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Combustion and Emissions Characteristics of Biodiesel Fuels

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1. Introduction

The production and use of biodiesel as an alternative diesel fuel in compression-ignition engines and boilers has increased significantly in the recent years. Biodiesel is considered to be an immediate alternative energy, providing a solution to help decrease the effects of harmful global green house gases, why decreasing the dependency of fossil fuels (Demirbas, 2008, Gärtner and Reinhardt, 2003). Biodiesel is derived from plant oils, animal fats and recycled cooking oils (Biodiesel Handling and Use Guide, 2009). Bio-Diesel is a renewable fuel produced by a chemical reaction of alcohol and vegetable or animal oils, fats, or greases. Bio-Diesel offers a safer and cleaner alternative to petroleum Diesel. Biodiesel is renewable fuel, its is energy efficicient, it can be used as a 20% blend in most diesel equipment with no or only minor modifications, can reduce global warming gas emissions, it is nontoxic, biodegradable, and suitable for sensitive environments (Biodiesel Handling and Use Guide, 2009).

Biodiesel is produced when vegetable oil or animal fat is chemically reacted with alcohol (methanol or ethanol) in the presence of catalyst such as sodium or potassium hydroxide (Van Gerpen, 2004). Glycerin is produced as a co-product. Biodiesel fuel is produced from oil feedstock such as soybean oil, corn oil, canola oil, cottonseed oil, mustard oil, palm oil, restaurant waste oils such as frying oils, animal fats such as beef tallow or lard, trap grease (from restaurant grease traps), float grease (from waste water treatment plants - Van Gerpen, 2004). The oil or animal fat can be converted to methyl or ethylesters (biodiesel) directly, using a base reaction (catalyze) to accelerate the transesterification reaction. The most common method of production of biodiesel is by mixing the vegetable oil with methanol in the presence of sodium hydroxide.

The reaction produces methyl esters (Biodiesel) and glycerin (by product). Biodiesel can be used in its pure form B100, which requires some modification to the engine, to prevent any decomposition of plastic parts. Because the level of special care needed is high, the National Renewable Energy Laboratory (NREL) and the U.S. Department of Energy (DOE) do not recommend the use of high-level biodiesel blends. When human exposure to diesel particulate matter (PM) is elevated, additional attention to equipment and fuel handling is needed (Biodiesel Handling and Use Guide, 2009). More commonly biodiesel is run as a blend, such as B5, B10, and B20 (Example: B20 is 20% of biodiesel blended with 80% of petroleum diesel). No modification of engine is needed if Biodiesel fuel blends are used. At concentrations of up to 5 vol % (B5) in conventional diesel fuel, the mixture will meet the ASTM D975 diesel fuel specification and can be used in any application as if it was pure petroleum diesel; for home heating oil, B5 will meet the D396 home heating oil specification (Biodiesel Handling and Use Guide, 2009). At concentrations of 6% to 20%, biodiesel blends can be used in many applications that use diesel fuel with minor or no modifications to the equipment. B20 is the most commonly used biodiesel blend in the United States because it provides a good balance between material compatibility, cold weather operability, performance, emission benefits, and costs (Biodiesel Handling and Use Guide, 2009). Equipment that can use B20 includes compression-ignition (CI) engines, fuel oil and heating oil boilers, and turbines. The analysis, fuel quality, and production monitoring of biodiesel have been discussed in more details in previous studies (Knothe, 2005, Mittelbach and Remschmidt, 2004, Knothe, 2001, Mittelbach, 1996 and Komers et al., 1998).

2. Biodiesel basics

Biodiesel is produced from plant oils (soybean oil, cotton seed oil, canola oil), recycled cooking greases or oils (e.g., yellow grease), or animal fats (beef tallow, pork lard). Biodiesel is the result of a chemical reaction process on oils or fats called transesterification. A simple diagram of the transesterification process is shown in Figure 1. Vegetable oil, animal fats or waste oil react with alcohol in the presence of catalysts to form Biodiesel and Glycerin. Glycerin is a co-product of the biodiesel process. There are three distinct types of transesterification process: (1) Base catalyzed transesterification of the oil, (2) Direct acid catalyzed transesterification of the oil, and (3) conversion of the oil to its fatty acids and then to biodiesel. For the direct acid catalyzed transesterification of the oil, the transesterification process is catalyzed by bronsted acids, preferably by sulfonic and sulfuric acids. These catalysts give very high yields in alkylesters, but the reactions are slow, requiring, typically, temperatures above 100 °C and more than 3 h to reach complete conversion. The base-catalyzed transesterification of vegetable oils proceeds faster than the acid-catalyzed reaction and the alkaline catalysts are less corrosives than acidic compounds. From these three basic route to biodiesel production the base catalyzed transesterification of the oil present many advantages. First the base catalyzed transesterification has high conversion efficiency. With this process around 98 percent of all the reactants will effectively mix to produce biodiesel. This chemical reaction is also efficient at low temperature and low pressure. This is great advantages because it means that no heavy pressure unit or heating unit would be required. Furthermore this transesterification lead to a direct conversion and does not need any intermediate compounds to achieved biodiesel production.

