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PERFORMANCE AND EMISSIONS OF A TRADITIONAL DIESEL ENGINE OPERATED WITH ESTERIFIED WASTE VEGETABLE OIL BIODIESEL BLENDS

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Abstract

The expected depletion of crude oil forced researchers to seek other alternative fuel sources and biodiesel pops up as the most suitable renewable fuel. Biodiesel is produced from many feedstocks and non-edible plants, but that produced from waste vegetable oil (WVO) is the most economic one. In this paper, the effects of blending biodiesel produced from WVO with conventional diesel fuel on engine performance and emission characteristics were investigated. A traditional constant speed, DI, diesel engine is considered in the study to assess the possibility of using this biodiesel in such type of engines without any modifications. A baseline test with diesel fuel (B0) is first conducted and then five biodiesel/diesel fuel blends starting from 20% (B20) up to 100% (B100) biodiesel with 20% increments by volume was tested. Experiments showed that biodiesel blends give rise to BSFC and specific energy consumption mainly due to biodiesel lower heating value and higher density. Exhaust emissions showed an increase in CO_2 and NO_x values with a decrease in CO emission since biodiesel blends have higher oxygen content enhancing the combustion process. In conclusion, running old traditional, DI diesel engines with biodiesel extracted from WVO gives satisfactory performance and better emission characteristics which confirmed its suitability as a vital renewable fuel for conventional diesel.

Keywords Biodiesel, Waste vegetable oil; Esterification; Diesel engine performance; Exhaust emissions.

Nomenclature

A/F	air to fuel ratio	CI	Compression ignition
B0	conventional diesel fuel	CO	carbon monoxide
B20	20% biodiesel + 80% diesel	CO_2	carbon dioxide
B40	40% biodiesel + 60% diesel	DI	direct injection
B60	60% biodiesel + 40% diesel	NO_x	nitrogen oxides
B80	80% biodiesel + 20% diesel	O_2	oxygen gas
B100	100% biodiesel	SEC	specific energy consumption
BMEP	brake mean effective pressure	TC	turbo-charged
BSFC	brake specific fuel consumption	WCO	waste cooking oil
BP	brake power	WVO	waste vegetable oil

1. Introduction

Diesel engines are widely used all over the world especially in power generation, heavy-duty and prime mover sectors since they exhibit superior thermal efficiency and specific fuel consumption. However, their exhaust emissions are a major concern due to their severe impacts on environment and human health. Nowadays, emission regulations become more restrictive which imposes serious challenges to researchers and engine manufactures.

It is a fact that world is facing a depletion in petroleum resources as well as a degradation in environmental quality. The world reserves of primary energy and raw materials are obviously limited and some estimated that oil and natural gas will last for 40 and 60 years, respectively [1]. This has stimulated an active research efforts regarding non-petroleum, renewable and non-polluting fuels during the past four decades. Therefore, the development and commercialization of renewable fuels have internationally received great interest particularly in the field of unconventional bio-energy sources and fuels. ASTM set specifications (D975) for biodiesel-fuel production of up to 5% (B5) [2]. M. A. Kalam et al. [3] tabled the worldwide production of biodiesel fuel produced from WVO in 2011 that confirms the growing interest in many countries. This is attributed to the advances in the biodiesel-production technologies and their availability [4-13]. Therefore, biodiesel has become a promising unconventional alternative for diesel fuel [1-3, 5-11, 14-20].

H. An et al. [16] tested a 4-cylinder, 4-stroke, turbocharged (TC), direct injection (DI), diesel engine. The fuel injection system is of the common rail type. They used WVO and its blends and reported that the brake power (BP) at full load conditions was nearly the same for B10 and diesel fuel with a slight increase in BP for B10. However, for higher blend ratios between B50 and B100, they found a notable drop in BP at all engine speeds. This was assigned to the lower heating value of biodiesel.

E. Alptekin et al. [14] tested a 6-cylinders, 4-stroke, constant speed (1400 rpm), TC, DI diesel engine. They reported an increase in BSFC at all loads for B20 by about 15.7%. Biodiesel emission results were lower for CO and higher for CO_2 and NO_x as compared to B0. Z. Utlu et al. [1٧], used a 4-cylinder, TC and DI engine and obtained similar results of [14] concerning engine specific fuel consumption. Also, they observed that the amount of CO, CO_2, NOx emissions and smoke darkness of (B100) were less than (B0) diesel fuel.

