تقييم أداء وانبعاثات محرك ديزل ذو حقن مباشر يعمل بالوقود الحيوى المنتج من زيوت القلى المستعملة

Evaluation of the Performance and Emissions of a DI Diesel Engine Burning Biodiesel Produced from Used Frying Oil

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ملخص البحث

في الدراسة الحالية، تم تصميم وتنفيذ وحدة معملية لإنتاج الوقود الحيوى من زيوت القلى المستعملة بإستخدام عملية الأسترة. وبقياس الخواص الفيزيائية والكيميائية للوقود الحيوى المنتج، وجد أن اللزوجة مرتفعة للحد الذى قد يؤثر على آداء منظومة الحقن وتذرير الوقود وبالتالى على أداء المحرك. وللتغلب على هذا العيب تم عمل توليفات من الوقود الحيوى المنتج مع وقود الديزل بنسب حجمية مختلفة. كما تم دراسة تأثير هذة التوليفات على الأداء والإنبعاثات لمحرك ديزل تبريد هواء ذو حقن مباشر ذو أسطوانة واحدة عند سرعة 1500 لفة فى الدقيقة عند احمال مختلفة. توليفات الوقود الحيوى المنتج من زيوت القلى المستعملة مع الديزل يعتبر كوقود متجدد بديل لمحركات الديزل بدون أى تعديل فى المحرك، وجد أن الخلائط 10%و 15% و 20% و 30% تؤدى الى تحسين آداء المحرك بزيادة متوسط الكفاءة الحرارية الفرملية بنسبة 1.0768 : 2.8288 % مقارنة بوقود الديزل عند الأحمال المختلفة. ونظرا لنقص المحتوى الحرارى للوقود الحيوى عن وقود الديزل، فإن معدل الإستهلاك النوعى للوقود الفرملى يزداد عند استخدام خلائط الوقود الحيوى بنسبة تتراوح بين 1.855 : 10.63 %. كما وجد ان متوسط انبعاثات أول أكسيد الكربون وأول أكسيد النيتروجين تقل عن نظيرتها للديزل بنسب 32.232 و 10.13 % على الترتيب. كما أن درجات حرارة العادم تقل بأستخدام توليفات الوقود الحيوى عند جميع التحميلات بنسبة تخفيض 13.38% .

Abstract

In this study, the effect of using Used Frying Oil Methyl Ester (UFOME) and diesel fuel mixture in direct injection diesel engine on the engine performance and emission is investigated. A reactor has been designed and manufactured for the production of methyl ester from used frying oil. Five blends at different volume proportions of diesel with the extracted methyl ester are used. The physical and chemical properties of methyl ester and its blends are measured. The experiments are carried out using a single cylinder direct injection diesel engine at the constant engine speed mode (1500 rpm) at five different engine loads. The results are compared with ordinary diesel fuel. It is found that blend B25 (25% of biodiesel in a mixture of biodiesel and Petrodiesel fuel) led to the highest brake specific fuel consumption by about (6.5-14%) compared with that when pure Petrodiesel is used. B30 gives the highest brake thermal efficiency. Carbon monoxide average emission values decreases by 32.232% for all UFOME blends with maximum average reduction of 44.4% for B10. Exhaust temperature and nitrogyn monoxide emissions are minimum at 50% engine load with average reduction of 13.38% and 10.13% ,respectively.

Keywords

Alternative Fuels, Biodiesel, Used Frying Oil, Methyl Ester, Transesterification

1. Introduction

Based on many research works it became evident that the world is in the midst of an on going fuel supply shortage. This is not a surprise, since research showed that the oil resources are declining and will become more difficult and expensive to extract. According to the BP (British Petroleum) statistical review of world energy in June 2014, the world primary energy consumption in 2013 was 12730.4 million

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toe (ton oil equivalent, 1 toe = 41.868 GJ), which is gross higher than that in 2012 by about 2.3%. The energy consumption is not expected to be decreased in the current century. This is because both world population and urbanization are increasing. Energy consumption is mainly based on fossil fuels, which account for 87% among the other energy sources. Crude oil represents 32.87%, coal 30.06% and natural gas 23.73%, respectively. The share of nuclear energy, hydropower and renewable energy are very small with only 4.42%, 6.72% and 2.19 of total energy usages, respectively [1].