2.1 Reactants

Two reactants are present during the chemical reaction. The first one is the triglycerides from the vegetable oil and the second is the alcohol. Triglycerides can have different alkyl groups as biodiesel can be made out of different kind of straight vegetable oil or waste vegetable oil. Two different kind of alcohol can be used: methanol or ethanol. These two alcohols are used in particular for this chemical reaction because there is very little space between triglycerides atoms for the alcohol to react with.

2.2 Products

From this chemical reaction there are two main products: Glycerol also named glycerin and methyl or ethyl ester which is Biodiesel. Glycerin is denser than biodiesel and would consequently stay under it.
The equation below will resume the reaction:

$$\text{Vegetable oil + alcohol} \dashrightarrow \text{glycerin + Biodiesel} \quad (1)$$

If we consider the concentrations:

$$\text{80\% Vegetable Oil + 20\% Alcohol} \dashrightarrow \text{90\% Biodiesel + 10\% Glycerin} \quad (2)$$

2.3 Catalyst

The catalyst if added in the good proportion will neutralize the free fatty acids (FFA) from the waste vegetable oil and also accelerates the reaction. For this type of transesterification two different catalysts are usually used: Sodium Hydroxide NaOH or Potassium Hydroxide KOH. The catalyst is used to accelerate the chemical reaction. The quantity of catalyst needed depend on the amount of free fatty acids in the waste oil and will be determine by the titration of the oil (process used for the determination of the right amount of catalyst that will be use for the chemical process).

2.4 Transesterification of vegetable oils

In the transesterification of vegetable oils (see Fig.2), a triglyceride reacts with an alcohol in the presence of a strong acid or base, producing a mixture of fatty acids alkyl esters and glycerol (Wright et al., 1944 and Freedman, 1996). The stoichiometric reaction requires 1 mol of a triglyceride and 3 mol of the alcohol. However, an excess of the alcohol is used to increase the yields of the alkyl esters and to allow its phase separation from the glycerol formed. Several aspects, including the type of catalyst (alkaline or acid), alcohol/vegetable oil molar ratio, temperature, purity of the reactants (mainly water content) and free fatty acid content have an influence on the course of the transesterification (Schuchardta, 1998) based on the type of catalyst used.

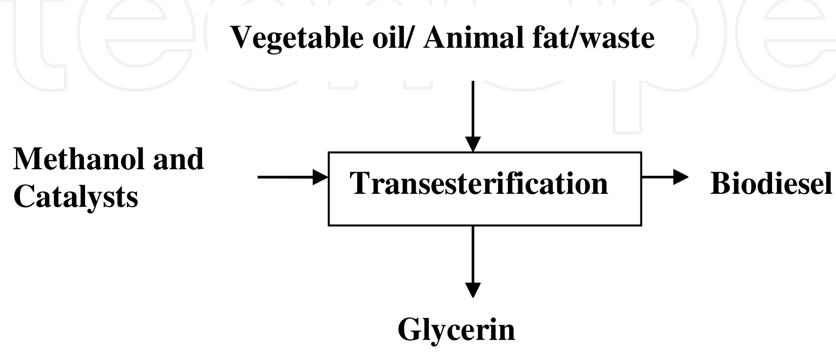


Fig. 1. Basic transesterification process

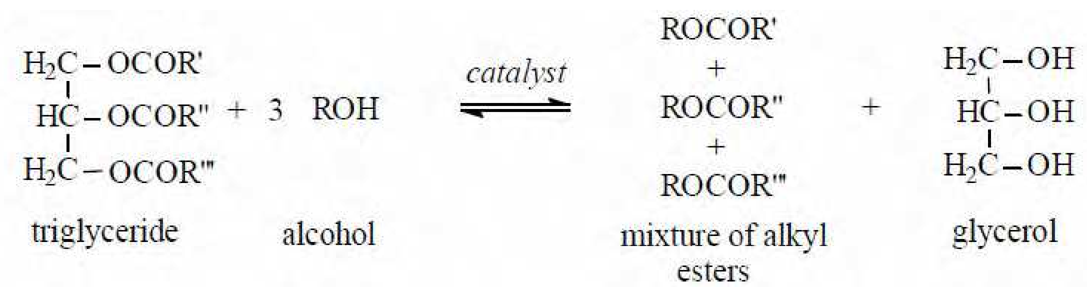


Fig. 2. Transesterification of Vegetable Oils

The principal objective of this study is to produce quality biodiesel fuels using different oil feed stocks and test the performance and emissions of Diesel engine using different biodiesel fuel blends (B5, B10, B15 and B20). The combustion performance (torque and engine horsepoqer) and emissions (CO, CO2, HC's, and NOX) from the Diesel engine using a Bio-Diesel fuel blends and the conventional petroleum Diesel fuel will be compared.

