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Effects Of Biodiesel Fuel Upon The Exhaust Emission And The Performance Of Compression Ignition Engine

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Abstract :

Biodiesel is a renewable source of energy since it is made of renewable sources such as corn and soybeans, thus reduces the dependence on oil and eliminates the monopoly of certain countries on oil.

This research studied effects of three types of fuel, biodiesel from new oil, biodiesel from waste cooking oil and diesel fuel on engine performance and emissions. A diesel engine and a gas analyzer is used in this research. The effect of each fuel on the performance of the engine at different set of speeds at a fixed throttle setting (full throttle and medium throttle) is studied, with the recording of amounts of gas emissions from the exhaust, and compare the results obtained for these cases. Also obtained a set of fuel characteristics to help with the calculations for better understanding of fuels through various experimentations.

The results showed that waste cooking oil performance is a mediate one between new oil biodiesel and diesel fuel. The emissions of waste cooking oil biodiesel are low with consideration to its efficient combustion. Biodiesel in general has a higher brake power and torque because it is clean burning and has a smoother running.

Key words: ***Biodiesel fuel, diesel fuel, exhaust emission, diesel engine performance.***

تأثير وقود البيوديزل على انبعاثات وأداء مكائن الاحتراق الداخلي

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الخلاصة :

الوقود الحيوي (الديزل الحيوي) يعتبر مصدر طاقة متجددة حيث يصنع من مصادر قابلة للتجدد مثل الذرة وحب الصويا، هذا يخفض الاعتماد على النفط ويزيل احتكار بعض البلدان للنفط.

في هذا البحث تم دراسة تأثير ثلاثة أنواع من الوقود هي الديزل الحيوي من زيت نقي والديزل الحيوي من مخلفات زيت الطهي ووقود الديزل على أداء وانبعاثات الغازات من المحرك عمليا باستخدام محرك ديزل ومحلل غازات مختبريه. تم حساب تأثير كل نوع من الوقود المستخدمة على أداء المحرك لمجموعة من السرع المختلفة ولوضع صمام

الخنق بحالتين خنق تام وخنق متوسط حيث تم تسجيل كميات انبعاث الغازات من العادم. وكذلك تم الحصول على مجموعة من خصائص الوقود وبمساعدة الحسابات لفهم أفضل للوقود من خلال التجارب المختلفة.
بينت النتائج إن أداء وقود الديزل الحيوي من مخلفات زيت الطهي يتوسط بين أداء الوقود الحيوي الجديد ووقود الديزل. انبعاثات الوقود الحيوي من مخلفات زيت الطهي هي الأقل نتيجة احتراقه الكفؤ. عموما الديزل الحيوي له عزم وقدرة كبح أعلى من وقود الديزل بسب احتراقه النظيف والدوران المنتظم.

Nomenclature

The following symbols are used generally throughout the text. Others are defined as when used.

Symbols	Meaning	Units
A	Cross-sectional area of the orifice	m^2
Bp	Brake power	kW
C_d	Coefficient of discharge	——
CV	Calorific value of fuel	kJ/kg
F	Force (Brake loads)	N
g	Gravitational acceleration	m/s^2
Δh	Manometer reading (mm of water)	mm
$\dot{m}_f$	Mass flow rate of fuel	kg/sec
$\dot{m}_{air}$	Air consumption	kg/sec
$\dot{m}_{fuel}$	Fuel consumption	kg/sec
N	Speed of engine	r.p.s
P_{FE}	Fuel equivalent of power	kW
SFC	Specific fuel consumption	Kg/kW.hr
T	Torque	N.m
V	Volume of the fuel	mL
V_a	Velocity of air	m/sec
W	Weight	kg
WCO	waste cooking oil	
Greek Symbol		
η_{bth}	Brake thermal efficiency	——
ρ_{air}	Air density	Kg/m^3
ρ_{water}	Water density	Kg/m^3

1. Introduction

Biodiesel is a clean-burning fuel currently being produced from grease, vegetable oils, or animal fats. Its chemical structure is that of fatty acid alkyl esters. Biodiesel is produced by transesterification of oils with short-chain alcohols or by the transesterification of fatty acids.

The transesterification reaction consists of transforming triglycerides into fatty acid alkyl ester, in the presence of an alcohol, such as methanol or ethanol, and a catalyst, such as an alkali or acid, with glycerol as a byproduct [1].

Thus, because of diminishing petroleum reserves and the deleterious environmental consequences of exhaust gases from petroleum diesel, biodiesel has attracted attention during the past few years as a renewable and environmentally friendly fuel. Since biodiesel is made entirely from vegetable oil or animal fats, it is renewable and biodegradable. Biodiesel also contains very little sulfur, polycyclic aromatic hydrocarbons, and metals. Petroleum-derived diesel fuels can contain up to 20% polycyclic aromatic hydrocarbons. For an equivalent number of carbon atoms, polycyclic aromatic hydrocarbons are up to three orders of magnitude more soluble in water than straight chain aliphatic. The fact that biodiesel does not contain polycyclic aromatic hydrocarbons makes it a safe alternative for storage and transportation [2].