In addition, emissions which are produced from burning petrofuels have a serious effect on both environment and human health [2, 3]. Therefore, it becomes a global agenda to develop clean alternative fuels. These fuels should be domestically available, environmentally acceptable and technically feasible. It has been found that the vegetable oils (VO), as a kind of renewable clean energy resource, fulfill these conditions and hence capable of replacing fossil fuel. VO are promising fuels because their properties are similar to that of diesel and are produced easily and renewably from the crops. Vegetable oils have comparable energy density, cetane number, heat of vaporization and stoichiometric air–fuel ratio as compared with diesel fuel. However, using crude vegetable oils in engine may cause various engine problems such as injectors coking, carbon deposits on piston and head of engine and excessive engine wear [4]. For this reason it is recommended by many researchers to transesterify vegetable oils to reduce its high viscosity. This transesterified vegetable oil is known as biodiesel or fatty acid methyl esters (FAME).

Biodiesel is produced by chemical reaction from vegetable oils, used frying oils and animal fats with an alcohol such as methanol. The reaction requires a catalyst, usually a strong base such as sodium or potassium hydroxide. The reaction produces new chemical compounds called methyl ester [5-7].

Biodiesel has many advantages like low emissions, biodegradable, non-toxic and better lubricity compared with diesel fuel. Biodiesel can be directly used in neat form in unmodified diesel engine or can be mixed with petroleum diesel fuel [8, 9].

The choice of vegetable oil as a feedstock for producing biodiesel depends on the cost of production, reliability of supply and high yield. At present, the high cost of biodiesel is the major obstacle to its commercialization. It is reported that the high cost of biodiesel is mainly due to the cost of virgin vegetable oil [10]. The use of waste frying oil instead of virgin oil to produce biodiesel is an effective way to reduce the cost of the feed stock.

In some countries such as Egypt, cooked oils are usually reused several times for cooking in different applications. The degree of reuse of waste oils differs from country to another which in turn will vary the properties of the biodiesel produced. There are many sources for used frying oils such as food processing plants, restaurants, homes, and street vendors. Producing biodiesel from used frying oil will discourage the reuse of frying oil and prevent used cooking oil (which contains carcinogenic dioxin materials) from being used in animal feed preparation [11].

Results of performance and emission tested in short periods of UFOME blends' power, specific fuel consumption, and emission values are encouraging as reported by other researchers [12-17].

The objective of the present study is to investigate the effect of using Egyptian Used Frying Oil Methyl Ester (UFOME) and diesel fuel mixture as a fuel in direct injection diesel engine on the engine performance and exhaust emissions characteristics.

2. Experimental work

The experimental study includes two steps. The first one is the reactor to produce the methyl ester from the used fry oil and the determination of its physical and chemical properties. The second section consists of engine performance tests, as fuel usage of UFOME blends and comparison to diesel fuel.

2.1 Feedstock for the production of Methyl Ester

Alkali-catalyzed process was used to produce biodiesel from the used frying oil. The used frying oil is collected from chips factories in Egypt. The major ingredients of this oil are sunflower oil and soybean oil. The supplied oil is filtered from impurities, using 15um diameter filter.

2.1.1 Design of the Reactor for Methyl Ester Production

The production system was designed and installed to obtain methyl ester from UFO. The installed system consists of a filter to strain used frying oil and a batch type reactor. A representation of the biodiesel production system is shown in Figure (1).

2.1.2 Production process

Transesterification method is used for methyl ester production from used frying oil. This method is a chemical reaction, which refers to the conversion of an organic acid ester into another ester of the same acid so-called biodiesel using an alcohol in presence of a catalyst. The method is affected by several variable including; reaction temperature, type and concentration of the alcohol and type of the catalyst. In this study, 1 kg of used frying oil is taken in a round flask and a separately prepared mixture of 8 g NaOH is dissolved in 240 g of methanol and is added to this round flask. The mixture is stirred and maintained at 65 ℃ for 1 hour and then allowed to settle down under gravity in a separating funnel. Ester forms the upper layer in separating funnel and Glycerol in the lower layer. The separated ester is mixed twice with 0.25 kg of hot water and allowed to settle under gravity for 24 hours. The catalyst dissolved in water, forms the lower layer and can be separated. Moisture is removed from this ester using silica gel crystals. About 0.905 kg of purified ester is obtained at the end. The entire process takes 48 hours. The purified used frying oil methyl ester (UFOME) is then blended with petrodiesel to be used in a diesel engine as a fuel.

2.1.3 Fuel properties

The properties of UFOME blends are measured in the Egyptian Petroleum Research Institute according to ASTM standard procedures. The properties of the waste cooking oil (methyl esters) and its blends are listed in Table 1. It could be noted from this Table that the viscosity, flash point, and density of used frying oil methyl ester are higher than those of Petrodiesel. Heating value and Cetane number of UFOME are lower than those of petrodiesel. To overcome the problem of the high viscosity of UFOME, it is blended with diesel fuel. The blends considered in this study are: 10% (B10), 15% (B15), 20% (B20), 25% (B25), and 30% (B30).