3. Biodiesel production and engine testing

3.1 Biodiesel production

The biodiesel fuel was produced through the base catalyst transterification process. This provides one of the easiest and more efficient ways to produce the fuel, yielding a return of close to 98%. A biodiesel processor (see Figure 3) with a production capacity of 40 gallons/day was used to produce the biodiesel. The processor contains two tanks: (1) a small tanks for mixing the base catalyst and methanol to create the methoxide required for the reaction, and (2) bigger tank (40 gallons) for mixing the oil with methoxide. The processor contains a small 120V pump which transfers the methoxide into the base oil for mixing. The processor is also equipped with heated coil (in the main reaction tank) to speed up the time required to produce the biodiesel fuel and the glycerin.

Four different oil feedstocks (see Fig .4) were tested in thi study: (1) Waste vegetable oil from Coyote Jacks, (2) Waste vegetable oil from JC Alexander, (3) straight or non used peanit oil, and (4) straight or non used coconnut oil. It is noted that Coyote Jacks and JC Alexander are two dinning facilities inside and outside the University. Waste and straight (non used) oils were testd in this to see the effcet of the quality of oil feedstocks on the produced biodiesl fuesl. For the waste vegetbale oil, the waste oil is first heated up to 120°F to evaporate any water present and filtered to eliminate any solid particles in the oil. For all the oil feedstocks use in this study, a titration was performed to determine the exact amount of base catalyst needed for the reaction based on the amount of biodiesel fuel to be produced.

The mixing of the base oil (See Figure 3) and methoxide (methol and cataltyst) will help to break down all the fatty amino acids present in the base oil. The mixing process takes up to 1 hour. After that, we let the mixture to settle down for 7 to 8 hours. This will help to separate the Biodiesel fuel from Glycerin as shown in Fig. 5 (the Biodiesel is on the top and Glycerin in the bottom). After the separation of Glycerin from the Biodiesel, the fuel is washed with water and dried to remove any excess methanol and glycerin present in the final product (B100 Biodiesel fuel). The quality of the final biodiesel product is tested in the laboratory and the correponsding biodiesel fuel blends (B5, B10, B15, B20) are prepared for the engine testing. It is noted that B20 for example is 20% biodiesel and 80% petroleum diesel fuel.

Fig. 3. Biodiesel Processor with a capacity of 40 gallons/day

Fig. 4. Straight and waste vegetable oil before transesterification

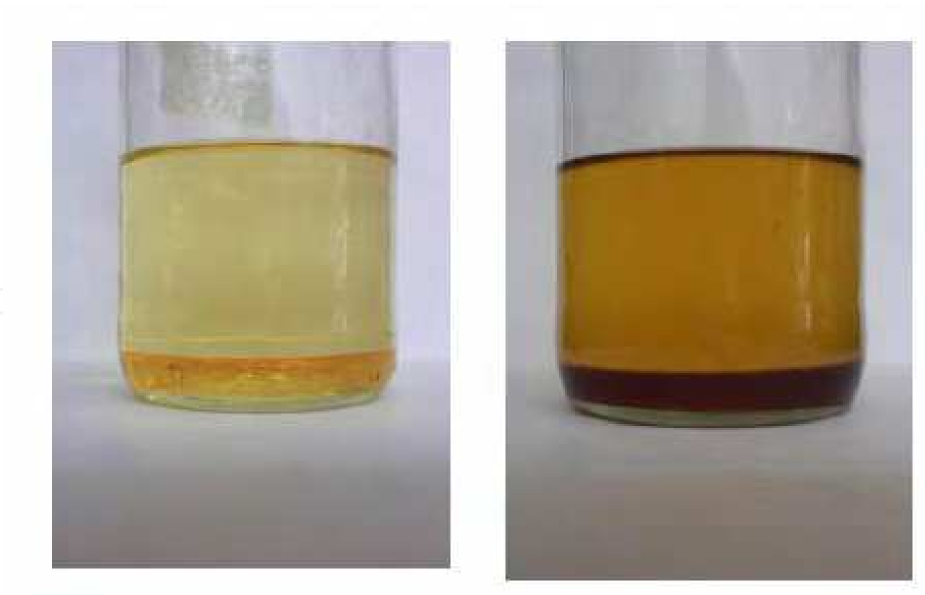


Fig. 5. Biodiesel and Glycerin

3.2 Diesel engine

The Diesel engine used for this study is an air cooled, 4-cycles, single cylinder and 8 horse power Robin Engine. The Diesel engine is compact, lightweight and designed for generators, air compressor, water pumps, pressure washer and light construction machines (see Figure 6). The engine has a fuel tank of a capacity of approximately 14.5 liters (3.83 gallons), and a maximum horsepower rating of 8 HP at 3600 rotation per minute. The piston displacement is 348 cubic centimeters. The bore and stroke are respectively 82 and 78 mm. The engine combustion system has a direct injection. The engine dimensions are 435x370x478 mm and the engine weight is 46 Kg. A fuel flow meter is connected to the engine (see Figure 7) to record in real time the fuel consumption during engine testing.

