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Performance and emissions of compression ignition engines using waste cooked oil as fuel

PERFORMANCE AND EMISSIONS OF COMPRESSION IGNITION ENGINES USING WASTE COOKED OIL AS FUEL

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Abstract

Public and Government concern about environmental pollution and the high price of petroleum products have forced the development of alternative fuels for automotive applications. Biodiesel is one of the alternative fuels which can be produced from vegetable oils (either pure or waste) or animal fats. Since biodiesel has properties similar to diesel, it can be substituted for the latter with little or no engine modification. Also, its use can reduce the engine emissions. In this study, biodiesel is produced from waste vegetable oil using Fuel Pod 2™ system. The chemical catalists used were methanol and Sodium hydroxide. The production process yielded 87% biodiesel with the remaining being glycerin and soap. The biodiesel production cost was evaluated considering the chemical costs, running costs, waste oil collection costs, etc. The biodiesel price was found to be about 60 pence per litre which is nearly half of the petro-diesel price. A Ford Puma 2.4 litre diesel engine was used to investigate the effects of petro-diesel/biodiesel blends on the performance and emissions of the diesel engine. Petro-diesel and biodiesel (B100) fuels was tested in addition to three blends B10 (10% biodiesel and 90% petro-diesel), B15 and B20. The engine load varied as 25, 50, 75, and 100% full load. Also, the engine speed varied as 1500, 2200, 2600, 3000 and 3300 rpm. At these conditions, the engine torque, fuel consumption and emissions were measured. Accordingly, the performance parameters were evaluated such as engine power, specific fuel consumption and engine efficiency. The monitored exhaust emission included carbon dioxide (CO2), carbon monoxide (CO), total unburned hydrocarbons (THC), and nitric oxides (NOx).

Keywords: Fossil fuel, Biodiesel, alternative fuels, Engine performance, Exhaust emissions

1. Introduction

In 2007 the global manufacturing output of the automotive industry peaked at over 73 million vehicles (Figure 1). There was a slight dip due the the recession but in 2011 the output is expected to reach 80 million vehicles. This number does not include 2-wheeled vehicles. Within 5 years the number of vehicles on the road will be over one billion – 96% powered by IC engines. That number of vehicles demands something in the order of 9 trillion litres of fuel per year.

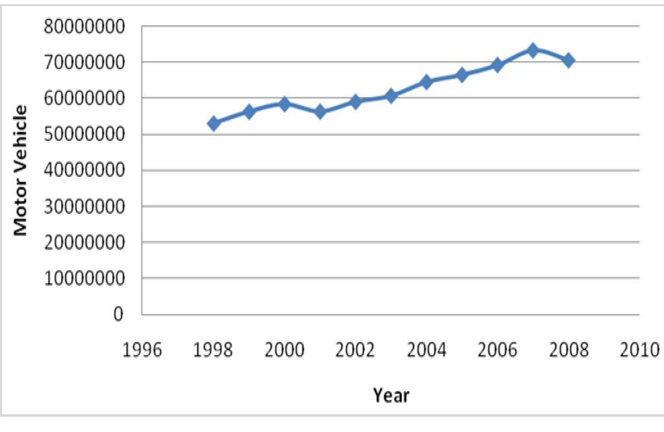

Figure 1 – World Vehicle production 1998 to 2008.

Diesel fuel is one of the major transportation fuels used in the motor vehicles including cars, trucks, and ships. Fossil fuels such as diesel, kerosene, etc. are a non-renewable sources of energy and hence, their use must be limited. It is anticipated that as fossiol fuels become scarce its supply will be limited to the commercial market, the public transportation making use of alternative sources of energy. Therefore, diesel must be carefully used as the cost of using diesel engines is lower than the gasoline SI engines. The use of diesel in engines could lead to a lot of knocking in the engine, which can cause damage to the engine. Diesel engines produce large amount of polluting gases such as carbon monoxide, unburnt hydrocarbons (THC - smoke) and oxides of nitrogen (NOx). In shipping Oxides of Sulfur (SOx) is of concern. This can be very harmful to the environment and can cause health problems to the surrounding population, town and city emissions maps now being produced by the Enviromental Agencies. In addition to the emission of this gases, diesel engines produce more airborne substances such as soot, lead and black carbon particles than the gasoline engines. This can also harm the environment and cause respiratory problems for the young and old. Emission of these harmful gases and particles result in greenhouse effect, air pollution, and acid rain which is very harmful to the environment. If these gases and particles are constantly inhaled by the local populous it will cause various diseases such as skin cancer, lung cancer, breathing problem, and poisoning.