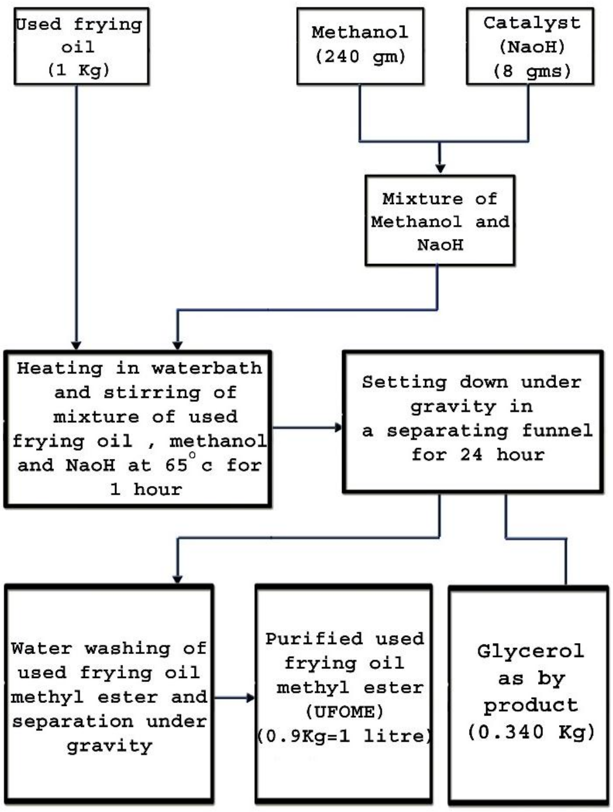

Fig. (1) Schematic representation of biodiesel production system from used frying oil.

2.2 Experimental set up

The performance of a DI diesel engine has been studied considering different blends of petrodiesel and biodiesel. These have been evaluated against those measured when pure petrodiesel is used. Experiments are carried out by using a single cylinder, four stroke cycle, naturally aspirated, air cooled direct injection diesel engine. The specifications of the engine are given in table (2). A schematic layout of the experimental setup is depicted in Figure (2). Engine performance and exhaust emission tests were carried out at constant speed of 1500 RPM with various engine loading a t; no, 25%, 50%, 75%, and 90% loads. The procedures followed during the experiments are given below:

I. Fuel injector pressure is adjusted at 185 bar and valves adjustments are checked according to the engine catalog, and engine oil was changed before engine tests.
II. At first, the test is run with standard diesel (sold commercially) and followed by the biodiesel blends.
III. The engine is started using an electric motor coupled with the fly wheel with a belt.
IV. Engine power and fuel consumption are measured after the engine is sufficiently warmed up and stabilized.
V. Loading the engine is applied by using electrical load (set of bulbs). Voltage and current are measured by voltmeter and ammeter, respectively.
VI. An orifice meter and a U-tube manometer are used to measure the engine air flow rate. A surge tank fixed on the inlet side of the engine maintains a constant airflow through the orifice meter and dampens cyclic fluctuations.
VII. Fuel consumption is calculated by measuring the time at which a certain fuel volume is consumed.
VIII. Exhaust emission values are measured by using Landcom 6500A Portable Gas Analyzer monitoring system. The gas analyzer is calibrated before measurements, and its probe is inserted into the exhaust pipe at 1.2 m away from the exhaust manifold. The temperature of exhaust gases (℃), ambient temperature (℃), O2 (%), CO (ppm and mg/N m3), NO (ppm and mg/N m3), and combustion efficiency (%) are measured.

The performance characteristics of the engine are evaluated in terms of; air to fuel mass ratio (AFR), brake specific fuel consumption (BSFC), and brake thermal efficiency (BTE). On the other hand emissions are evaluated in terms of the

Properties	Testing method	ASTM Standard	UFOME	Diesel fuel	B15	B20	B25
Density (at 15.65℃, kg/m^3)	ASTM D-1298	—	883.5	824.4	838.7	840.4	845.5
Kinematic viscosity (at 40℃, mm^2/s)	ASTM D-445	1.9 - 6	5.25	3.68	4.18	4.26	4.34
Flash point, (℃)	ASTM D-92	> 130	176	58	92	98	102
Cetane number	—	—	31	58	46	42	37
pH value (mg KOH/g)	ASTM D-664	< 0.8	0.605	—	0.337	0.835	0.377
Lower heating value (kJ/kg)	ASTM D-240	—	38 500	42 700	40 780	40 148	39 510

Table (1) Physical and chemical specifications of UFOME, diesel, and biodiesel blends.