Fig. 6. 8 Horse Power Diesel Engine

Fig. 7. Fuel flow meter

3.3 Diesel engine torque and horse power measurements

A small engine dynamometer (See Figure 8) was used to test the performance (torque and horse power) of the Diesel engine. The dynamometer is a water brake load system. The pump pressurizes the water which then goes into the water brake connected to the engine shaft. Part of the energy produced by the engine goes to the exhaust while the rest of it is released as calorific calories to the water that passes thru the water brake. For this reason the water has to be cooled down, as it will over heat over time and loose efficiency. The dynamometer is equipped with sensors, data acquisition system and software to measure the Torque and engine RPM (rotation per minutes). The measured values of the torque and RPM are used to determine the horsepower:

$$\text{Horsepower} = (\text{RPM} * \text{Torque}) / 5252 \qquad (3)$$

Fig. 8. Engine Dynamomter

3.4 Emissions characterization - Engine exhaust gas measurements

A gas analyzer DYNOmite EMS (See Figure 9) was used in this study to measure the emissions from the engine. The real time gas analyzer is used to measure the concentrations of oxygen (O2), carbon monoxide (CO), carbon dioxide (CO2), hydrocarbons (HC) and nitrogen oxides NOx. The gas emissions from the engine are recorded simultaneously during engine dynamometer testing using the data acquisition system. The torque; RPM; horse power; O2, CO, CO2, HC's and NOx concentrations are measured simultaneously.

Fig. 9. Gas Analyszer and emission probe

3.5 Data acquisition system

The dynamometer data acquisition system (see Figure 10) is used to record the engine performance (Torque, RPM, and Horse power), fuel consumption and the exhaust gas emissions (CO, CO2, NOx, and HCs). All these data are recorded simultaneously during engine testing.

4. Results and discussions

4.1 Combustion and emission characteristics of petroleum diesel fuels

Figures 11 and 12 show the engine performance and emissions using conventional petroleum Diesel fuel at different engine speed or rotation per minutes (RPM). The engine starts running at low RPM (~ 1230 RPM) for six seconds after that the RPM of the engine was increased until it reached the maximum value of 3650 RPM. The engine performances (engine horse power and torque) and emissions (CO2, CO, HC and NOX) were recorded for about 18 seconds during this change of the engine RPM. Figure 11 shows that horse power increases from 2.3 HP at low RPM to about 8 HP at high RPM and the torque increases from 10 ft lb at low RPM to about 12 ft lb at high RPM. Figure 12 shows the variation of the engine emissions (CO2, CO, NOX, HCs) with the engine speed or RPM.