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One of the alternatives to fossil fuels for the internal combustion engine is biofuel, or non-fossil fuels. Biofuels are renewable sources of energy and produces globally zero net amount of carbon dioxide (CO2). Biofuel, however, is more expensive than fossil fuels such as diesel. Therefore, for the biofuels to be used widely it is important that the government support research and development of more economical manufacturing techniques in form of subsidies and grants. Without the subsidies biofuel will not be widely used as the consumers will prefer using cheaper fuels such as diesel [1, 2, 3]. Using biodiesel helps to reduce the carbon dioxide emission to the atmosphere and the dependence on fuel imports, it is renewable in nature and safer to handle, it has no aromatic compounds, practically no sulfur content, and oxygen atoms in the molecule of fuel which may reduce the emissions of CO, total hydrocarbon (THC) and particulate matters (PM) [4,5,6].

Vegetable oil is used extensively in cooking and is needed especially to fry food. After using the same oil over and over again, the remaining oil becomes tainted with old food remains and can no longer be used for cooking the food. This waste oil has to be disposed of, which can be a problem. It is possible that this waste oil be used in the diesel engines as a fuel if cleaned and properly converted to combustible diesel oil. If a large amount of waste vegetable oil is used in the diesel engine, it can reduce the large amount of waste oil which has to be disposed of safely and cleanly by alternative means. The large amount of waste oil and fresh-pressed vegetable oil as produced by the food industry and restaurants is a source of "free" and sustainable oils available for conversion. Used cooking oil is essentially a waste product [7] and for that reason it is cheaper than unused (virgin) vegetable oil [8, 9]. There are two methods in which the vegetable oil can be used as an engine fuel;

- One of the methods is to use chemical reactions of methanol and sodium hydroxide to convert the waste oils and fats to biodiesel. The resulting biodiesel can be used in the diesel engine and the engine does not require any changes for it use this biodiesel. This method of converting waste oil to biodiesel has some problems as it uses toxic or corrosive materials. This process also produces by-products which must also be disposed. As a result this process of conversion reduces the economic attractions for using the waste oil.
- A second method of using waste oil as a fuel in the engine is to use the waste oil, without making any changes, directly in the diesel engine. This process will not produce any by-product as the waste oil is not converted into biodiesel. However, the typical engine will be modified so that it is able to use waste oil as a fuel [10]. The costs of conversion and the inherent warrant issues with engines will not favour this as a sensible move to using waste oils. The emissions are unknown at this stage but long term degradation of the engine and subsequent increased in emissions issues and loss of engine performance again place this approach to using waste oils in the subjective arena.

In the present state of energy consumption there is a shortage of mineral oil. The oil exporting countries are taking advantage of the situation by increasing the cost of crude oil and at same time the sources of non-renewable mineral oil are getting depleted. Thus, there is a need to find out an effective alternative fuel to meet the demands of the economic development aimed for each country. Recently, attraction of using waste oil has increased due to their environmental benefits and their renewable nature [11]. Approximately, 2.2 million tonnes of waste cooking oil is available around the world and its large amount is illegally dumped into rivers and landfills causing environmental pollution [12]. Socially this is unacceptable practice. Management of such waste cooking oils pose a significant challenge due to disposal problems and its possible contaminating characteristics of water and land resources. Even though certain amount of waste cooking oil is used for soap production, it is still a pollutant [13].

2. Experimental setup

2.1. Biodiesel Production from Waste Oil

In order to produce biodiesel from waste cooked oil, the Fuel Pod 2™ was used as shown in Figure 2. This is a complete commercially available system and comes complete with a corresponding methodology for making biodiesel. The oil has to be pre-heated to a minimum of 50ºC and a maximum of 65ºC before transfer to the reaction tank. A band heater is used to heat the oil and to keep the mixture at a constant temperature. This process generally takes 3 to 4 hours for the 50 litres batch. The biodiesel is known by the chemical name "Fatty-Acid Methyl Ester" (FAME), which means that it is a simple molecule obtained from vegetable oil. This fuel has higher content of energy and suitable viscosity which makes it a reliable fuel for diesel vehicles and equipment. Since it is made from natural crops, it is considered as liquid form of solar energy. The chemical reaction used for producing biodiesel is relatively understandable. Vegetable oil is a 'triglyceride', which means three hydrocarbon chains all attached to the same glycerine molecule. To break these hydrocarbons some form of catalyst is used. In used vegetable oils the catalyst (caustic) is added to the chemical reaction to neutralise the "free fatty acids" which have been formed in the waste oil. In methyl alcohol (methanol), this catalyst is dissolved in 20% volume of the oil which is to be converted. This mixture is vigorously blended with the oil so that the oil is completely converted. Due to the blending the catalyst breaks off, one by one, each hydrocarbon chain and combines with the methanol molecule, which is floating, to produce biodiesel. The freed glycerine molecule goes to the bottom of the tank, from where it is removed. The total mixture volume contains 10% glycerine.