Biodiesel is most often blended with petroleum diesel in ratios of 2% (B2), 5% (B5), or 20% (B20). It can also be used as pure biodiesel (B100). Biodiesel fuels can be used in regular diesel vehicles without making any changes to the engines, although older vehicles may require replacement of fuel lines and other rubber components. (Biodiesel has similar materials compatibility to ultralow sulfur diesel (ULSD); so vehicles built to run on that should be compatible with pure biodiesel.) It can also be stored and transported using diesel tanks and equipment. Since biodiesel is oxygenated, it is a better lubricant than diesel fuel, increasing the life of engines, and is combusted more completely. Indeed, many countries are introducing biodiesel blends to enhance the lubricity of low-sulfur diesel fuels [3]. The higher flash point of biodiesel makes it a safer fuel to use, handle, and store. With its relatively low emission profile, it is an ideal fuel for use in sensitive environments, such as heavily polluted cities.

Considerable research has been done on biodiesel made from virgin vegetable oils (e.g., soybean oil, sunflower oil, rapeseed oil) using alkali catalysts.

Refaat, A. A., (2010) [4] Study the production of biodiesel from waste vegetable oil offers a triple-facet solution: economic, environmental and waste management. The quality of biodiesel produced from waste vegetable oil in previous studies is also reviewed and the performance of engines fueled with this biodiesel and the characteristics of the exhaust emissions resulting from it are highlighted. The overarching goal is to stimulate further activities in the field.

Supple et al. (2002) [5] investigated the effect of steam injection and sedimentation treatment of waste cooking oil on the quality of TG to be used as a raw material for the production of biodiesel. The effect of steam GC analysis of the treated materials demonstrated little change in either the overall composition of the oils or the iodine value. The decreases in moisture from 1.4 to 0.4 % and in free fatty acid (FFA) from 6.27 to 4.28 % were found to correlate strongly with an increase in yield of ester from 67.5 to 83.5 %.

Ghobadian et. al. (2009) [6] study deals with artificial neural network (ANN) modeling a diesel engine using waste cooking biodiesel fuel to predict the brake power, torque, specific fuel consumption and exhaust emissions of engine. It was observed that the ANN model can predict the engine performance and exhaust emissions quite well with correlation coefficient (R) were 0.9487, 0.999, 0.929 and 0.999 for the engine torque, SFC, CO and HC emissions, respectively.

Karmee and Chadha (2005) [7] have investigated biodiesel production from the nonedible oil of Pongamia pinnata by transesterification of the crude oil with methanol and KOH as catalyst. A maximum conversion of 92% (oil to ester) was achieved using a 1:10 molar ratio of oil to methanol at 60 °C. When tetrahydrofuran was used as cosolvent, the conversion increased to 95%. Important fuel properties of methyl esters of Pongamia oil biodiesel compared well with ASTM standards.

Tiwari et al. (2007) [8] optimized the three important reaction variables in biodiesel production—methanol quantity, acid concentration, and reaction time for reduction of free fatty acid (FFA) content of Jatropha curcas oil. The optimum combination for reducing the FFA of Jatropha curcas oil from 14% to less than 1% was found to be 1.43% v/v H2SO4 acid catalyst, 0.28 v/v methanol-to-oil ratio, and 88-min reaction time at a reaction temperature of 60 °C. This process gave an average yield of biodiesel of more than 99%.

Sang-Min and Hye-Sung (2008) [9] take a close at Korea's biodiesel developing trends and assess economic feasibility based on benefit cost analysis. This study finally present directions to actively promote the biodiesel in Korea.

Chhetri et. al. (2008) [10] in this work, prepared biodiesel (ethyl ester) from waste cooking oil collected from a local restaurant in Halifax, Nova Scotia, Canada. Ethyl alcohol with sodium hydroxide as a catalyst was used for the transesterification process.

Khan et. al. (2007) [11] a comparison to petroleum diesel, biodiesel has lower emission of pollutants, it is biodegradable and enhances the engine lubricity and contributes to sustainability.

Canakci (2007) [12] used biodiesel which has a higher cetane number than diesel fuel, no aromatics, no sulfur, and contains 10–11% oxygen by weight.

Zhang et. al. (2003) [13] studied four different continuous process flow sheets for biodiesel production from virgin vegetable oil or waste cooking oil under alkaline or acidic conditions on a commercial scale. Detailed operating conditions and equipment designs for each process were obtained.

Wei et. al. (2009) [14] investigated waste eggshell in triglyceride transesterification with a view to determine its viability as a solid catalyst for use in biodiesel synthesis. Effect of calcination temperature on structure and activity of eggshell catalysts was investigated.

Marchetti et. al. (2007) [15] made a review of the alternative technological methods that could be used to produce this fuel. Different studies have been carried out using different oils as raw material, different alcohol (methanol, ethanol, buthanol) as well as different catalysts, homogeneous ones such as sodium hydroxide, potassium hydroxide, sulfuric acid and supercritical fluids, and heterogeneous ones such as lipases.

2. Experimental Work

2.1 Making Biodiesel

The primary process behind making the biodiesel is the transesterification, of which the exchange of the Alkoxy group of an ester compound by another alcohol, these reactions are often catalyzed by the addition of an acid or base [16].