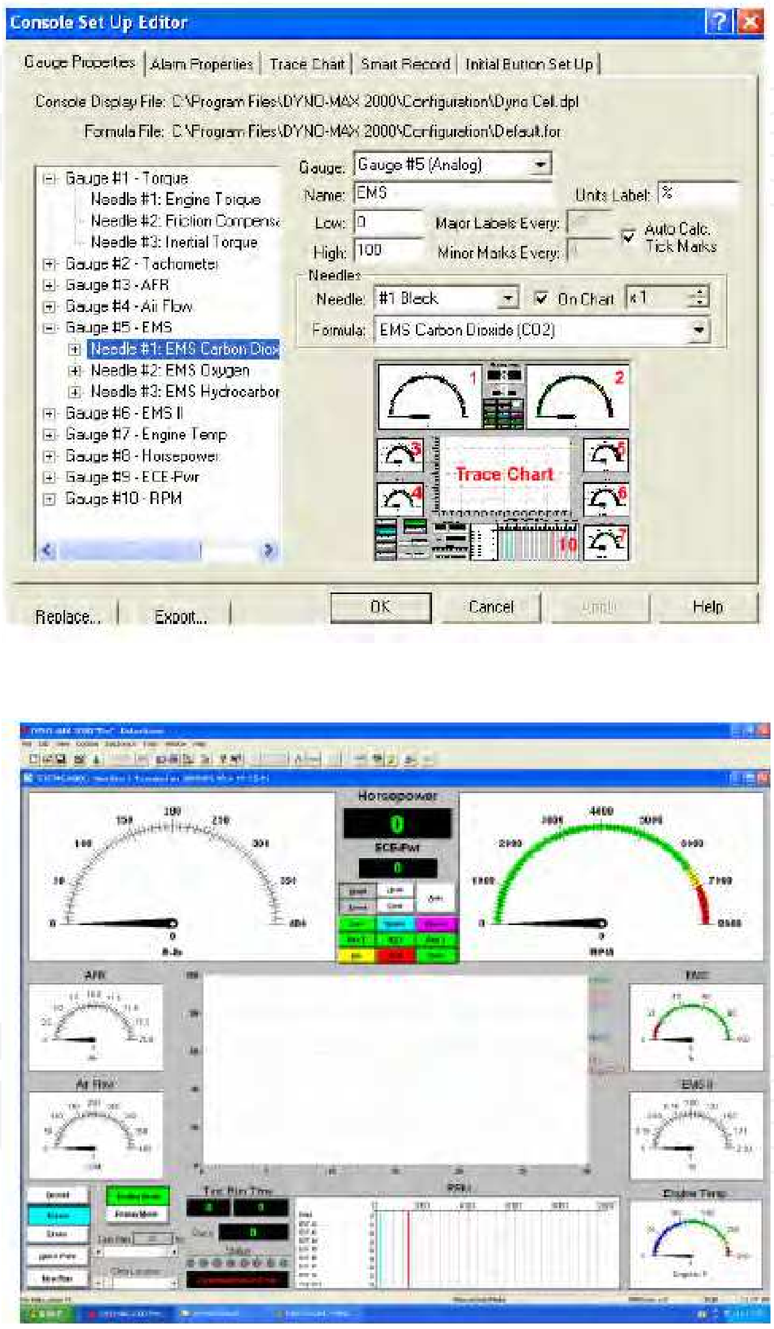


Fig. 10. Data acquisition system

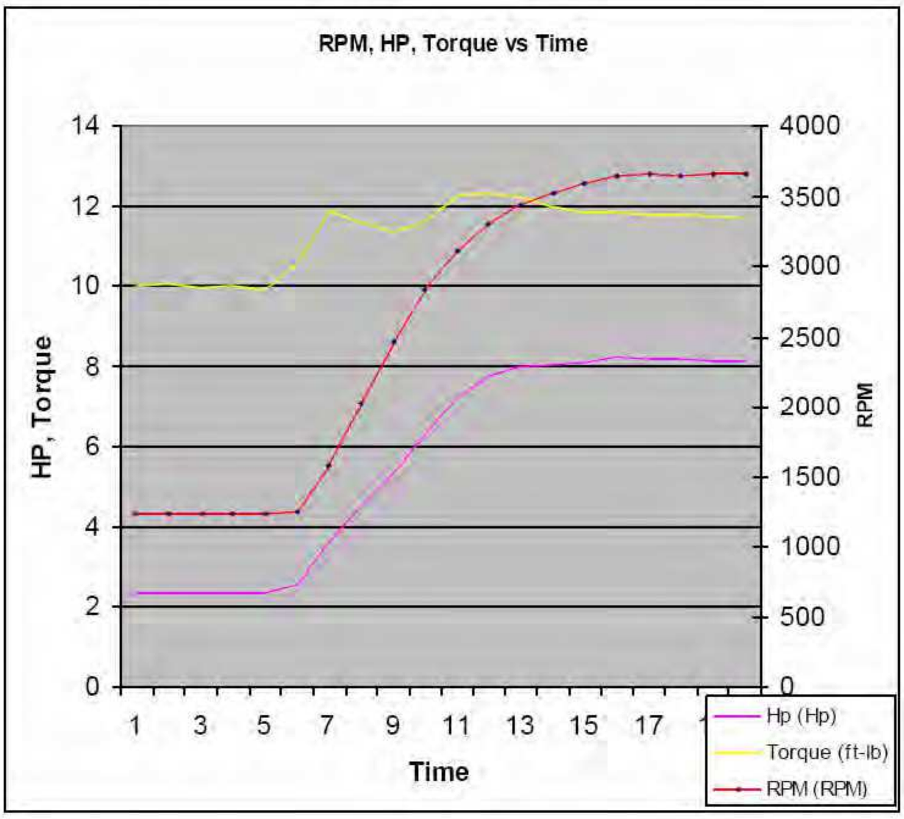


Fig. 11. Engine horse power, torque, and RPM - Petroleum Diesel fuel

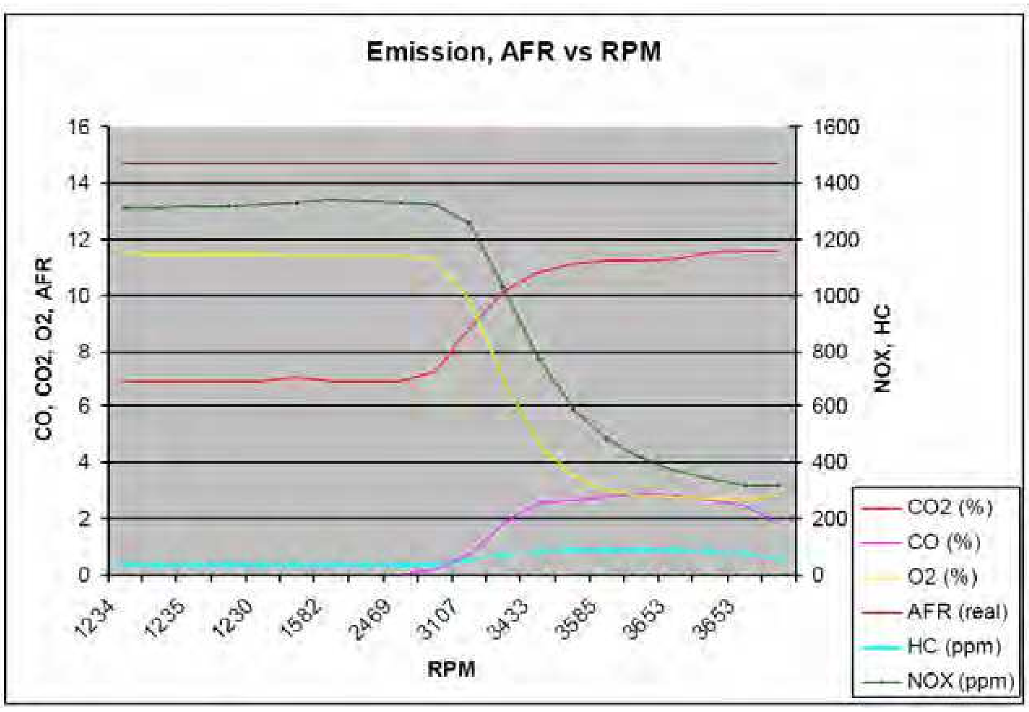


Fig. 12. Engine emissions at different RPM - Petroleum Diesel fuel

4.2 Combustion and emission characteristics of biodiesel fuel blends

Four different oil feed stocks were used in this study to produce pure bio-diesel fuel. The Biodiesel fuel produced from each oil feed stocks was converted into fuel blends of B5, B10, B15, and B20. The Biodiesel fuel blends are obtained by mixing biodiesel fuel with petroleum Diesel fuel (ex: B5: 5% Biodiesel and 95% Diesel fuel by volume). Two of the oil feed stocks are waste cooking oil collected from two different restaurants. The first waste cooking oil was collected from Coyote Jacks, a restaurant located inside the premises of Florida Atlantic University. This restaurant is more focused on deep fried fast food, and the oil is used over and over for up to 3 weeks before it is changed. The second waste cooking oil comes from J.C. Alexander restaurant located outside Florida Atlantic University. This restaurant uses its oil for shorter periods of time, and is mainly used to sauté food instead of deep frying. The reason for using two different waste cooking oils from two different places is to see if the quality of the oil feed stocks will affect the quality of the biodiesel produced. The third and fourth oils tested in this study were Peanut and Coconut oils (not used oils). The peanut and coconut oils have not been used for cooking prior to being converted into bio-diesel fuel. The procedure for each test was: (1) the engine was allowed to run for 2 minutes to allow the engine to clear any residue