Figure 2 – Fuel pod to manufacture bio-diesel

2.2 . Cost estimates and comparison

Waste cooking (Vegetable) oil collectors almost do not pay any charges or prices for the oil. However, the waste oil collection and cleaning process are of considerable costs. Several authors have attempted to evaluate the production costs of biodiesel from waste cooking oil [14, 15]. Based on these researchers, the assumptions used to evaluate an approximate cost of biodiesel from waste oil include the collection and chemical prices are as follows. The collection and cleaning costs are £250 per tonne. Every tonne of waste oil yields 1085 litres of biodiesel (considering the density variations from oil to biodiesel). Therefore, the collection cost = 23 pence per litre of end product. The glycerol by-product will be sold without any refining for £250 per tonne. The selling price of the glycerine is 10 pence per kg. Each litre of biodiesel is accompanied by about 10% glycerine i.e. 0.1 kg. Then, the glycerine selling price = 2.5 pence per litre of end product. Other assumptions can be made based on the results of Lewis [16] as follows: The operating costs including labour, energy requirements, water requirements, maintenance and repairs, insurance 10 pence per litre of end product. The methanol and sodium hydroxide together cost about 17 pence per litre of end product. Total costs = collection + operating + chemicals = 23 + 10 + 17 = 50 pence/litre. Therefore, the production costs = costs – glycerine price = 50 – 2.5 = 47.5 pence per litre. The price of biodiesel production evaluated above is 47.5 pence per litre excluding the capital costs for the production plant. The capital cost per litre can be assumed at 12.5 pence. Therefore, the final price of biodiesel can reach 60 pence per litre. However, the petro-diesel price at the gasoline stations is about 120 pence per litre. Therefore, the biodiesel price is nearly half the petro-diesel price.

2.3. Biodiesel Test facility description

The experimental test facility consists of a steady state diesel engine, dynamometer, control system and data recording system (Figure 3). To measure the torque, the engine is connected to eddy current dynamometer through couplings. The engine and dynamometer are controlled by microprocessor connected to data acquisition system. Sensors are used to measure the engine and dynamometer data and send these data to the control system. The sensors measure engine throttle setting (load), speed (rpm), inlet temperature, exhaust temperature, engine oil temperature and cooling water temperature. The engine performance and engine emissions was evaluated at different engine speeds of 1500, 2200, 2600, 3000 and 3300 rpm, at different throttle settings i.e. engine loads of 25%, 50%, 75% and 100% of the full load. These measurements were used to evaluate the performance and emissions parameters of the engine. During the experiments. Figure 2. The engine test runs were carried out on a steady state engine test bed with a 2009 2.2L Ford puma engine from the Ford Transit van. Emissions were measured using a Horiba EXSA 1500 system. The specifications of the four-stroke, direct injection diesel engine, turbocharged diesel test engine are given in the following: Bore = 89.9 mm, stroke = 94.6 mm, engine capacity = 2402 cc, compression ratio = 17.5:1, fuel injection release pressure = 135 bar, max power = 130 kW @ 3500 rpm, max torque = 375.0 Nm @ 2000-2250.