A. N. Ozsezen et al. [1٨] compared the combustion characteristics of Canola oil methyl ester (COME) and waste palm oil methyl ester (WPOME) with petroleum based diesel fuel in a CI engine. The engine has 6-cylinder, 4-stroke with an inline direct fuel injection at 197bar and constant running speed of 1500 rpm. When the engine was fueled with WPOME or COME, they noticed that the engine performance was slightly weakened while the combustion characteristics were slightly changed. Although the emission results showed reductions in CO and unburned HC emission along with smoke opacity, the NOx emission was higher than before.

K. N. Gopal et al. [19] tested a one-cylinder, 4-stroke, air-cooled, CI engine with inline fuel injection at 200 bar, running at constant speed of 1500 rpm. They reported that the BSFC, CO, unburned HC and smoke opacity values were lower in the case of WCO blends than B0. On the other hand, an increase in the values of NOx and specific energy consumption was observed for WCO blends compared to diesel fuel. They stated that the higher oxygen content of the WCO, mentioned in [21], is the reason beyond these results.

In closing, it should be mentioned that biodiesel can be produced from many feedstocks such as animal fats or virgin vegetable oil. The latter depends on food production and this situation will boost the food prices. Therefore, the use of waste vegetable oil (WVO) is of utmost importance [14]. Moreover, the economics of biodiesel production will be greatly improved and its cost will be less.

The present study aims to assess the impact of using WVO biodiesel blends with traditional diesel on the performance and emission without any modifications. Engine represents an old-version one currently in use for some years and a baseline test is considered to the current reference state. The considered blends cover the range from 20% biodiesel (by volume) to 100% in increments of 20%. The test engine has a constant speed of 1450 rpm and usually used in running small generators and water pumps. The engine was tested under different load conditions to appraise the suitability of biodiesel blends produced by esterification from waste vegetable oils.

2. Experiments

2.1. WVO Biodiesel production

Biodiesel production is carried out in several steps following the procedure mentioned in [13, 19]. First, WVO was collected and filtered. Secondly, oil was heated to 100°C to get rid of the water molecules in the WVO, and then it was allowed to cool down to 60°C. At the same time a titration process was made to find the required amount of base catalyst (NaOH) that should be added to methyl ester (methanol) of 20% by weight of WVO. Thirdly, the mixture of methanol with sodium hydroxide was added to the cooled WVO (60°C) in the reaction tank and the mixing process took place for 30 minutes to ensure complete reaction. Mixture was then left for at least 24 hours to allow the deposition of formed glycerol during the reaction at the bottom of the tank. Fourthly, the deposited glycerol was removed from the reaction tank bottom via a drain valve. Afterwards, a washing process by water was proceeded to reduce the fatty content of the WVO. Washing was repeated for three times or till water comes out clear without soap traces. Biodiesel was then left for 24 hours to allow evaporation of the remaining humidity.