from previous tests with different fuel blends, and warm up the engine and catalyst, (2) after the 2 minutes warm up, the engine was run at high RPM (3550 rpm) for 5 minutes, (3) drop the engine speed to medium RPM (2400 rpm) and run the engine for 5 minutes, and (4) finally set the engine to low RPM (1250 rpm) and run for 5 minutes. The sampling rate was set to 1 Hz. This will produce a total of 300 data points for each RPM. For each Biodiesel fuel blend and for each RPM, the measurement was run at least three times to check the consistency of the data produced. The data produced from these tests includes: Torque (lbs-feet), Horse Power (HP), Carbon Dioxide CO2 (%), Carbon Monoxide CO (%), Oxygen O2 (%), Hydro Carbon HC (ppm) and Nitric Oxide NOx (ppm). The torque and horsepower readings where measured directly from the dynamometer, while the emissions where obtained from the gas analyzer. The mean value (over 5 minutes) of the diesel engine tests for low, medium and high RPM using petroleum diesel (benchmark) are shown in Table 1. It is noted that the horse power, CO2 and CO emissions increase and the HC and NOx emissions decrease when the speed (rpm) of the engine increases. The baseline data with the petroleum Diesel fuel will be compared to those obtained with Biodiesel fuel blends using different type of oil feed stocks. Typical results of the Diesel engine tests at high RPM using biodiesel fuel blends (B5, B10, B15 and B20) produced from waste vegetable oil coyote Jacks are shown in Table 2. The results show a small change of the engine horse power, torque, CO2 and NOx emissions when the amount of biodiesel blended with petroleum Diesel increases from 5% to 20%. The CO emissions dropped from 0.27% to 0.25% and the HC emissions from 14.06 ppm to 12.14 ppm.

