluate their performance in diesel engines (Senthil Kumar *et al.*, 2010). Among these, jatropha oil was found as the most suitable for diesel (Pramanik, 2003). As a compression ignition engine fuel, jatropha oil has a high cetane number, which is very close to diesel (Deepak Agarwal *et al.*, 2008). The flash point of jatropha oil is high 240°C as compared with 75°C for diesel. Due to its high flash point, jatropha oil has certain advantages like greater safety during storage, handling, and transport. However, this may create problems during starting. The viscosity of jatropha oil is less as compared with other vegetable oils but it is higher than diesel (Senthil Kumar *et al.*, 2010).



The main problem associated with the use of vegetable oils is their high viscosity and poor volatility. Since straight vegetable oils are not suitable as fuels for diesel engines, they have to be modified to bring their combustion related properties closer to diesel. This fuel modification is mainly aimed at reducing the viscosity to eliminate flow/atomization related problems (Deepak Agarwal *et al.*, 2007). Different methods have been tried to use vegetable oils efficiently. Some of them are: 1) heating/pyrolysis, 2) transesterification with alcohols, 3) dilution/blending with diesel / alcohol, 4) dual fueling with gaseous and liquid fuels, 5) micro-emulsion, and 6) use of additives (Nwafor, 2003; Deepak Agarwal *et al.*, 2007).

In rural and remote areas of developing countries, where grid power is not available, vegetable oils can play a vital role in decentralized power generation for irrigation and electrification. In these remote areas, different types of vegetable oils are produced locally but it may not be possible to chemically process them due to logistics problems in rural settings. Hence using heated or blended vegetable oils as petroleum fuel substitutes is an attractive proposition (Deepak Agarwal *et al.*, 2007). Keeping these facts in mind, a set of engine experiments were conducted using neat *Jatropha* oil on a engine, which is typically used for agriculture, irrigation and decentralised electricity generation.

The properties of neat *Jatropha* oil used for the purpose of simulation are derived from already published reports (Pramanik, 2003; Agrawal *et al.*, 2007; Sundarapandian *et al.*, 2007; Baitiang *et al.*, 2008; Harumi Veny *et al.*, 2009; Rao *et al.*, 2009; Singh *et al.*, 2009). Heating were used to lower the viscosity of *Jatropha* oil in order to eliminate various operational difficulties. Forson *et al.* (2004) used *Jatropha* oil and diesel blends in compression ignition engines and found its performance and emissions characteristics similar to that of mineral diesel at low concentration of *Jatropha* oil in blends. Higher viscosity is a major problem in using vegetable oil as fuel for diesel engines. Deepak Agarwal *et al.* (2007) and Pramanik (2003) tried to reduce viscosity of *Jatropha* oil by heating it and also blending it with mineral diesel. Viscosity of *Jatropha* oil was measured at different temperatures in the range of 40-100°C. The results are shown in Fig. 1.

Viscosity of *Jatropha* oil decreases remarkably with increasing temperature and it becomes close to diesel at temperature above 90°C (within ASTM limits). Viscosity of diesel was 2.44 cSt at 40°C. For *Jatropha* oil, viscosity was found below 6 cSt at a temperature above 100°C (Deepak Agarwal *et al.*, 2007). Harumi Veny *et al.* (2009) determined densities at temperatures above their melting point ranging from 15°C to 90°C at 1°C intervals, and the results show that the liquid densities of *Jatropha* oil decrease linearly with an increase in temperature.

Therefore, *Jatropha* oil should be heated to 100°C before injecting it into the engine in order to bring its physical properties close to mineral diesel (at 40°C).