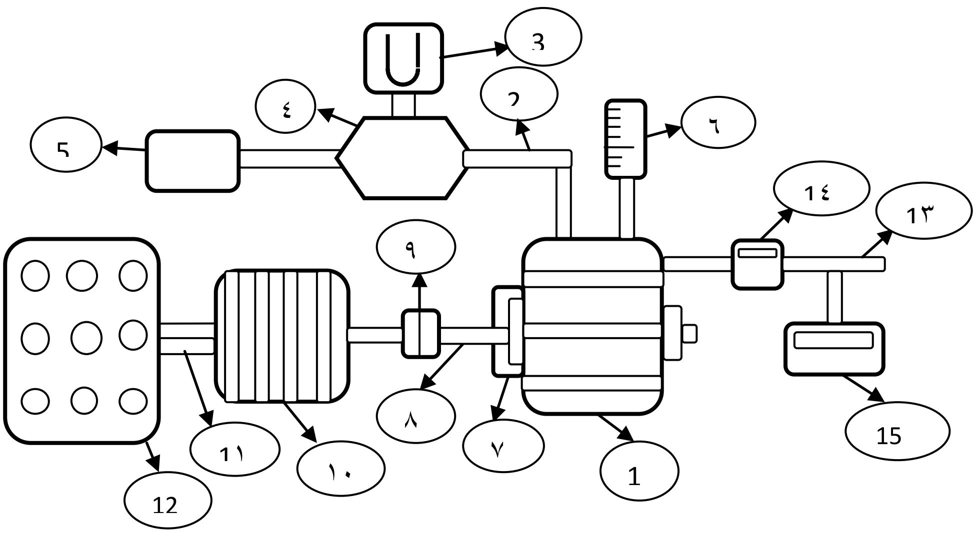
The biodiesel which prepared in the lab from waste vegetable oil was mixed, on a volumetric base, with commercial diesel (base fuel = B0) to produce blends in the range of 20% (B20) to 100% biodiesel (B100) in increments of 20%. The prepared different blends were kept in separate tight glass bottles for later use. The properties of the employed diesel oil and the biodiesel blends are given in Table 1. Examination of Table 1 reveals that the heating value of WVO biodiesel and its blends are lower than that of conventional diesel while their densities show the opposite trend.

2.2 Experimental set up

Figure 1 shows the schematic diagram of the experimental test engine set up. The diesel engine used in this study is a 2-cylinder, 4-stroke, DI, constant speed (1450 rpm), air cooled engine made by Lester (England). It has a bore and stroke of 101.6 and 114.3 mm, respectively, with a common rail injection and multi-hole injectors developing 14 kW. A 3-phase generator was directly coupled to the engine shaft to measure the engine output power. A LAND LanCom series II gas analyzer was used to measure exhaust emissions of CO, CO_2, O_2 and NO_x.

Table 1: Properties of experimented diesel fuel and biodiesel blends [22].

Fuel type	**B0**	**B20**	**B40**	**B60**	**B80**	**B100**
Density (kg/m^3)	854.2	861.72	869.24	876.76	884.24	891.8
Flash point ($^\circ$C)	68	88.4	108.8	129.2	149.6	170
Kinematic viscosity(mm^2/s)	3.4202	4.555	5.6897	6.8244	7.9592	9.094
LHV (MJ/kg)	45.44	45.336	45.232	45.128	45.024	44.92
Pour point ($^\circ$C)	0	1.2	2.4	3.6	4.8	6



1-Diesel engine	2-Air inlet pipe	3-Manometer	4-Air flow meter
5-Air filter	6-Bruette	7- Flywheel	8-Shaft
9- Coupling	10-Generator	11- 3-phase cable	12-Electric bulbs
13- Exhaust outlet	14-Digital Thermometer		15-Gas analyzer

Fig.1: Test engine set-up.

2.3 Experimental procedure

Conventional diesel fuel was used first to run the engine to get the base data regarding the engine performance and emission characteristics at different loads. The tests were repeated for various WVO biodiesel blends in the range of 20% - 100%. In each test, engine was started with commercial fuel and let to warm up till the exhaust gas temperature reaches almost a constant one. Then biodiesel blend was admitted and engine allowed to reach steady state condition before recording any data. At the end of each test and before shutting down, engine had to run on commercial fuel. The measured engine operation parameters were: engine speed, output power and fuel and air consumption. These parameters are employed in calculating engine air-fuel ratio, BMEP, BSFC, and SEC for diesel and biodiesel blends. In addition, engine exhaust emission pollutants were measured for each test of a certain blend as mentioned above.

3. Results and discussion

Experimental results of the tested biodiesel/diesel blends are presented and compared with that of the diesel base fuel (B0) in terms of performance and emission parameters, figures 3 - 9. Five fuel blends by volume ratio were tested (B20, B40, B60, B80 and B100) and compared with the data of diesel fuel (B0) to assess engine performance and emissions at different engine loads.