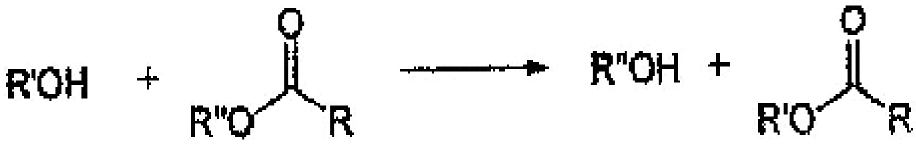
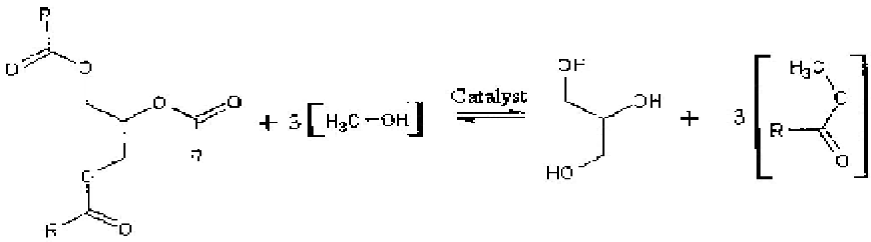


Fig. (1): illustrated Transesterification: alcohol + ester ® different alcohol + different ester

The purpose of adding acid or base is that Acids can catalyze the reaction by donating a proton to the carbonyl group, thus making it more reactive, while bases can catalyze the reaction by removing a proton from the alcohol, thus making it more reactive, in addition the presence of slight source of heat can also help in catalyzing.

The following figure displays the exact chemical formula of the reaction [17]:



Triglyceride Methanol Glycerol Methyl Ester

Fig. (2) Transesterification reaction in skeletal formula

The addition of both the methanol and the lye (a strong base catalyst, such as sodium hydroxide) (NaOH) is a variable quantity due to different types of oils that can be used thus different types of fatty acids; therefore a titration process is needed to determine how much lye and methanol to be used per liter of oil. It is found in previous researches that an average of 3.5grams of lye / liter of oil is needed, and that the stoichiometric amount of methanol required to convert the amount of oil needed varies from 11.3% for rapeseed oil to a maximum of 16.3% for coconut oil. Therefore an average of 12.5% is taken, but to ensure a good process completion, an excess of 60% to 100% of the stoichiometric amount is needed, making the final amounts per one liter of new oil is 250 ml of methanol and 5grams of lye.

The reactor was initially charged with the amount of (WCO) oil then heated to certain temperature 40-60^{o}C. The sodium hydroxide was dissolve in the methanol and then the solution was fed to the reactor feeder. The solution was also heated to certain temperature (similar to oil temperature in the reactor) then was flowed to the reactor. The reaction was timed as soon as the sodium hydroxide – methanol solution was fed to the reactor. The reaction was kept at a desired temperature for 2 hr. After 2hr, the mixture was poured into a separating funnel. The ester layer was separated by gravity and located in the upper layer. The glycerol, extra methanol and undesired product were in the lower layer and were decanted. The ester layer was washed several with a small amount of distilled water each until the washings were neutral. The ester layer was then dried. Repeat the process for new oil.

For the complete production of biodiesel of both kinds the following materials are needed:

1) 10 liters of new corn oil.
2) 10 liters of used corn oil,
3) A minimum of 5 liters of Methanol is to be provided.
4) A minimum of 100 grams of lye (NaOH) powder or pellets.
5) An electric heater.
6) Thermometer.
7) Measuring cylinder.
8) Two top opened tin containers.
9) Filtrate.

Due to the long use of the waste oil, it was found through much experimentation that the oil contains a lot of dissolved materials, which can only be excluded by leaving the oil to settle for along period of time at least a one month and then through decantation the oil on top can be taken for procedure.

2.2 Fuel Types and Specifications of Test Engine

In this research a performance and emissions tests on three different fuels, the properties of these fuel are shown in table (1) these result obtained from Petroleum Research and Development Center/Iraqi Oil Ministry, will be performed for:

1) Biodiesel from new oil.
2) Biodiesel from waste cooking oil.
3) Diesel fuel.

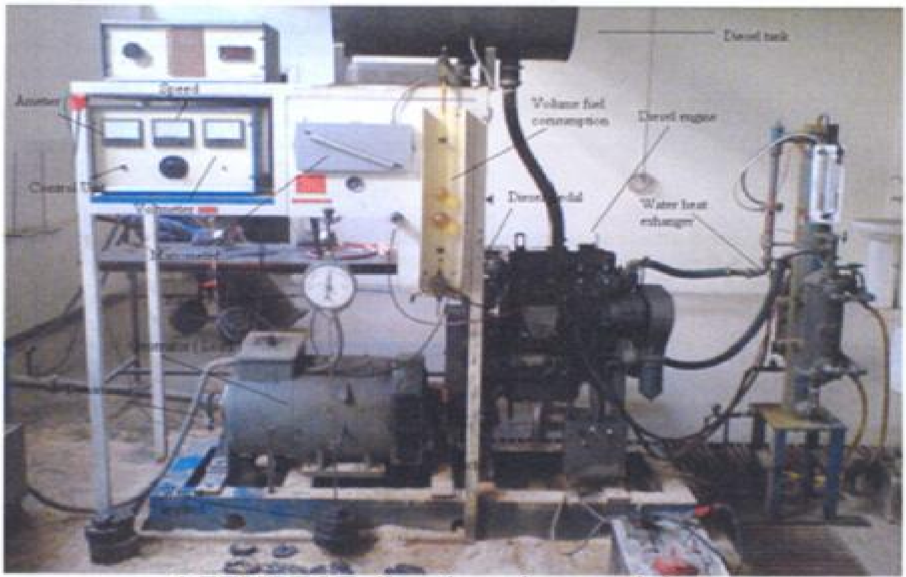
A TEMPEST diesel engine model which major specifications shown in **Table (2)** and **Figure (3a),** and a PROTECH flux 4005 gas analyzer shown in **Figure (3b)** are used. The purpose of performing this test; is to evaluate the effect of each fuel on the performance of the engine at a different set of speeds at a fixed throttle setting, with the recording of amounts of gas emissions from the exhaust, and compare the results obtained. Also a set of fuel characteristics will also be obtained to help with the calculations and better understanding of fuels through various experimentations.