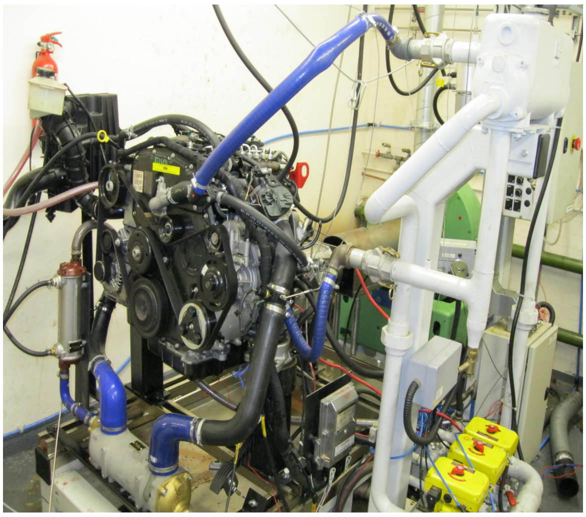

Figure 3 – Engine test bed fitted with Ford Puma Engine

3. Results and discussion

3.1 Effect biodiesel on engine performance

The variation of torque and brake power output of the engine and speed with the test engine operated at full load condition of standard diesel and different fuels are presented in Figures 4 and 5. The Engine test results with standard diesel fuel showed that maximum torque was about 137 Nm which occurred at 1800 rpm and the maximum power was about 32.5 kW at 2500 rpm. The torque and brake power of the engine with standard diesel was higher than all other types of fuel. This was probably due to increase in fuel consumption with increase of engine speed. The torque and brake power produced the lowest rate with used the pure of biodiesel and that was probably due to uncompleted combustion of fuels. Otherwise the curves show that torque and brake power of fuel blends trends is very similar to standard diesel fuel.

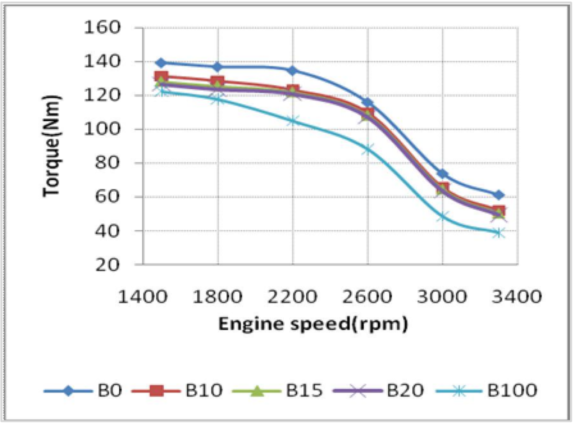

Figure 4 - Brake torque versus engine speed for fuels tested at full load

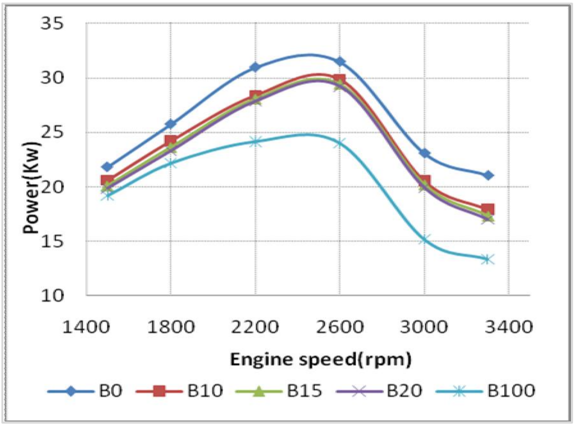

Figure 5 - Brake power versus engine speed for fuels tested at full load

Fuel consumption curves of standard diesel fuel at full load are shown in Figures 6. The curves show that fuel consumption at full load condition speeds is high. Fuel consumption increases with increasing of engine speed. The reason is that, the produced power in low speeds is low and the main part of fuel is consumed to overcome the engine friction. Irrespective of fuel consumption at low speed (1500 rpm), fuel consumption is increased with increasing speed. The reason probably is that, friction power increases with increasing speed. The curves show that brake specific fuel consumption of fuel blends trends is very similar to standard diesel fuel except the curves of pure biodiesel B100 and that probably due to lower calorific value of the biodiesel. Brake specific fuel consumption of fuel blends is higher than standard diesel fuel. On the other hand, it can be seen that the increasing of fuel blend percentage, a mild increase in brake specific fuel consumption is observed. The Brake thermal efficiency is defined as the ratio of output energy available at the engine shaft to the input energy given to the engine. Figure 7 shows the variation of brake thermal efficiency with different engine speeds. Brake thermal efficiency is decreased when the speed of the engine is increased and the maximum efficiency was obtained at 1800 rpm. In addition the brake thermal efficiency for biodiesel for all blends range was fond almost comparable to efficiency of diesel fuel except the curves of pure biodiesel B100. It was seen that standard diesel has higher thermal efficiency than biodiesel and the reason for the higher efficiency probably duo to better combustion due to oxygen content and higher cetane number.