3.1 Air / fuel ratio (A/F)

The A/F ratios for all biodiesel blends and diesel fuel against the BMEP are shown in Fig. 2. Clearly, all curves exhibit the normal trend of the continuous decrease in A/F ratio with increasing the engine load due to the increase in fuel mass flow-rate against the constant air mass flow-rate. Also, it can be seen that all biodiesel curves exhibit the same trend of the base diesel fuel (B0) while biodiesel; B100, shows 20% - 10% lower A/F values. The marginal differences between the A/F curves, except for B100, are attributed to the lower heating values of biodiesel blends (Table 1) which are balanced by the increase in the injected fuel mass since biodiesel blends have higher densities. To check the accuracy of the presented measurements, the experimental A/F-ratio values were compared with those calculated using engine emission data (presented in the next section) and taking N-dodecane standard fuel. The results were in good agreement with 10% tolerance mainly due to the differences between the assumed fuel composition and the actual one.

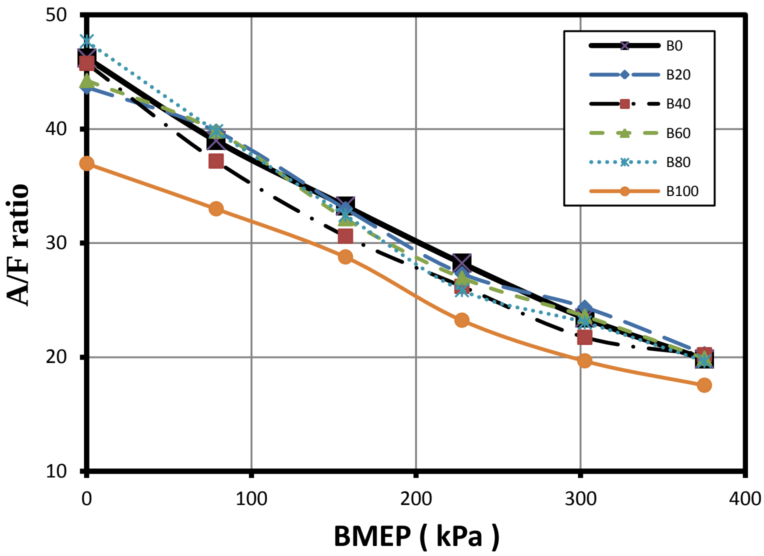


Fig.2: A/F ratios versus BMEP values for different fuel blends.

3.2 Brake specific fuel consumption (BSFC)

BSFC curves against the BMEP for the tested fuels are depicted in Fig. 3. It is clear that the BSFC for B100 exhibits the highest value and that of B0 is the lowest while the other biodiesel blends show a marginal increase over B0. This is explained by the fact that biodiesel fuel has a lower heating value than that of base diesel and thus more fuel per stroke is demanded to carry the same engine load. Higher densities and viscosities of biodiesel blends also contribute to the increase in the BSFC since the rate of blend evaporation is less, see table [1]. In addition, as the mechanical injection pump sweep a constant volume, it would inject a higher mass of blended fuel since biodiesel has a higher density. Consequently, biodiesel blends have a density higher than B0 but less than that of B100. Moreover, slight differences between the curves of biodiesel blends indicate that the effect of higher density is opposed by the higher kinematic viscosity of the blend. Indeed, the increase in density leads to higher injection pressure, better atomization enhances the combustion process. Also, the increase in the injection pressure advances the start of injection. In contrast is the increase in the kinematic viscosity which slows down the atomization and mixing processes so that combined effect of these two factors minimizes the differences between the curves of biodiesel blends. Compared to B0, the BSFC of B100 is higher by about 12.07% and 13.58% at no load and full load, respectively. This trend agrees with the published results of other researchers [14, 16-19]. As the fuels under comparison have different heating values, it is more realistic to compare these fuels based on their heating values instead of fuel consumption [19]. This can be done by comparing the specific energy consumption SEC as discussed in the next section.