Table (1): Properties of three types of fuels.

Fuel	Viscosity $\times10^{-3}$ (N/m.sec)	Density (kg/L)	Calorific Value (kJ/kg)	Sulfur Content wt%
New Biodiesel	5.8638	0.8849	38846	0%
Waste cooking Biodiesel	5.90	0.88524	36256	0%
Diesel Fuel	5.21	0.84	39000	1.2%

Table (2): Specifications of the engine test.

Engine type	TEMPEST diesel engine model 1.5
Diameter	72.25mm
Stroke Length	88.2mm
Cylinder number	4-cylinder
Stroke number	4-stroke
Load	Variable
Engine Speed	10-60 rps
Cooling system	Water cooled
Swept volume	1500cc



a) TEMPEST diesel engine model.

b) Gas analyzer.

Fig. (3): illustrated test engine setup, (a) TEMPEST diesel engine model and (b) PROTECH FLUX 4005 gas analyzer.

2.3 Experimental Procedure

The following steps are brief of experimental procedure:

- Engine was started to run.
- The gas analyzer was started and the pump activated to intake fresh air then the hose in the exhaust pipe was installed.
- Brake load was introduced and the throttle was opened to its widest setting.
- The brake load was increased to reduce the speed to the lowest possible value consistent with stability of operations.
- Where possible, ignition and timing and mixture strength controls could be adjusted (if appropriate) to optimum settings.
- The readings listed below were observed:
    - Engine speed.
    - Brake loads (Newton).
    - Fuel consumption timing (sec)
    - Manometer reading Δp = mm
    - The printed results on the gas analyzer
- The speed was increased in even steps by reducing the load and observations were recorded after each step. Care was taken to ensure that steady conditions have been reached.
- The test procedure was repeated for a medium throttle (50%) to observe the displacement of the peak power and peak torque values.
- The engine was turned off.
- The gas analyzer was turned off.

3. Mathematical Calculations

The thermal efficiency is defined for a cycle to show the efficiency of conversion of heat into work:

$$h_{th} = \frac{Work}{Heat\ \text{Supplied}} \quad (1)$$

The force and torque were calculate by using

$$F = W * g \quad (2)$$

$$T = F.r \quad (3)$$

The brake power was calculated by using

$$Bp = 2p\left(T.N/1000\right) \quad (4)$$

The rate of fuel consumption was calculated by

$$\dot{m}_f = (Volume / Time) * r_{\text{fuel}} \qquad (5)$$

$$\dot{m}_f = \left(\frac{V}{t}\right) * r_{fuel} \qquad (6)$$

Where V the volume of fuel (50 ml) and ρ_{fuel} is the density of fuel.
The specific fuel consumption was calculated by using

$$BSFC = \left(\frac{\dot{m}_f}{Bp}\right) 3600 \qquad (7)$$

The brake thermal efficiency was calculated by using

$$h_{bth} = \frac{Bp}{P_{FE}} \qquad (8)$$

Rate of heat input was calculated by using

$$P_{FE} = \dot{m}_f * CV \qquad (9)$$

The combustion air flow rate was calculated by using

$$\dot{m}_{air} = r_{air} * V_{air} * A * C_d \qquad (10)$$

Cd = 0.625

The air velocity

$$V_{air} = \sqrt{2\Delta h_o g \left({r_{water}} \big/ {r_{air}} \right)} \qquad (11)$$

$$\dot{m}_{air} = Const * \sqrt{\Delta h_o} \qquad (12)$$

4. Results and Discussion

In this section the results of the experimental work for using three types of fuel on performance of diesel engine. All the results are presented for different engine speeds and loads. And the three types of fuel (new biodiesel, waste cooking biodiesel and diesel fuel) experimental work and calculations were performed for both full throttle and medium.

Tables (3, 4, and 5) show variation of fuel consumption time with engine speed for both full throttle and medium. These tables illustrated the fuel consumption time decrease with increasing speed, the maximum values occur at diesel fuel and minimum values for waste coking biodiesel at full. While the minimum values of medium throttle for new biodiesel.

Tables (3, 4, and 5) also show variation of force and torque with speed. These tables illustrated, where as the speed increases the torque increase until it reaches an optimum value then starts to drop down, that happens because every engine cycle results in decreases because the engine is unable to ingest a full charge of air at higher speed. It is obvious that tables of full throttle are higher than medium throttle.

Figures (4), (5) and (6) show the emissions of CO, CO_2 and O_2, it could be seen that emissions of carbon dioxide are low for all fuels less than the critical limit of 2%, and the emission of hydrocarbons are almost zero for all fuels and that emission of carbon dioxide are close to each other for all fuels and in general biodiesel has a slightly higher emissions, but fact that the air fuel ratio for diesel fuel is a lot higher compared to biodiesel,and maximum values for waste cooking biodiesel and minimum values for diesel fuel at full throttle.