Simulation model

The theoretical models used in the case of internal combustion engines can be classified into two main groups viz., thermodynamic models and fluid dynamic models. Thermodynamic models are mainly based on the first law of thermodynamics and are used to analyze the performance characteristics of engines. Pressure, temperature and other required properties are evaluated with respect to crank angle or in other words with respect to time. The engine friction and heat transfer are taken into account using empirical equations obtained from experiments. These models are further classified into two groups namely single-zone models and multi-zone models. On the other hand, multi-zone models are also called computational fluid dynamics models. These are also applied for the simulation of combustion process in the internal combustion engines. They are based on the numerical calculation of mass, momentum, energy and species conservation equations in either one, two or three dimensions to follow the propagation of flame or combustion front within the engine combustion chamber. Several software, which are based on the above models, were commercialized in order to be used for the simulation of compression ignition engines, namely; ProRacing engine simulation, Virtual engine DYNO, ECFM-3Z (three zone extended coherent flame model), Advisor (Advanced Vehicle SimulatOR) and DIESEL-RK Software etc., In this work the Diesel-RK software was used since its agreement with experimental data was very good as indicated in references (Hamdan & Khalil, 2009). It is a multi-zone model of diesel sprays evolution and combustion, it takes into account: the shape of injection profile, including split injection; drop sizes; direction of each spray in the combustion chamber; the swirl intensity; the piston bowl shape. Evolution of wall surface flows generated by each spray depends on the spray and wall impingement angle and the swirl intensity. Interaction between near-wall flows (further named wall surface flows) generated by the adjacent sprays is taken into account. The method considers hitting of fuel on the cylinder head and liner surfaces. The evaporation rate in each zone is determined by Nusselt number for the diffusion process, the pressure and the temperature, including temperatures of different walls where a fuel spray reaches. A parametric study of the swirl intensity effect has been performed and a good agreement with experimental data was obtained. The calculations results allow describing the phenomenon of increased fuel consumption with increase of swirl ratio over the optimum value. The model has been used for simulation of different engines performances. The model does not require recalibration for different operating modes of a diesel engine (Hamdan & Khalil, 2009).

Theoretical studies using DIESEL-RK software

Thermodynamic software DIESEL-RK was used for calculations and optimization of the performance for compression ignition engine when it is powered by neat

vegetable oil. The main reason of using the software is to do a theoretical study at different fuel inlet temperatures and up to the maximum value of 120°C. It is also used to determine the temperature, pressure and heat released or transferred at each stroke or crank angle (Alahmer *et al.*, 2009).

The parameters related to the performance of the engine, which were evaluated, are: specific fuel consumption, the thermal efficiency, brake power and NO_x emissions. These parameters were evaluated for each fuel inlet temperature and at different engine speed. The engine used in this work has the specification as shown in Table 1 and the properties of the diesel fuel and neat jatropha oil, used as input data to the software, at different temperatures are cited in Table 2.

Table 1. Engine Specification

Item	Technical Data
Model	VRC 1
Make	COMET
Rated BHP / kW	5.0 / 3.7
Bore x Stroke (mm)	80.0 x 110.0
Swept Volume (CC)	553
Compression Ratio	17.5:1
Rated RPM	1500
No. of Cylinder	1
Method of Cooling	Air
Bearing Type	Bush
Sp. Fuel Consumption gms / Kwhr	251
Lubrication System	Plunger pump
Crank Shaft Height (mm)	203

Deepak Agarwal *et al.*, 2007; Harumi Veny *et al.*, 2009). The test results showed that heating neat jatropha oil to a temperature above 100°C brings its physical properties close to mineral diesel at 40°C (Deepak Agarwal *et al.*, 2007).

Engine performance

The results obtained under full engine load conditions, are presented in Fig. 1 through fig. 4, with variation in speed for various fuel inlet temperatures. The variation of Brake-specific fuel consumption, Thermal efficiency, effective engine

power and NO_x emissions with engine speed is shown in Fig. 1-4, respectively. Brake-specific fuel consumption and NO_x Emissions are high at low engine speed but when engine speed is increased, the NO_x emissions are higher and Brake-specific fuel consumption is quite

similar to that of diesel operation.

From Fig. 3, it can also be observed that when the power reaches its maximum value, then it decreases. The engine power and thermal efficiency are generally slightly lower than the corresponding values using ordinary diesel fuel.

The thermophysical and chemical properties of the jatropha oil fuel such as low heating value and high viscosity as compared to diesel fuel and improper air and jatropha oil fuel mixture cause inefficient combustion due to improper atomization of vegetable oil fuel.

Brake-specific fuel consumption

Brake-specific fuel consumption (bsfc) is the ratio between mass fuel consumption and brake effective power, and for a given fuel, it is inversely

proportional to thermal efficiency (Lapuerta *et al.*, 2008).

The results for the variation in the brake specific fuel consumption (bsfc) with increasing fuel inlet temperature on the engine at various speed range studied are presented in Fig. 3. For all fuel inlet temperatures, the specific fuel consumption varies with increasing speed. For neat jatropha oil fuel, brake specific fuel consumption has high value at low speed but decreases as the speed increases, and then it reaches the value to that of a diesel fuel operation. The brake specific fuel consumption (bsfc) becomes equal at the maximum speed for both neat jatropha oil fuel and diesel fuel (within the speed range studied).