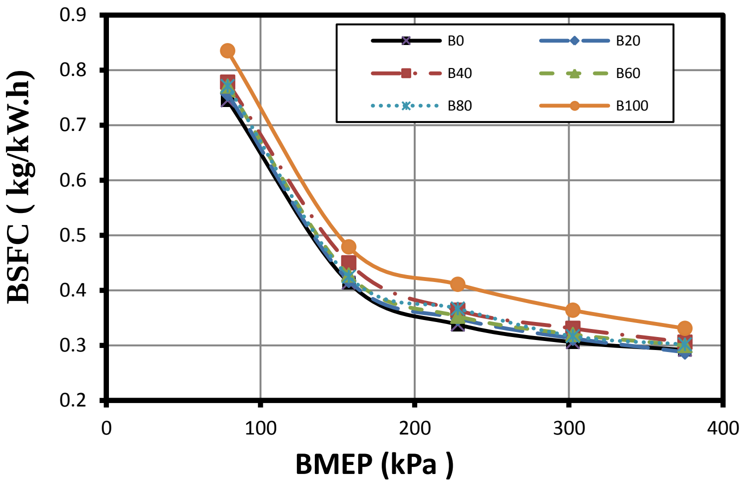


Fig.3: BSFC values for the tested fuels versus BMEP.

3.3 Specific energy consumption (SEC)

The specific energy consumptions for the tested fuels versus the BMEP values are shown in Fig. 4. Clearly, all curves of biodiesel blends show similar trend with marginal differences even with that of base diesel. This means that the differences in the heating values of the blends are neutralized. Further, the diesel oil (B0) exhibits the lowest SEC while pure biodiesel (B100) shows the opposite trend. Thus, it could be concluded that blend density (higher mass of injected fuel) and viscosity have dominant effects over the blend heating value. This result is in contradiction with the findings of K. N. Gopal et al. [19] who showed that SEC of diesel (B0) is between those of biodiesel blends and that of B100 which possesses the lowest SEC at low and medium engine loads. The differences between present results and those of [19] are believed to be due to the differences in the thermo-physical properties (density: 854 vs. 840 kg/m^3, viscosity: 3.4 vs. 4.2mm^2/s, and heating values: 45.5 vs. 44.5 MJ/kg) of the employed biodiesel fuels.

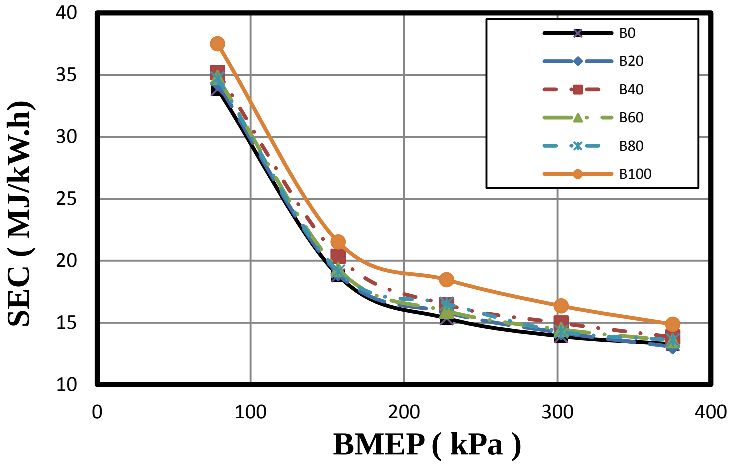


Fig.4: Specific energy consumption for tested fuels versus BMEP.

3-4. Exhaust gas temperature:

The exhaust gas temperature for the tested fuels versus the BMEP is shown in Fig. (5.5). Figure depicts the slight difference between B100 and B0 at no-load, about 9%. At high loads, figure shows the intense convergence in the exhaust temperature curve for all fuels. This is due to the convergence in the A/F ratio between tall fuels with the increase in load, Fig. 5.