Figure (7) shows the variation of fuel consumption rate with speed for three types of fuel, the maximum rate for waste cooking biodiesel while minimum rate for diesel fuel at full throttle and the rate increase with increased engine speed. The same behavior will be showed at medium throttle but the maximum values were occurring for new biodiesel.

Figure (8) shows variation of brake power with speed for three types of fuel at full and medium throttle. This figure shown the new biodiesel has the highest power after that the waste cooking biodiesel then finally comes the diesel fuel. It is attributed to clean burning of biodiesel than diesel fuel at full throttle.

Figure (9) shows variation of brake specific fuel consumption with speed for three types of fuel at full and medium throttle respectively. The diesel fuel has lower fuel consumption than biodiesel, because the diesel has lower density than biodiesel, because of weaker molecule bonds which leads to a lower flash point, making of this sentence that, diesel has faster burning than biodiesel which attributes to a higher amount of power in the same period of time while burning biodiesel. The same behavior which be seen in medium throttle.

Figure (10) shows variation of fuel equivalent of power with speed for three types of fuel at full and medium throttle. This figure shown the waste biodiesel has the highest fuel equivalent of power after that the new biodiesel then finally comes the diesel fuel for two cases of full and medium throttle and 50 ml fuel consumption.

Figure (11) shows variation of brake thermal efficiency with speed for three types of fuel for two cases full and medium throttle, the figures took a shape of concave down, because as the fuel rate increase the brake power increase unit it reaches an optimum, and then decreases because the higher amount fuel ingest do not compensate for friction losses at high speeds.

Figure (12) and (13) show variation of air mass flow rate and air velocity with speed for three types of fuel respectively. The biodiesel fuel has higher values than diesel fuel for two cases full and medium throttle at low speed (10-25 rps) and lower values for higher speed (25-50 rps).

Figure (14) shows the air fuel ratio for diesel fuel is a lot higher compared to biodiesel, where the air fuel ratio for new oil biodiesel ranged (25-65; full throttle, 25-57; medium throttle), waste cooking oil ranged between(22-51; full throttle, 26-66; medium throttle), and diesel fuel ranged between (28-87; full throttle, 31-93; medium throttle).

Table (3) New Oil Biodiesel Calculation for both Throttle and Medium

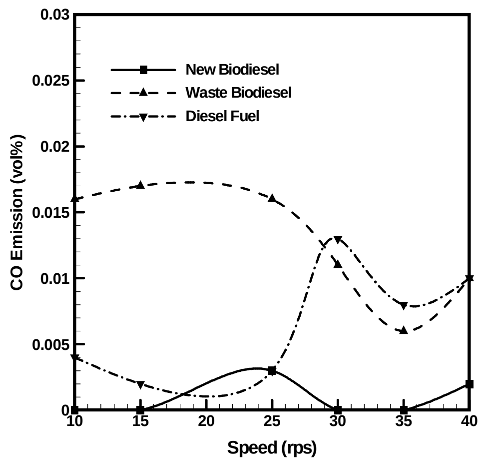
	N(rps)	Time (s)	Δh_o(mm water)	F(N)	T(N.m)
full	10	134	14.5	85.3	34.1
	15.5	99	15.5	99. 1	39.6
	24	65	18.0	104.0	41.6
	30	54	18.0	107.9	43.2
	35.5	48	50.5	103.0	41.2
	40	42	23.0	106.0	42.4
medium	10	117	15.5	88.3	35.3
	15	95	16.0	90.3	36.1
	25	62	18.5	98.1	39.2
	30	51	18.5	103.0	41.2
	35	47	20.0	100.1	40.0
	40	40	24.5	98.1	39.2

Table (4) Waste Cooking Oil Biodiesel Calculation for both Throttle and Medium

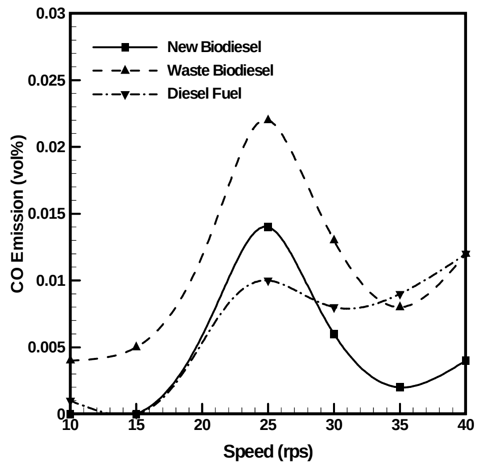
	N(rps)	Time (s)	Δh_o(mm water)	F(N)	T(N.m)
full	10	107	14.5	25.3	34.1
	15	90	14.5	88.3	35.3
	25	59	17.0	98.1	39.2
	30	49	18.5	103.0	41.2
	35	40	19.5	103.0	41.2
	40	38	22.5	100.1	40.0
medium	10	129	17.0	93.2	37.3
	15	104	17.5	95.2	32.1
	25	67	17.5	98.1	39.2
	30	55	18.0	102.0	40.8
	35	50	19.0	195.2	38.1
	40	45	22.0	92.2	36.9

Table (5) diesel Calculation for both Throttle and Medium

	N(rps)	Time (s)	Δh_o(mm water)	F(N)	T(N.m)
full	10	162	17.0	73.6	29.4
	15	126	17.0	80.4	32.2
	25	75	17.0	92.2	36.9
	30	65	18.0	88.3	35.3
	35	58	18.5	90.3	36.1
	40	46	21.0	103.0	41.2
medium	10	177	16.0	62.8	25.1
	15	136	16.0	72.6	29.0
	25	80	17.5	88.3	35.3
	30	70	17.5	83.4	33.4
	35	59	18.5	88.3	35.3
	40	50	22.0	90.3	36.1