RPM	HP	Torque Lbs-feet	CO2 %	CO %	O2 %	HC ppm	NOx ppm
1250	2.34	9.84	7.28	0.02	12.10	33.74	1157
2400	4.50	9.86	7.58	0.02	12.30	30.77	617
3550	7.97	11.80	11.45	0.28	3.98	14.50	398

Table 1. Mean value of the Diesel engine tests using petroleum Diesel

	B5	B10	B15	B20
HP	7.89	7.82	7.80	7.88
Torque, Lbs-feet	11.71	11.66	11.58	11.49
CO2 %	11.68	11.70	11.60	11.43
CO %	0.27	0.26	0.259	0.25
O2 %	3.55	3.50	3.49	3.47
HC ppm	14.06	13.18	12.82	12.14
NOx ppm	398	402	405	406

Table 2. Mean value of the Diesel engine tests at high RPM (3550) using Biodiesel Fuel Blends produced from waste vegetable oil Coyote Jacks

The results obtained in this study with the three other oil feed stocks (waste cooking oil JC Alexander, peanut and coconut oils) show the same trends. Figure 13 shows the percentage difference of the data obtained with the Biodiesel fuel blend B20 from the four oil feed stocks and the petroleum diesel fuel. The results show a net decrease of the Hydrocarbons HC and CO emissions for the B20 biodiesel fuel blend compared to the petroleum diesel fuel for all the four oil feed stocks. Biodiesel fuel contains fewer hydrocarbons than those present in petroleum diesel. It is natural to expect a decrease in HC emissions as the blends increase. The Hydrocarbons emissions for the B20 decreases by about 20% compared to the petroleum Diesel fuel. The carbon monoxide emissions decrease by about 12 % for the B20. Although the hydrocarbon HC and CO emissions decreased drastically, a small change (< 2%) of the engine power HP and CO2 emissions are reported for the B20 compared to the petroleum Diesel fuel. The NOx emissions also increase by about 2% for the B20. This is due probably to an increase of thermal NOx because of the combustion temperature increase for the B20.

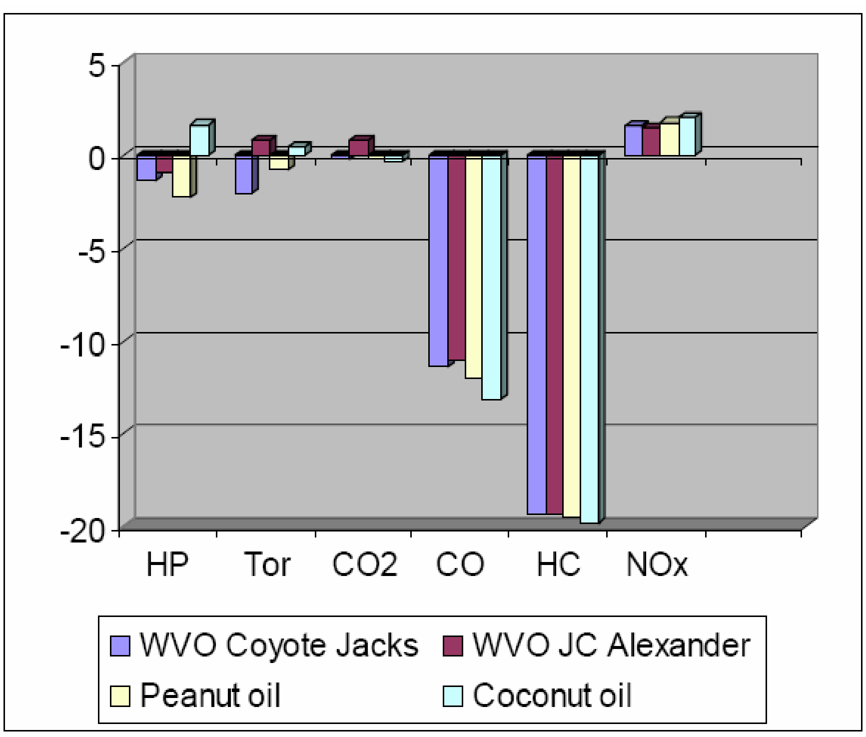
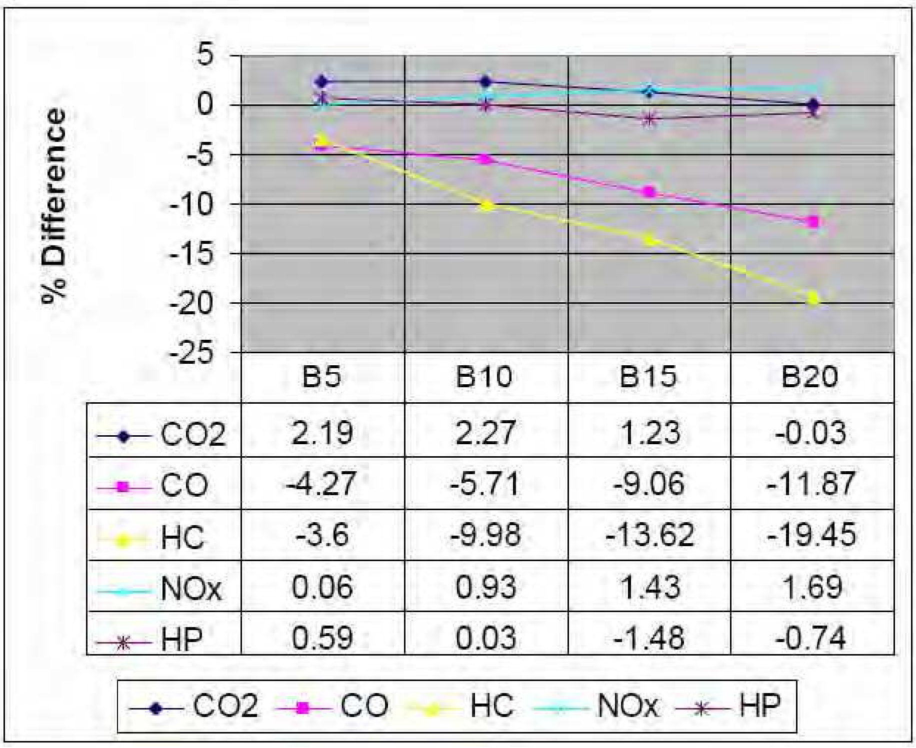