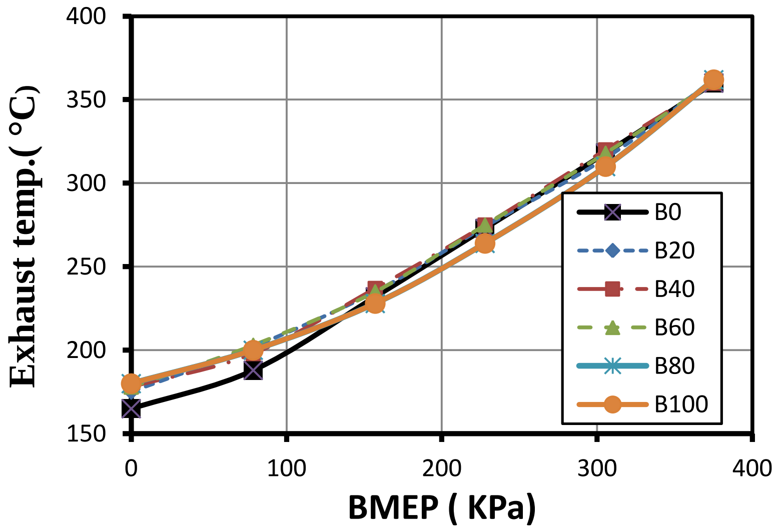


Fig. 5: Exhaust gas temperature for the tested fuel versus BMEP.

4. Exhaust gas emissions

Engine gas emissions are another important parameter in studying engine performance when operated with biodiesel fuels. In the following sections, results of CO, CO_2, and NO_X gas emissions are presented and discussed.

4.1 CO emission

The CO emissions of conventional diesel and biodiesel blends versus the BMEP are shown in Fig. 6. The figure depicts that the biodiesel blends have CO emission values less than those of diesel fuel. The decrease in the CO emissions is about 21.7% and 58.7% for B100 compared with B0 at no-load (zero BMEP) and full-load (maximum BMEP) conditions, respectively. This is because biodiesel (B0) has a larger oxygen content than B0 which enhances the combustion process. The more O_2 content is the less CO gas emission as depicted in Fig. 5 for different biodiesel blends. The curve of B100 confirms this fact as it possesses the lowest value of CO among the tested fuels. In addition, as the engine load increases, the engine temperature gets higher promoting better combustion process. This result agrees with those published in references [16-19] and disagrees with the results of [14]. This disagreement may be attributed to the relatively lower heating value of the biodiesel produced from fatty acids (according to [14] about 37 kJ/kg) as compared with current WVO biodiesel B100 which has a heating value of 43.2 kJ/kg. In general, as the engine load increases, more fuel injected which consumes more O_2 and in turn narrowing the differences between the tested fuels at high loads.

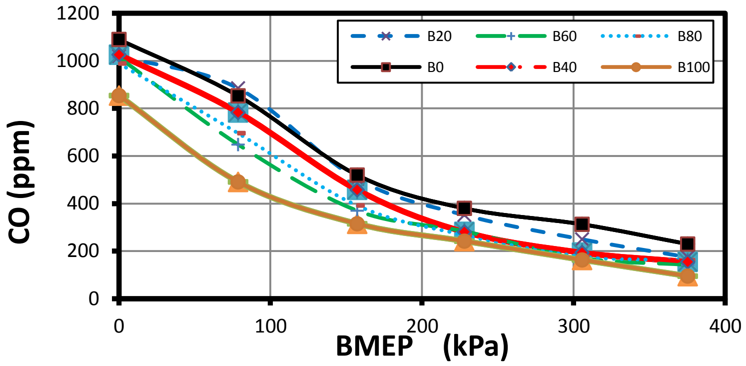


Fig. 6: CO gas emissions for the tested fuels versus the BMEP.

4.2 CO_2 emission

Figure 7 displays the CO_2gas emissions for the experimented fuels versus the BMEP. Obviously, the CO_2 emission increases with increasing engine load regardless of the blending value. This is expected as the CO_2 emission should have the opposite trend of CO behavior. Also, it can be noticed that the diesel fuel possesses the lowest value compared to biodiesel blends which have higher values especially B100. This is attributed to the presence of O_2 in the chemical structure of biodiesel blend so that O_2 content is increased with increasing blend ratio. The CO_2 emission of B100 is higher than that if diesel fuel, B0, by 66.7% and 27.7% at no- and full-load, respectively.