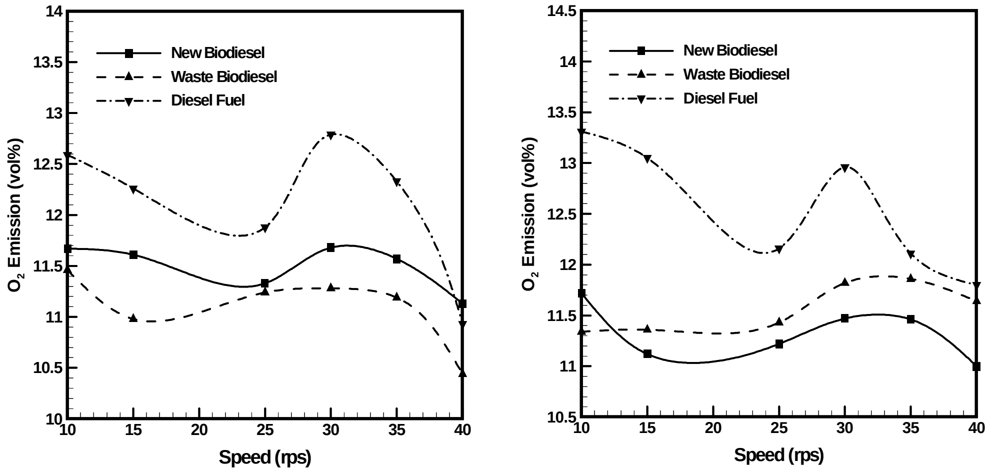


a) Full Throttle



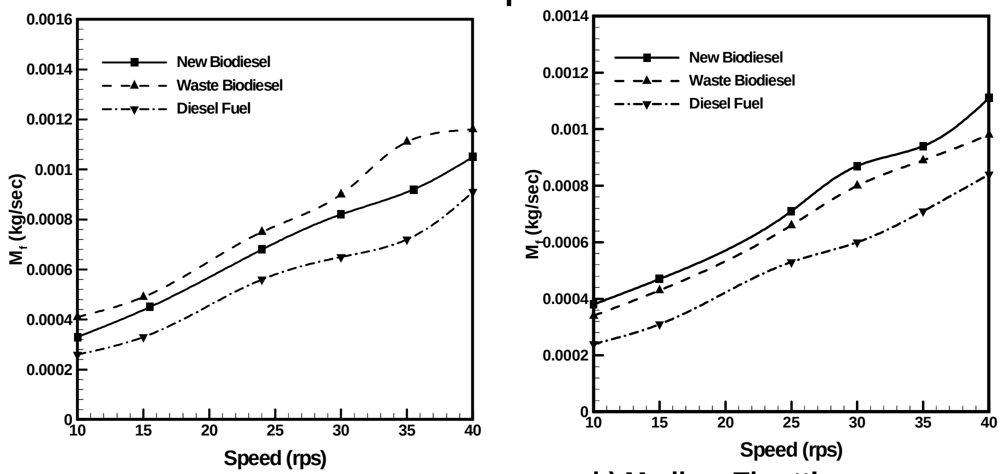
b) Medium Throttle

Fig.(4): illustrated emission of CO for three types of fuel with engine speed.



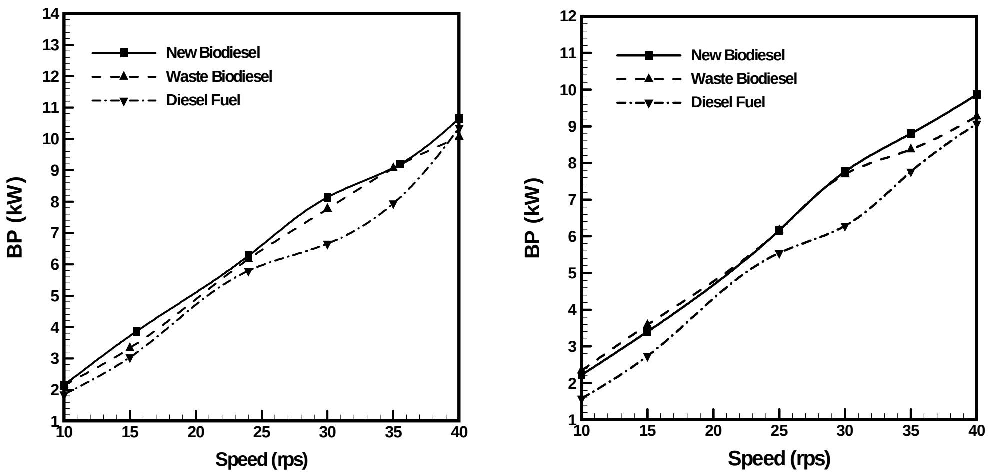
a) Full Throttle   b) Medium Throttle

Fig. (6): illustrated emission of O_2 for three types of fuel with engine speed.