Fig. 13. Percentage difference of the B20 (produced from different oil feed stocks) with Respect to Petroleum Diesel

Figure 14 shows the overall effect by averaging all the four diverse oils and normalizing them over the petroleum diesel (baseline data). It is shown clearly the benefits of Biodiesel fuel blends compared to the petroleum diesel fuel. The HC and CO emissions decrease drastically by increasing the amount of biodiesel blended with Diesel fuel, while the power of the engine is kept almost the same and the NOx emissions increase by not more than 2%.



	B5	B10	B15	B20
CO2	2.19	2.27	1.23	-0.03
CO	-4.27	-5.71	-9.06	-11.87
HC	-3.6	-9.98	-13.62	-19.45
NOx	0.06	0.93	1.43	1.69
HP	0.59	0.03	-1.48	-0.74

Fig. 14. Overall percentage differences of biodiesel fuel blends with respect to petroleum Diesel

4. Conclusions

Biodiesel fuel was produced from four different oil feed stocks: waste cooking oil Coyote Jacks, waste cooking oil JC Alexander, and not used peanut and coconut oils. Biodiesel fuel blends (B5, B10, B15 and B20) for each oil feed stock were prepared by mixing the biodiesel fuel with Petroleum Diesel. The biodiesel fuel blends were tested on the Diesel Engine and the results were compared to those obtained with Petroleum Diesel Fuel. The results obtained with the four oil feed stocks show the same trends. The hydrocarbons HC and CO emissions decreased by increasing the amount of biodiesel blended with Petroleum Diesel. The HC and CO emissions decreased respectively by 20 % and 12 % for the B20 compared to the Petroleum Diesel while the NOx emissions increased by 2% and the change of the engine power was negligible (<2%).

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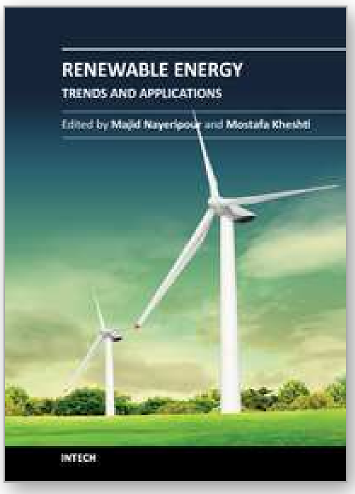

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Increase in electricity demand and environmental issues resulted in fast development of energy production from renewable resources. In the long term, application of RES can guarantee the ecologically sustainable energy supply. This book indicates recent trends and developments of renewable energy resources that organized in 11 chapters. It can be a source of information and basis for discussion for readers with different backgrounds.