Engine type	Kirloskar, four stroke cycle, air cooling, naturally aspirated
Bore × Stroke	102mm × 110mm
Displacement	889 cm3
Inlet valve diameter	42 mm
Exhaust valve diameter	36 mm
Engine speed	1500 rpm
Max. Power	7.35 kW (10 hp)
Exhaust valve Lift (max)	9.82 mm
Inlet valve Lift (max)	9.82 mm
Piston shape	half spherical bowl
Compression ratio	18.5
Injection pressure	185 bar

Table 2
Specifications of diesel engine

measured concentrations of carbon monoxide (CO), nitrogyn monoxide (NO), and exhaust temperature (T_{exh}). These concentrating parameters are measured for biodiesel blends and compared with the results of baseline diesel fuel.

3. Results and discussion

3.1 Engine performance

3.1.1 Brake power and indicated mean effective pressure

The brake power developed by the engine on different load conditions is presented in Figure (3). Brake power developed by B25 and B15 blends are very close to diesel for entire range of operation. At maximum load defined by the colorless exhaust limit, the maximum brake power (6.51 Kw) is obtained for B25, followed by B15(6.5 Kw) and standard diesel (6.456 kW). The variation of indicated mean effective pressure with engine load is shown in Figure (4). The indicated mean effective pressure for B25, B15, B10, and diesel are 5.976, 5.927, 5.88, and 5.858 bar respectively. It can be concluded from this result that the chemical energy contents of all tested fuels turn into mechanical work in a similar manner.

3.1.2 Air Fuel Ratio

The variation of air to fuel ratio (AFR) with brake power for diesel and biodiesel blends are shown in Figure (5). At constant speed,

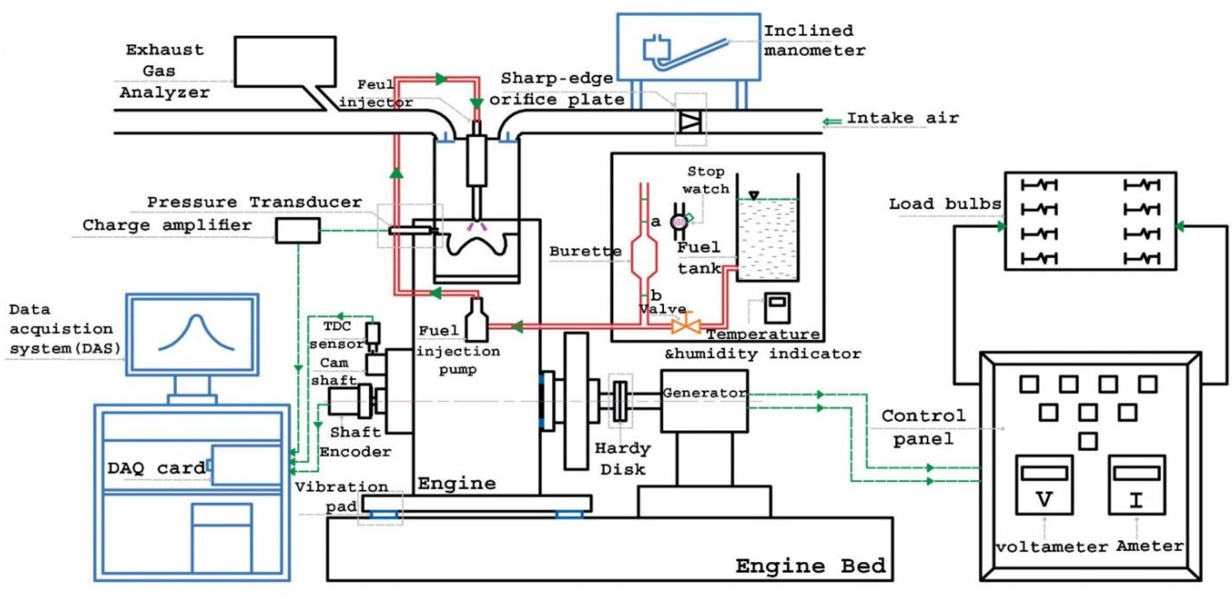

Fig. (2) Layout of experimental setup with instrumentation.

the amount of air flow rate to the engine cylinder is fixed. Therefore, air to fuel ratio, AFR, decreases as the engine load increases. AFR of all blends is lower than that for petrodiesel for entire range of operation. This may be due to the oxygen content in UFOME blends which contribute to more complete combustion, as shown in Fig. (5). For the different blends at low and medium loads, B25 has the minimum AFR value followed by B30. AFR of B25 and B30 blends at half load is 38.958 and 39.746 , repectively against 42.197 for diesel. At 90% load, B30 has a minimum value of 25.227 followed by 25.685 of B25 against 28.867 for diesel.