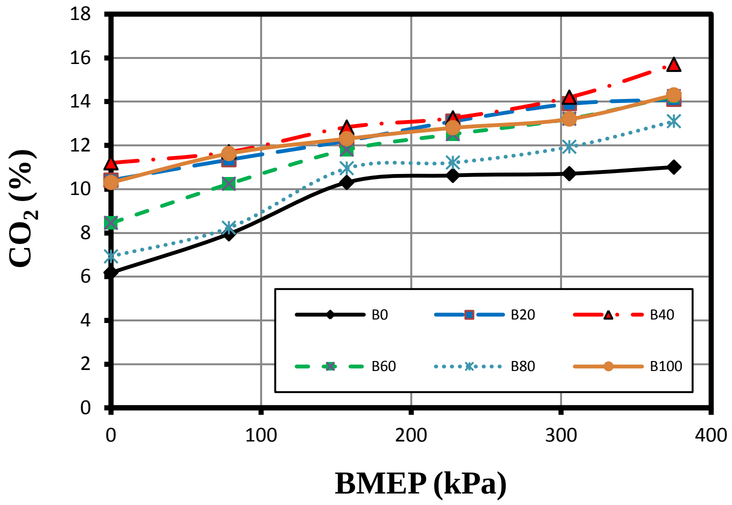


Fig.7: CO_2 gas emissions for tested fuels versus the BMEP.

4.3 NO_x gas emission

NO_x gas emissions versus the BMEP values are shown in Fig. 8. Since NO_x production is closely related to combustion temperature, then NO_x emission would increase with increasing engine load for all fuel-blends as indicated in Fig. 8. Further, the differences between the various fuel curves are marginal at engine higher loads as the combustion temperature is higher than the threshold temperature of NO_x formation (combustion temperature > 1400°C) as indicated by the exhaust gas temperature, Fig. 5. Furthermore, the curves of biodiesel blends indicate a slight increase in NO_x production compared to diesel fuel. In contrast is NO_x emission at engine low loads. The reason is attributed to the extra oxygen content in biodiesel blends which enhances the combustion process and in turn gives rise to combustion temperature and consequently the exhaust gas temperature, as shown in Fig. 5, and thus NO_x formation. As shown in Fig. 8, the NO_x emission for B100 is higher than that of B0 by about 69% at no-load and drops severely to 2.3% at full-load.

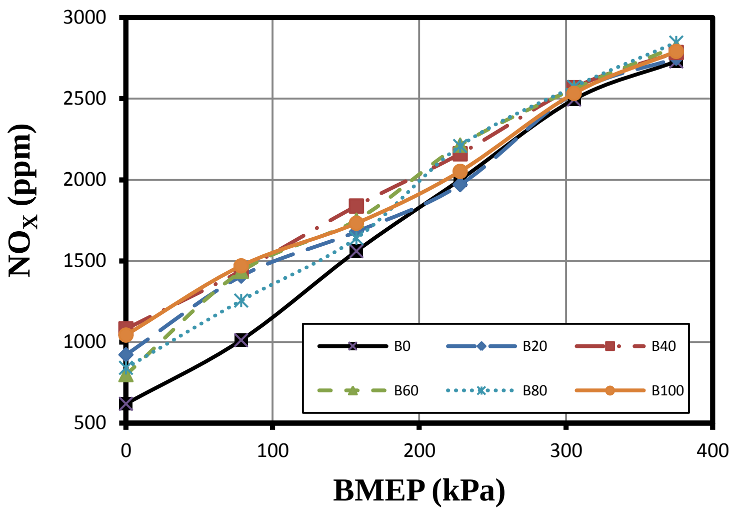


Fig. 8: NOx emissions for the tested fuels versus the BMEP.

4.4 O_2 gas emission

Figure 9 shows the variations of O_2 presence in the engine exhaust versus the BMEP. It is clear that the amount of O_2 in engine exhaust decreases with increasing engine load for all fuels indicating the consumption of O_2 in the combustion process. Comparing O_2 gas emission of diesel fuel with those of biodiesel reveals that biodiesel blends emit higher levels O_2 is present in their chemical structure. Accordingly, B100 contains more oxygen than B0 and thus emits more O_2 either at no-load condition or at engine full-load. The B100 emission of O_2 is higher than that of B0 by about 2.9% and 48.3% at no-load and full-load, respectively, Fig. 9.