Table 2. Properties of mineral diesel and Jatropha oil

Property	Fuel		30°C	80°C	100°C	Reference
	Mineral diesel	Jatropha oil				
Density (kg/m ³)	840 ± 1.732	917 ± 1	906.3	871.3	857.3	1,2, 4,5,6,7
Kinematic viscosity at 40°C (cSt)	2.44 ± 0.27	35.98 ± 1.3	52.76	9	5	1,2, 4,5,6,7
API gravity	36.95 ± 0.346	22.81 ± 0.165				4
Cloud point (°C)	3 ± 1	9 ± 1				4
Pour point (C)	6 ± 1	4 ± 1				2,4,6
Flash point (C)	71 ± 3	229 ± 4				2,4,5,6
Fire point (C)	103 ± 3	274 ± 3				2,4,
Conradson carbon residue (% w/w)	0.1 ± 0.0	0.8 ± 0.1				3,4,6
Ash content (% w/w)	0.01 ± 0.0	0.03 ± 0.0				2,4,6
Calorific value (MJ/kg)	45.343	39.071				2,3,4,5,6,7
Carbon (% w/w)	80.33	76.11				2,3,4,6
Hydrogen (% w/w)	12.36	10.52				4,6
Nitrogen (% w/w)	1.76	0				4,6
Oxygen (% w/w)	1.19	11.06				4,6,7
Sulfur (% w/w)	0.25	0				2,4,6
Cetane Number	46	23				2,4,5,6,7

Results and discussion

Fuel inlet temperature

The test results show the effect of increasing fuel inlet temperature on the viscosity of neat jatropha oil and its performance in a single cylinder unmodified diesel engine. The fuel inlet temperature was the only parameter that was changed and the shift in engine performance is attributed to these temperature changes. The flow of neat jatropha oil becomes a problem as the temperature drops down (Nwafor, 2003). Selection of fuel inlet temperature of 100°C was based on the laboratory test results of viscosity-temperature and density-temperature relationships shown in Fig. 1 & 2 (Pramanik, 2003;



Fig. 1. Effect of temperature on viscosity of Jatropha oil.

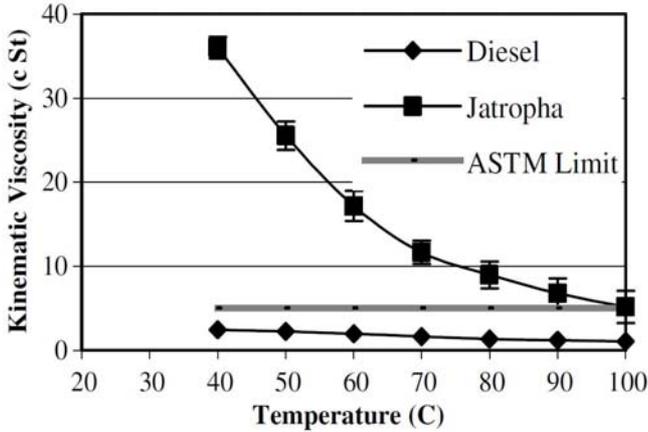


Fig. 2. Density comparisons of Jatropha oil with rapeseed, soybean, milkweed, and lesquerella oil

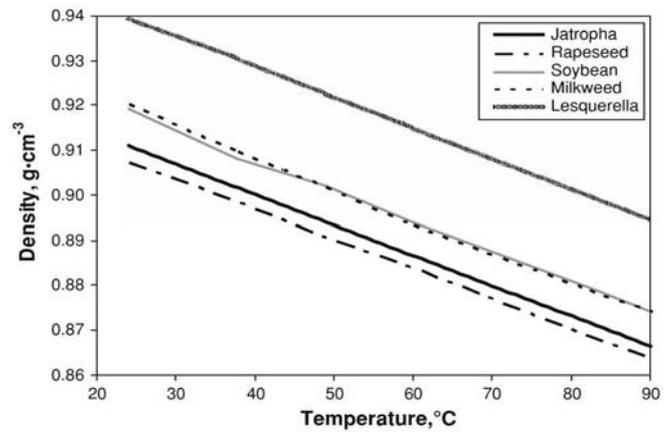


Fig 3. Variation of specific fuel consumption with speed at elevated fuel inlet temperatures