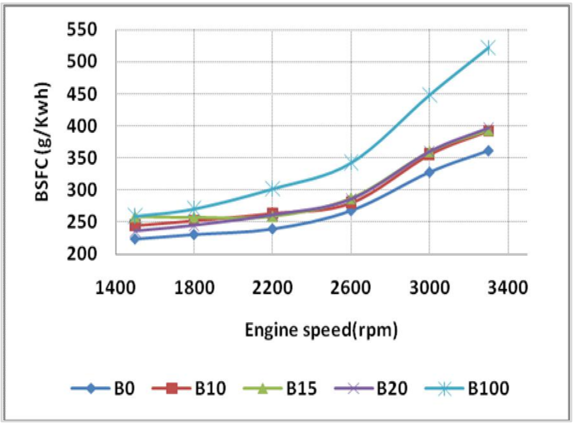

Figure 6 - BSFC versus engine speed for fuels tested at full load

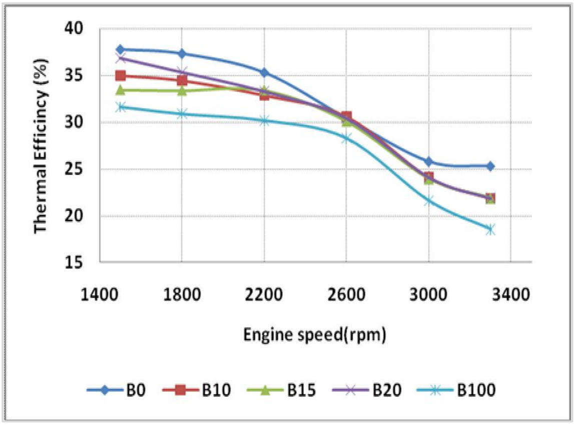

Figure 7 - Brake thermal efficiency versus engine speed for fuels tested at full load

3.2 Effect biodiesel on exhaust emissions

Figure 8 shows the variation of carbon dioxide emissions for tested fuels at different engine. As depicted from Figure 8, at lowest speed of 1500 rpm, the engine fuelled with standard diesel produced the highest CO_2 emissions. The addition of 10% biodiesel considerably decreased the CO_2 emissions by about 50%. The engine operated at 1500 rpm using 15% and 20% biodiesel also decreased the CO_2 emissions by 50% and then 27% compared with standard diesel operation.

Interestingly, at full load and speed of 1500 rpm, the pure biodiesel operation resulted only in 6.7% reduction in CO_2 emissions compared with standard diesel. At an engine speed of 2600 rpm, the standard diesel and biodiesel fuels produced nearly the same amount of CO_2 emissions. Meanwhile, the three biodiesel blends showed higher CO_2 levels compared with pure fuels. At higher speed of 3300 rpm, the lowest CO_2 emissions were recorded for B20 blend and the other two blends were also higher than the standard diesel CO_2 emissions. Figure 9 shows the variation of nitric oxides emissions for tested fuels at different engine. As depicted from Figure 9, the pure biodiesel fuel produced the highest NOx emissions followed by the pure diesel at an engine speed of 1500 rpm under full load operation. Under these conditions, the three biodiesel blends demonstrated less NOx emissions compared with pure fuels. When the engine speed was increased to 2600 rpm, considerable reduction in NOx emissions was found for all fuels, except the blend B20. The trend was reversed at the higher engine speed of 3300 rpm so that blend B20 produced the lowest NOx emissions compared with other fuels. This can be attributed to the variation of the maximum combustion temperature that can be reached inside the cylinder for the different fuels. Noticeably, the behaviour of B20 in producing CO emissions was the reverse to its behaviour in producing NOx emissions so sometimes it behaves the best and sometimes the reverse.