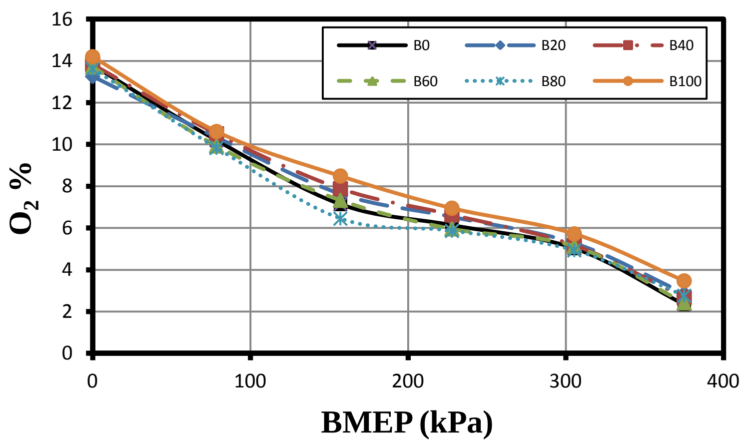


Figure 9: O_2 gas emissions for the tested fuels versus BMEP.

5. Conclusions

Blends of biodiesel produced from WVO are employed as fuels to run a traditional 2-cylinder, 4-stroke, DI constant speed diesel engine to assess the impact of burning such fuels on engine performance and emissions. The following conclusion are drawn from the results of present study:

1) Biodiesel produced from waste vegetable oil and its blends can be satisfactorily used in old traditional DI diesel engines without any modifications.
2) Thermo-physical properties of the tested biodiesel blends (B20-B100) (lower heating value, higher density, viscosity) have an important effect on engine performance and exhaust emissions.
3) Both the BSFC and SEC were found to increase by about 13% for B100 at all engine loads.
4) CO_2 and NO_x exhaust emissions showed an increase due to the enhancement in the combustion process. This is confirmed by the increase in the CO levels in engine exhaust.

5) The O_2 presence in engine exhaust was noticeably increased when biodiesel blends were employed due to the presence of O_2 in the biodiesel chemical structure.

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اداء وانبعاثات محرك ديزل تقليدى يعمل بخليط وقود حيوى من مخلفات زيت نباتى بالاسترة

ملخص البحث

توقع نضوب الزيت الخام دفع الباحثين للبحث عن مصادر بديلة فظهر الوقود الحيوى كأفضل مصدر متجدد للوقود. يمكن انتاج الوقود الحيوى من عدة مصادر نباتية متجددة ونباتات غير صالحة للاكل ، ولكن المستخرج من الزيت النباتى (WVO) يعتبر الافضل اقتصاديا. وفى هذه المقالة تم التحقيق من تاثير خلط الوقود الحيوي من (WVO) مع الوقود الديزل التقليدي على خواص وأداء وأنبعاثات محرك الديزل. وفى هذه الدراسة تم استخدام محرك ديزل تقليدي ثابت السرعة ذو حقن مباشر لامكانية استخدام هذا الوقود الحيوي فى المحرك بدون أي تعديلات. تم عمل اختبار مرجعى باستخدام الوقود الديزل ثم تلاه اجراءخمس اختبارات باستخدام خلائط مختلفة من الوقود الحيوي والديزل تبدأ من 20% وحتى ١٠٠% بزيادة حجمية ٢٠%. واظهرت التجارب ان الوقود الحيوي يتسبب فى زيادة معدل استهلاك الوقود النوعي ومعدل استهلاك الطاقة النوعي بسبب انخفاض الطاقة الحرارية وارتفاع الكثافة . واظهرت انبعاثات العادم زيادة فى قيم ثانى اكسيد الكربون واكاسيد النيتروجين مع انخفاض انبعاث اول اكسيد الكربون حيث ان الوقود الحيوي يحتوي على وفرة من الاكسجين تساعد فى عملية الاحتراق. ويخلص البحث الى ان تشغيل محركات الديزل التقليدية ذات الحقن المباشر باستخدام الوقود الحيوي المستخلص من بقايا الزيوت النباتية يعطى نتائج مرضية فى الاداء وانبعاثات افضل مما يؤكد امكانية استخدامه كوقود حيوي متجدد لمحركات الديزل التقليدية.