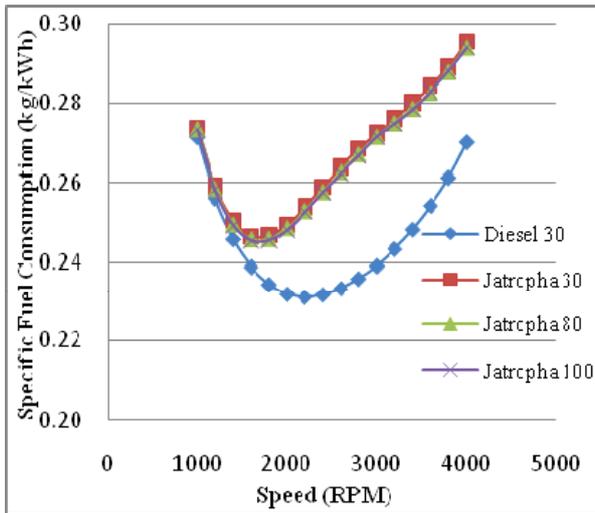


Fig 4. Variation of engine thermal efficiency with speed at elevated fuel inlet temperatures

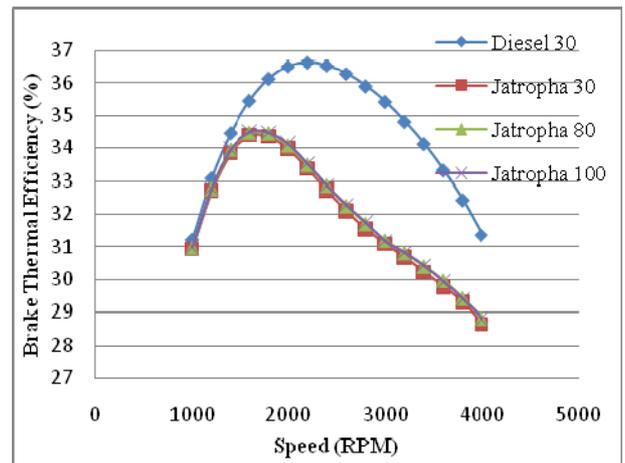


Fig 5. Variation of engine power with speed at elevated fuel inlet temperatures

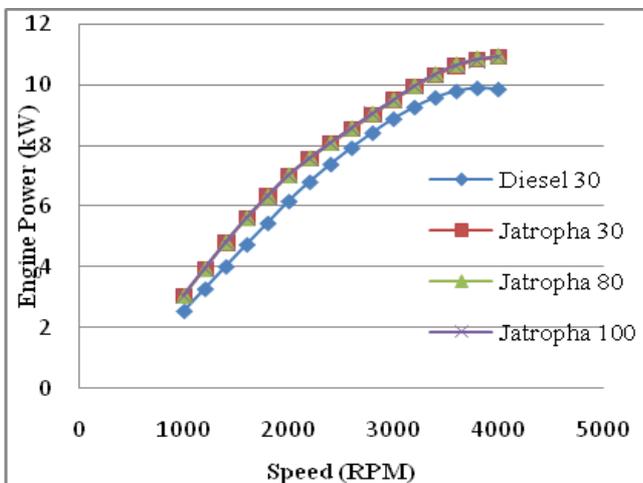
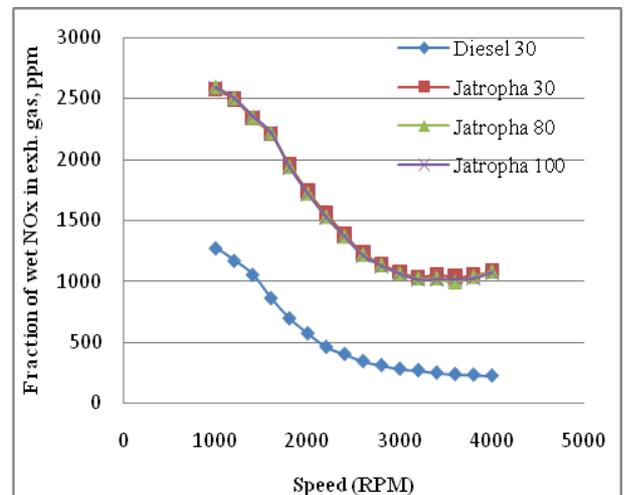


Fig 6. Variation of NO_x Emissions with speed at elevated fuel inlet temperatures





Thermal efficiency

Thermal efficiency is the ratio between the power output and the energy introduced through fuel injection, the latter being the product of the injected fuel mass flow rate and the lower heating value. Thus, the inverse of thermal efficiency is often referred to as brake-specific energy consumption (Lapuerta *et al.*, 2008; Hamdan & Khalil, 2009). Since it is usual to use the brake power for determining thermal efficiency in experimental engine studies, the efficiency obtained is really a brake-specific efficiency. Hence it is more appropriate to consider the brake-specific energy to compare the performance of different fuels instead of using their heating values (Lapuerta *et al.*, 2008; Hamdan & Khalil, 2009).