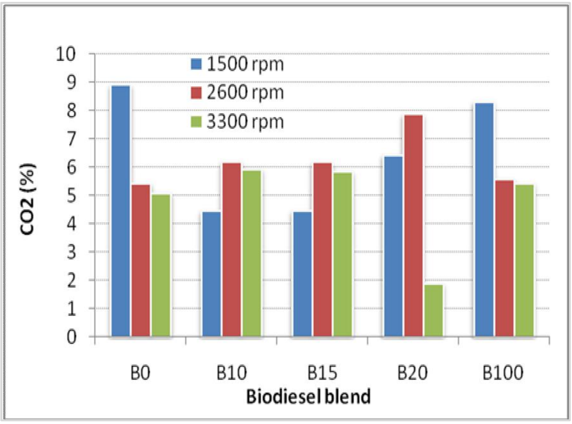

Figure 8 - Variation of carbon dioxide emissions with speed for fuels tested

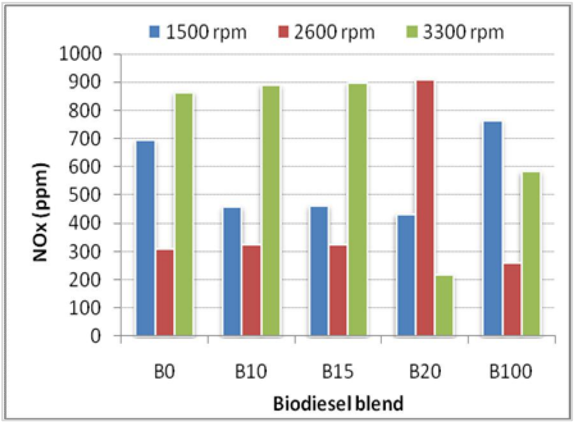

Figure 9 - Variation of oxides of nitrogen emissions with speed for fuels tested

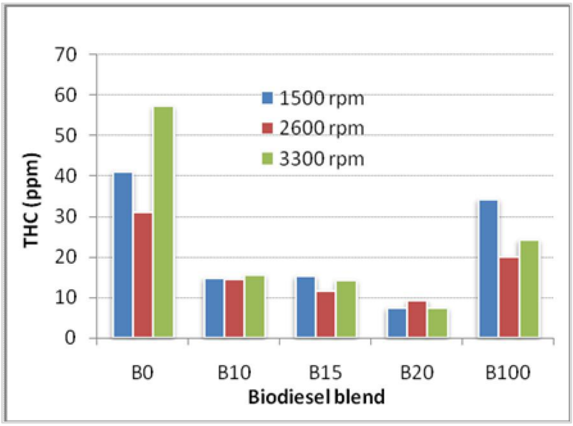

Figure 10 - Variation of total hydrocarbon emissions with speed for fuels tested

Figure 10 shows the variation of total unburned hydrocarbon emissions for tested fuels at different engine. As depicted from Figure 10, the pure petro-diesel fuel produced the highest total unburned hydrocarbon emissions followed by the pure biodiesel at an engine speed of 1500 rpm under full load operation. Under these conditions, the three biodiesel blends demonstrated less total unburned hydrocarbon emissions compared with pure fuels. When the engine speed was increased to 2600 rpm, reduction in total unburned hydrocarbon emissions was found for all fuels, except the blend B20. The trend was the same at the higher engine speed of 3300 rpm to that at 1500 rpm so that blend B20 produced the lowest total unburned hydrocarbon emissions compared with other fuels. Overall, the addition of biodiesel to the blends decreased the total unburned hydrocarbon emissions at different speed and full load operation.

4. Conclusions

Based on the results of this study, the following specific conclusions are drawn.
In order to produce biodiesel from waste cooked oil, the "FuelPod 2™" was used which is a complete system and corresponding methodology for making biodiesel.

- Standard diesel produced the highest brake torque and power at the engine for all engine speeds. This was due to the lower calorific value of the biodiesel compared to standard diesel.
- The higher the concentration of blend with bio-diesel the lower the engine performance. In addition to lower CV this is may be attributed to the decreased heating value of the fuel blend with biodiesel addition.
- In brake specific fuel consumption and thermal efficiency, the increase in engine speed decreased the brake thermal efficiency for all tested fuels. This can be attributed to the decreased torque and increased fuel consumption with the speed.
- At full load operation, the lowest specific fuel consumption was for the standard diesel comparative to biodiesel. The standard diesel produced the highest CO2 concentrations at the different loads at speed.
- The addition of the biodiesel to the blend decreased the CO2 emissions for blends B10, B15 and B20, except the 75% load operation of B15 blend. Such a rise at this loading could give rise for concern as the vehicle will most likely operate at 75% engine load.
- For nitric oxides (NOx): There was little observable difference in the NOx emissions at differing speeds with the addition of biodiesel to the blend. It was noted that in all cases NOx generally increased at the higher speeds.
- For Total unburned hydrocarbon: The pure standard diesel fuel produced the highest THC emissions followed by the pure biodiesel at an engine speed under full load. Overall, the addition of biodiesel to the blends decreased the THC emissions at different speed and full load operation.
- Biodiesel is better than the standard diesel in producing lower greenhouse gasses at different load operation. The biodiesel price was found about 60 pence per litre which is nearly half of the petro-diesel price.

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