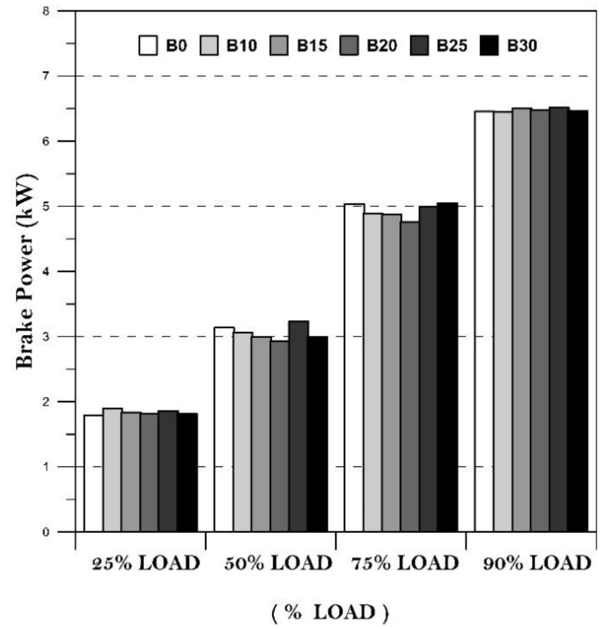

Fig. (3) Brake power of biodiesel blends versus loads.

3.1.3 Brake specific fuel consumption

Figure (6) shows the variation of brake specific fuel consumption (BSFC) with brake power for diesel and its blends with UFOME. It could be seen from this figure that for all biodiesel blends, minimum brake specific consumption was obtained at 90% engine load. The minimum BSFC for all blends at this load is 221.3 g/kW.hr for B15 compared to 219.26 g/kW.hr for diesel fuel. In average, the BSFC of B10, B15, B20, B30, and B25 are higher than that for biodiesel by 1.855%, 2.924%, 4.136%, 6.668%, and 10.63% ,respectively. This is because biodiesel has lower heating value and higher density than that for diesel fuel. The net heating value of UFOME is about 9.84% lower than that of diesel fuel. It can be observed that the trends of blends showed an increase in specific fuel consumption as the amount of UFOME in the blend is increased except B25. Blend B25 has the highest BSFC of all tested fuel for entire range of engine load and this may be because B25 has the minimum cetane number among all biodiesel blends and this causes longer burning and consequently more fuel consumption [18].

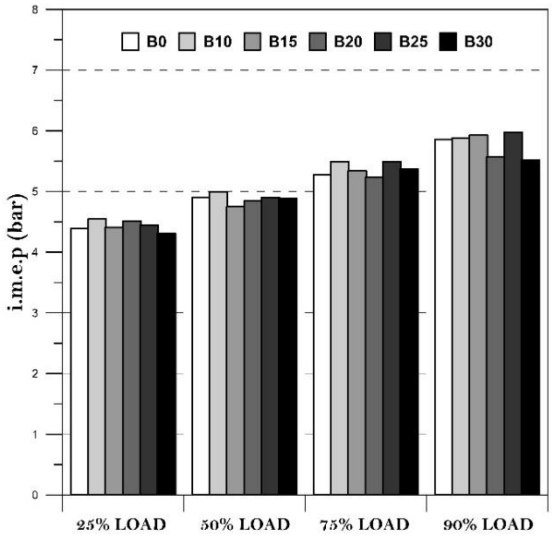

Fig. (4) Variation of indicated mean effective pressure (i.m.e.p) with brake power.

3.1.4 Brake thermal efficiency

Figure (7) shows the variation of brake thermal efficiency (BTE) with respect to load for diesel and different biodiesel blends. In all cases, brake thermal efficiency increases as engine load increases. This is due to the reduction in heat losses and the increament in power developed as the applied load increases. The maximum brake thermal efficiency obtained at 90% load is about 39.473% for B15, which is 3.287% higher than that of diesel (38.216%). The maximum brake thermal

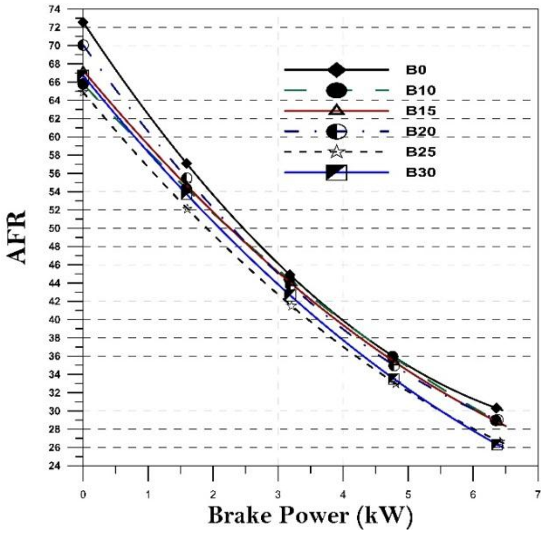

Fig. (5) Variation of air fuel ratio(AFR) with brake power.