It is observed that the brake thermal efficiency is slightly lower than that of the corresponding diesel fuel, at higher fuel inlet temperature and at higher speed of the engine. It can be seen from the Fig. 2 that the efficiency is quite close to that of a diesel at very high speed of the engine. This means that the increase of brake specific fuel consumption is lower than the corresponding decrease of the lower calorific value of the neat vegetable oil, which could have been caused by reductions in friction loss associated with higher lubricity of neat jatropha oil.

Engine power

Fig.3 shows the variation of the engine power with speed for diesel and neat jatropha oil at elevated temperature. As expected and as a general trend, initially the engine power increases with a speed to a maximum value at a engine speed of 3500 rpm, and decreases thereafter for speeds higher than 3500 rpm. The decrease in engine power after reaching its maximum value is an expected phenomenon as the speed further increases. Further, it may be noticed that the power produced is slightly higher than that of ordinary diesel fuel with the increasing speed of the engine for neat vegetable oil at higher speed of the engine and at high fuel inlet temperature.

NO_x emissions

Although most of the literatures reviewed show a slight increase in NO_x emissions when using biodiesel fuel, some works showing different effects have been found. Some of them found increase in NO_x emission only for certain operating conditions, some others did not report differences in NO_x emission between diesel and biodiesel fuels, and others reported even decrease in NO_x emissions when using biodiesel (Lapuerta *et al.*, 2008).

There are combustion models reporting simulated results of increase in NO_x emissions when using biodiesel fuels. As against this, Sundarapandian and Devaradjane (2007) reported the decrease in nitric oxide formation from the comparison of predicted result of nitric oxide formation with respect to engine load condition for different vegetable oil esters and diesel fuel. Choi and Reitz (1999) presented a model on auto-ignition delay times, and temperature distributions in the combustion

chamber using biodiesel from soybean oils as well as diesel fuel. They obtained reduced auto-ignition times and higher extension of the high-temperature areas when using biodiesel fuels and used the results obtained by their model to explain the typical increase in NO_x emissions.

Diesel engines operate with an excess air ratio on full load and higher values on lower loads. Diesel engine combustion generates large amounts of NO_x because of high flame temperatures (1800°K) in the presence of abundant oxygen and nitrogen in the combustion chamber (Deepak Agarwal *et al.*, 2006). The variation of NO_x emissions for both the fuels with engine speed is shown in Fig. 4.

The NO_x emission increases with the increase in engine speed and reaches its maximum value at a speed of 3500 rpm and further goes on decreasing and there is no significant change with increased fuel inlet temperature. To reduce NO_x emission, the temperature in the cylinder should be reduced. The NO_x emission increases with the engine load at 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. From Fig. 4, it can be seen that within the range of tests, the NO_x emissions from the neat vegetable oil are higher than that of diesel fuel. This is probably due to the increased fuel inlet temperature.

Conclusions

In this work a four stroke compression engine was simulated using DIESEL-RK software. The simulations were performed in order to find the performance of the engine when it is powered by neat jatropha oil at different fuel inlet temperatures. The fuel inlet temperatures and kinematic viscosity coefficients were the only parameters which were varied, and the shifts in engine performance must be attributed to these temperature and viscosity variations only. The results obtained through the simulations can be summarized as under:

1. At higher speed there is no significant difference in BSFC when the engine is operated with preheated and unheated vegetable oil fuels. In other words, BSFC is not affected due to temperature of fuel at inlet conditions.
2. The vegetable oil fuel produced the same brake thermal efficiency at high speed and low speed of the engine and slightly deviating in the mid of the speed range studied. The heated fuel showed a marginal decrease in brake thermal efficiency as compared to diesel fuel operation.
3. Engine power increases with speed to a maximum value at an engine speed of 3500 rpm. At speeds more than 3500 rpm the power produced is slightly higher than that of ordinary diesel fuel. This clearly indicates that at higher engine speed conditions the performance of vegetable oil fuel can exceed that of diesel fuel operation.



4. There was significant increase in NO_x emissions when running on neat vegetable oil fuel compared to diesel fuel operation. The overall test results showed that fuel heating was not beneficial at low speed operation. The higher combustion temperatures become the dominant factor at higher speed operations, making both heated and unheated vegetable oil fuels to acquire the same system temperature before fuel injection.

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