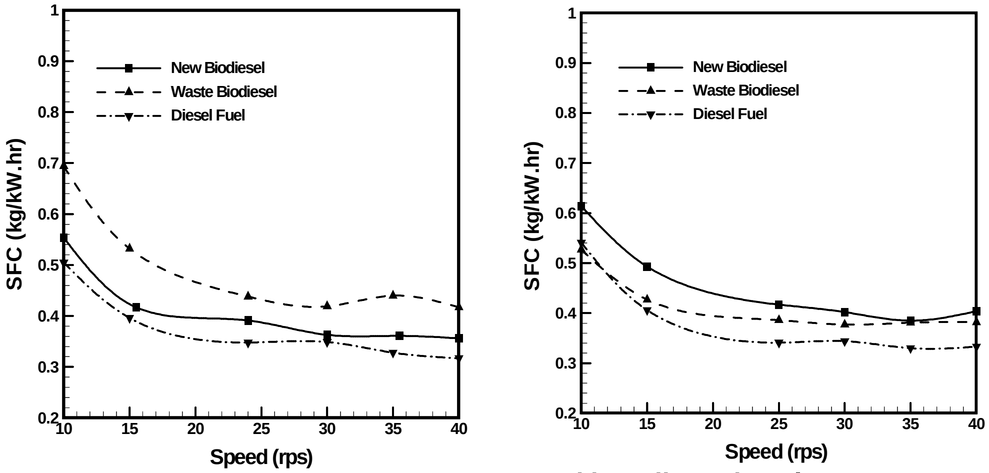
a) Full Throttle   b) Medium Throttle

Fig. (7): illustrated variation of rate of fuel consumption with speed for three types of fuel.



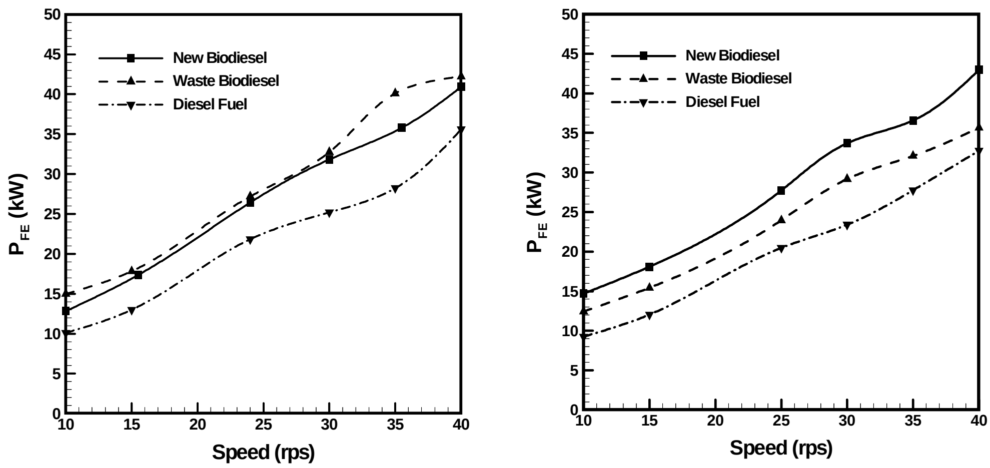
a) Full Throttle   b) Medium Throttle

Fig. (8): illustrated variation of brake power with speed for three types of fuel.



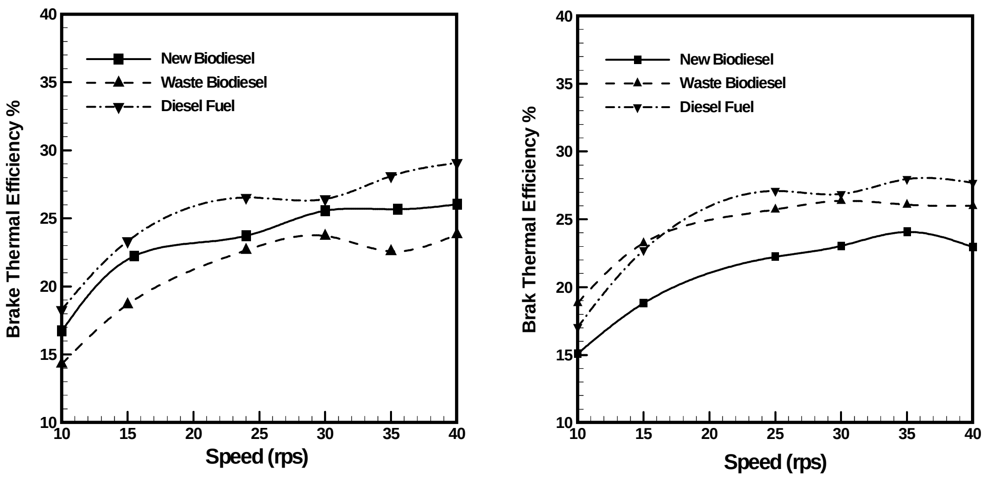
a) Full Throttle b) Medium Throttle

Fig. (9): illustrated variation of brake specific fuel consumption with speed for three types of fuel.