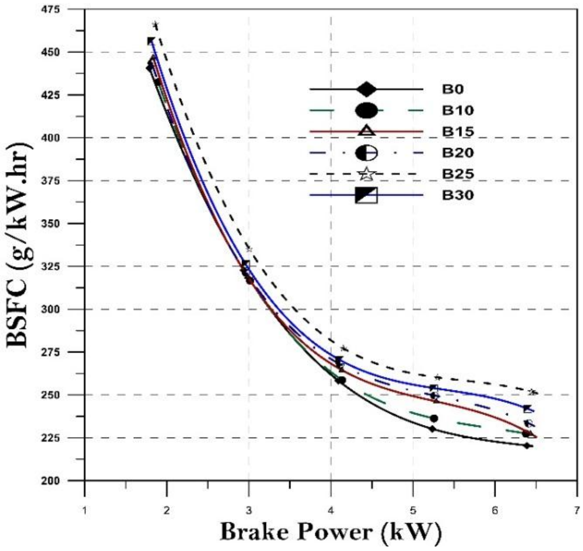

Figure (6) Variation of brake specific fuel consumption (BSFC) with brake power.

efficiency obtained when using B10, B20, B25, and B30 are 38.23%, 38.896%, 36.33%, and 38.672%, respectively. It could be seen from Figure (7) that the thermal efficiency of the engine is firstly increased with increasing the percentage of biodiesel in the blend then decreased, except B25. This is may be due to the lubricity effect of the biodiesel. It is to be noted that the oxygen contained in the biodiesel blends take part in combustion which in turn enhance the combustion process. The lower brake thermal efficiency obtained for B25 could be due to the reduction in calorific value and increase in fuel consumption as compared to diesel [19].

3.2 Exhaust emissions

3.2.1 CO emissions

Figure (8) shows the plots of carbon monoxide (CO) emissions with engine brake power. As a general trend, the carbon monoxide emissions are found to be increasing with the load. This is typical for all internal combustion engines since the air–fuel ratio (AFR) decreases with the load. In light of many literatures reviewed, a decrease in CO emissions when substituting diesel fuel with biodiesel can be considered as a general trend [20-22].

It is interesting to note from Fig. (8) that the engine emits more CO when using diesel fuel than that for biodiesel blends under all loading conditions. CO emissions are reduced when using biodiesel blends mainly due to the effect of extra oxygen in biodiesel blends which lead to complete combustion. Also it could be seen from Fig. (8) that CO formation decreases from no load till 25% load, then increases with engine loading. At the no load operation, poor atomization and uneven distribution of small portions of fuel across the combustion chamber, along with a low gas temperature, may lead to local oxygen deficiency and incomplete combustion. This could be the answer of why CO emissions tend to be relatively high at no loaded engine. As the load increases, the pressure and temperature increases in the combustion chamber. Moreover, the mixing of the fuel rich portions with fresh air should be improved. On the other hand, the time duration of the combustion process becomes very limited, which results in increasing CO emissions. As it could be noted from the figure that the minimum CO emissions value have found to be 133 ppm for B10 (at 25% load) followed by 167 ppm for B15 (at 25% load), 171 ppm for B25 (at 50 % load),

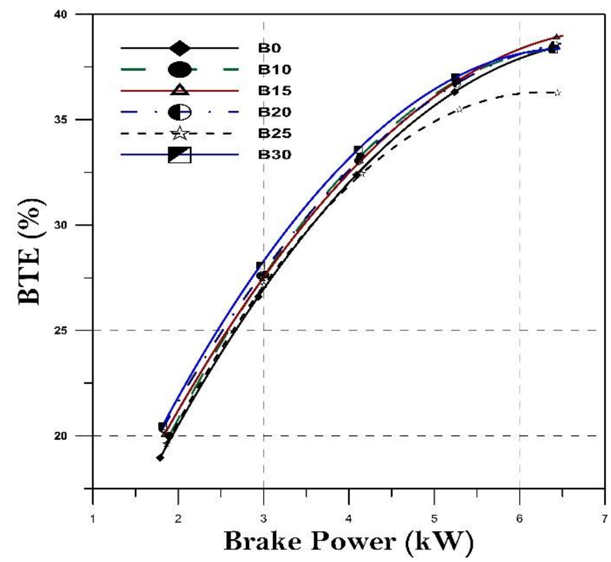

Fig. (7) Variation of brake thermal efficiency (BTE) with brake power.

181 ppm for B20 (at 50% load), and 199 ppm for B30 (at 50% load) against 230 for Petrodiesel (at 25% load), respectively. Average lessening of CO emissions is obtained as 44.4% for B10, 40% for B15, 33.28% for B20, 28.7% for B25, and 14.78% for B30. In the case of B30 blend, although B30 has the largest amount of oxygen, it has the minimum reduction of CO

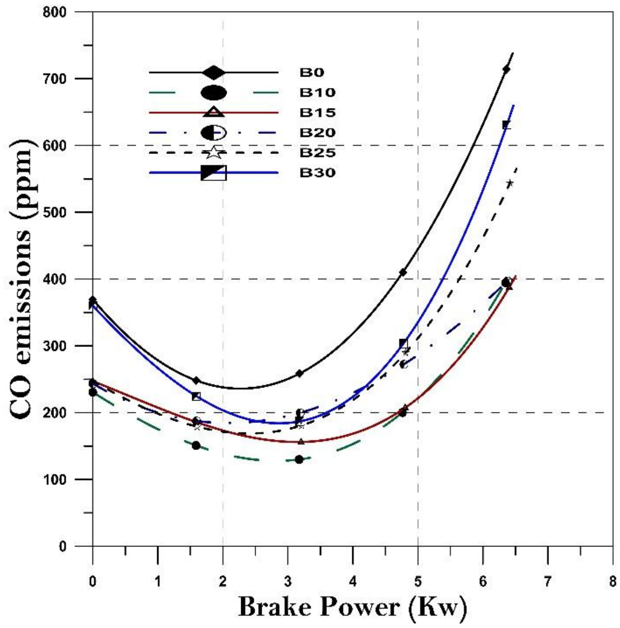

Fig. (8) Variation of carbon monoxide (co) with brake power.

emissions compared with diesel fuel. This is due to the higher viscosity which causes poor atomization and poor combustion.

3.2.2 NO emissions

NO emissions are very important in polluted air [23]. Diesel engines operate with an excess air ratio on full load and higher values on lower loads. Diesel engines combustion generates large amounts of NO because of high flame temperatures (> 1800 K) in the presence of abundant oxygen and nitrogen in the combustion chamber [24]. The variation of NO emissions of the diesel fuel and its blends with UFOME with engine brake power is shown in Figure (9).

NO emission increases with the engine load increases, due to a higher combustion temperature. This proves that the most important factor for emissions of NO is the combustion temperature in the engine cylinder and the local stoichiometry of the mixture. From Fig.(9), it can be seen that within the engine loading range, the NO emissions from the biodiesel blends are lower than that of diesel (except blend B10 which has higher NO emissions than that of diesel at low and medium load). The reduction of NO emissions is possibly due to the smaller calorific value of the blend [25].

From Fig.(9), at 90% engine load, all types of fuels give the highest NO emissions as follow: 2025 ppm for B25, 2171 ppm for B15, 2172 ppm for B30, 2218 ppm for B20, and 2481 ppm for B10 against 2465 ppm for diesel. For all engine loads, the engine maximum NO emission reduction for all biodiesel blends is occured somewhere between 50% load and 75% load, as shown in Fig (10-b). The average NO emissions reduction obtained when using biodiesel blends are as follow: 19.6% for B15, 14.28% for B25, 10.675% for B20, and 7.261% for B30, respectively for entire range of engine load . B10 has average NO emissions increment of 1.17% compared with diesel.

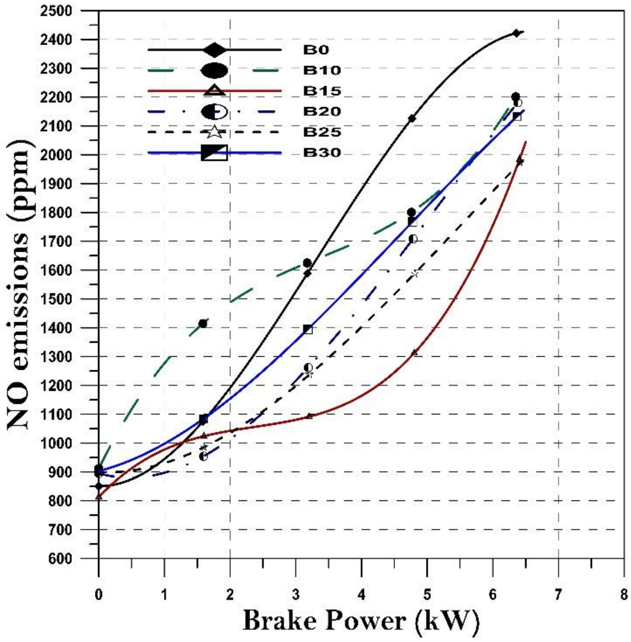

Fig. (9) Variation of nitrogyn monoxide (No) with brake power.