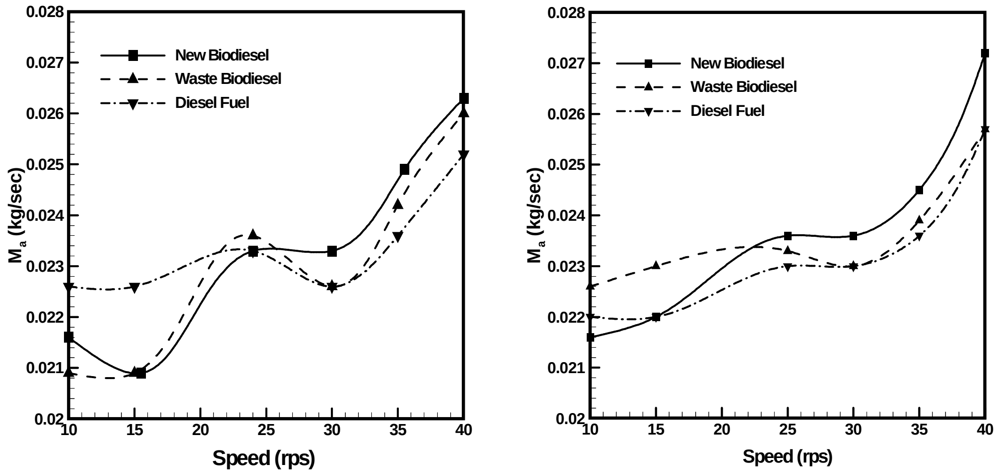
a) Full Throttle b) Medium Throttle

Fig. (10): illustrated variation of fuel equivalent of power with speed for three types of fuel.



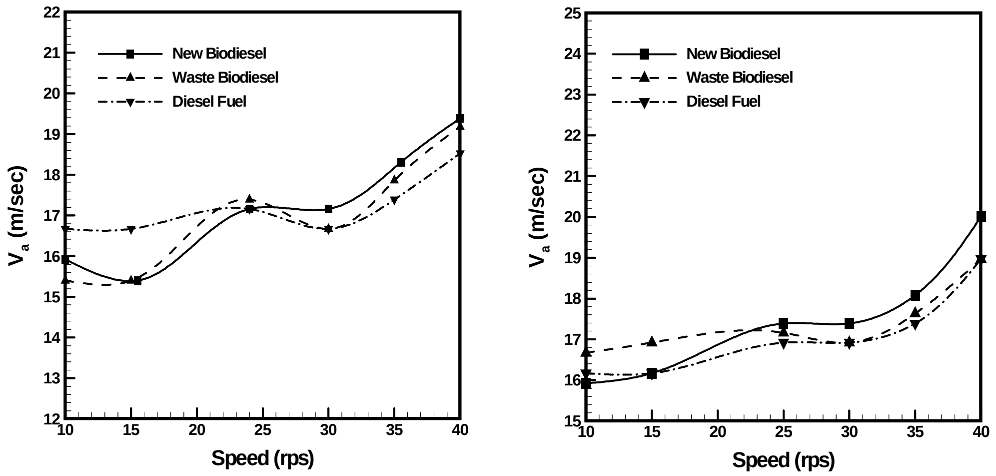
a) Full Throttle b) Medium Throttle

Fig. (11): illustrated variation of brake thermal efficiency with speed for three types of fuel.



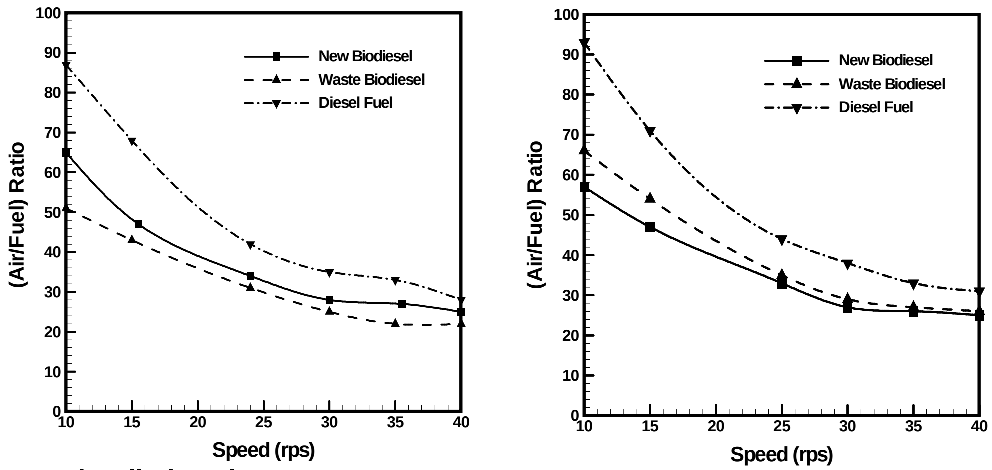
a) Full Throttle b) Medium Throttle

Fig. (12): illustrated variation of air mass flow rate with speed for three types of fuel.



a) Full Throttle b) Medium Throttle

Fig. (13): illustrated variation of air velocity with speed for three types of fuel.



a) Full Throttle b) Medium Throttle

Fig. (14): illustrated variation of (Air/Fuel) ratio with speed for different three types of fuel.

5. Conclusions

Biodiesel is a clean-burning fuel that is renewable and biodegradable.

The engine has been tested under same operating conditions with diesel fuel, new and waste cooking biodiesel. The results were found the following points:

- When the speed of engine increases the torque and brake power increases to an optimum range then decreases.
- When the engine speed increases the specific fuel consumption decreases to a minimum then starts to increases as speed increases.
- When the engine speed increases the brake thermal efficiency increases until it reaches an optimum then starts to decrease as speed increases.
- The biodiesel in general though having less heating value than diesel has and it higher brake power and torque because it is clean burning and smoother running.
- The biodiesel has more specific fuel consumption than diesel thus having less brake thermal efficiency.
- The biodiesel is safer for environment because it has low flue gas emissions taken in consideration that diesel has leaner combustion.

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