In addition, cetane number has also a great effect in NO emissions. Cetane number of the present biodiesel blends is smaller than that for diesel. The smaller the cetan number, the longer the ignition delay and hence burning time. This causes lower temperature inside the cylinder and low NO emissions in the exhaust gases. Although some researchers found that NO emissions were found to be insensitive to ignition delay [26], others stated that ignition delay could be a reason of increased NO emissions [27].

3.2.3 Exhaust gas temperature

The percent change (%) of exhaust gas temperature and NO emissions of biodiesel blends at various engine loading are shown in Fig. (10-a) and (10-b), respectively. It can be observed from Fig. (9-a) that exhaust gas temperature for all biodiesel blends at any load are lower than that for the diesel fuel due to the lower heating value of the biodiesel blends . The maximum relative exhaust temperature reduction for all biodiesel blends has been occurred at 50% engine load as follow: 31.29% for B20 followed by 24.78% for B30, 24.74% for B10, 23.61% for B25, and 21.1% for

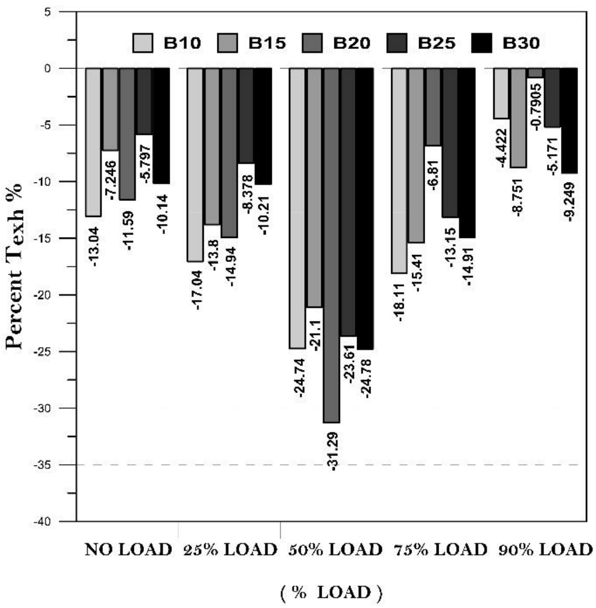

Fig. (10-a) Percent change in exhaust gas temperature with biodiesel blends compared to diesel fuel.

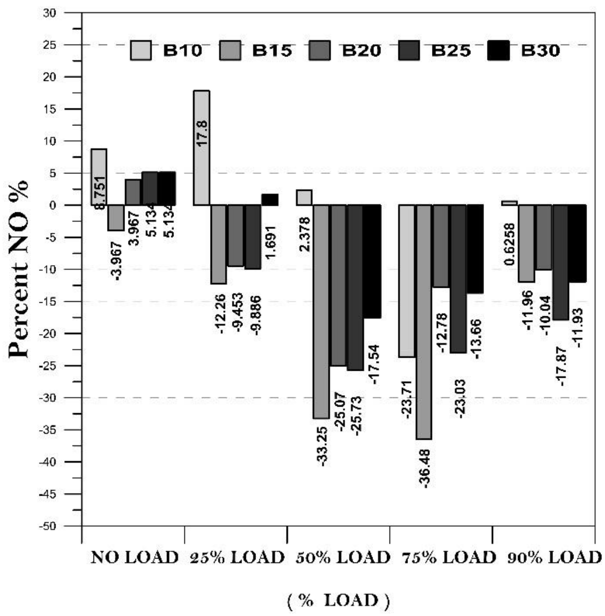

Fig. (10-b) Percent change in exhaust nitrogyn monoxide with biodiesel blends compared to diesel fuel.

B15.Also, it can be observed from Fig. (10) that there is a large extend between the NO reduction and exhaust gas reduction for all operating conditions.

4. Conclusions

In this study, the effect of used frying oil methyl ester- diesel mixture as an alternative fuel on diesel engine performance and exhaust gas emissions is investigated experimentally. Based on the experimental results, the following conclusions can be drawn:

1. The mixture of the used frying oil methyl ester (biodiesel) and diesel fuel can be used as fuel without any modifications in direct injection diesel engines successfully.
2. Although the power produced by the blends of UFOME and diesel fuel is close to that for the Petrodiesel fuel, specific fuel consumption of all blends is higher than that for diesel fuel by about 9%.
3. Emission values are decreased as:
   - -CO average emission values are decreased by 32.232% for UFOME blends with maximum average reduction of 44.4% for B10 followed by 40% for B15
   - NO average emission values are decreased by 10.13% for UFOME blends with maximum average reduction of 19.6% for B15 followed by 14.28% for B25.
4. Exhaust gas temperatures of UFOME blends are in average lower than that for Petrodiesel by about 13% .
5. Used frying oil has been proposed as an important possible future source of biodiesel in Egypt both as an added resource as well as to avoid its reuse.

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