Performance and emission characteristics of diesel sunflowers-based biodiesel fuels

Miqdam Tariq Chaichan

Abstract— Biodiesel is one of the most desirable alternative fuels to implement. Biodiesel pertains to alternative fuels called biofuels. Biofuels are the fuels that derived from biological resources. Biodiesel consists of long chains of carbon molecules attached to an alcohol molecule called fatty acid alkyl esters. Biodiesel is green and clean alternative to fossil diesel fuel.

In the present study, Iraqi sunflowers oil used as raw oil to produce biodiesel by a chemical process called transesterification reaction. A four-stroke diesel engine used to investigate the engine performance and emission characteristics of the neat biodiesel, two biodiesel-diesel blends compared to pure diesel.

The experimental results show that neat biodiesel fuel (B100) has the lowest CO, CO_2, unburnt hydrocarbon and PM emissions. It has the lowest exhaust gas temperature, heating value, and noise level. It has the largest brake specific fuel consumption of the four tested blends, and the highest NOx concentrations. The increase of engine speed causes the increase of exhaust gas temperature, CO_2 emissions, brake specific fuel consumption and NOx concentrations.

Index Terms— Sunflowers Oil, Biodiesel, the Transesterification Reaction, CO, CO_2, HC, PM, Noise

◆

1 INTRODUCTION

Nowadays most of the transportation vehicles run on gasoline or diesel fuel (Arapatsakos et al, 2008). Diesel engines widely used in medium and heavy-duty applications. It is characterized by its low fuel consumption compared with gasoline engines. Also, it emits lower exhaust emissions of carbon monoxide (CO) and unburned hydrocarbons (UHC) compared with gasoline engines [1]. The global population growth and economic development result in increasing the world's energy demand, in the last few years. Unfortunately, the most of the produced energy is from fossil energy sources. The problem is that fossil fuels limited in supply (depleted). From here an increased interest in alternative renewable fuels started. As the biodiesel is an environmentally friendly fuel, it is the best candidate to replace fossil diesel. It has lower emissions than that of fossil diesel; it is biodegradable, nontoxic, and essentially free of sulfur and aromatics [2].

The use of vegetable oils as motor fuels is not new. They were used during the oil shortages in the 1930s and 40s. In the latter part of the 20th-century attention in Europe and North America turned to the potential for replacement of petroleum diesel fuel with fuels derived from vegetable oils [3]. In order to make the use of vegetable oils and animal fats in engines as a more practical and less problematic; biodiesel made from oils in a process called transesterification. In this process, the triglyceride oils in the vegetable oils are reacted with the methanol or ethanol alcohols to form biodiesel and glycerin. The process requires heat and the use of a strong base catalyst, e.g., sodium hydroxide or potassium hydroxide [4].

The energy density of a fuel (energy per unit of volume) defines the power delivered by the fuel and as a result fuel economy. Energy content of petroleum diesel fuels can vary up to 15% between suppliers or seasons of the year because of different refining parameters [5]. Producing biodiesel (B100 if not blended with diesel fuel) process depends mainly on the feedstock. For this reason, the fuel energy density does not vary according to the used feedstock compared to petrol-diesel. This results from the fact that the feedstock for biodiesel do not vary as much as crude oil does for making diesel fuel. However, due to the high oxygen-contained of the biodiesel (about 11% by weight), it has less heat content than petrol-diesel. This results in lower engine power, torque, and fuel consumption for the biodiesel and its blends with diesel [6].

Using B100 as a diesel engine fuel reduces hydrocarbon emissions by almost 70%. Also, it reduces carbon monoxide and particulate matter emissions by about 50%. However, it tends to increase nitrogen oxides emissions. B100 and B20 increase nitrogen oxide emissions by approximately 10% and 2% respectively [7]. However, some specifications of biodiesel like the high viscosity, poor volatility and cold flow characteristics of vegetable oils can cause some problems. Operating problems as injector coking, severe engine deposits, filter gumming, and piston ring sticking are usual problems that need more investigations [8]. These problems can be eliminated or minimized by the transesterification process.

The lower exhaust gas emissions and its renewability compared with fossil diesel fuel are the primary advantages of biodiesel. Despite that many specifications like biodiesel lower heating value, viscosity and volatility are still worse than that of diesel fuel. Still the transesterification process improves the fuel properties of vegetable oil [9]. The fat causes longer ignition delay and lower combustion temperature, which results in less formation of nitrogen compounds. Also, toxic emissions are signifi-

---

- *Miqdam T Chaichan is currently Assistant Professor in Mechanical Eng. Dept., University of Technology, Baghdad, Iraq, PH-00964 7700120897. E-mail:Miqdam_tc@uotechnology.edu.iq*

cantly decreased for both types of vegetable-based fuels, as compared to petroleum diesel [10]. The emissions data does not include the poly-aromatic hydrocarbon content (PAC) of the total unburned hydrocarbons, which is an important aspect of engine emissions because it is suspected to be cancer-causing [11].

Lubrication of diesel engines accomplishes in large part by the fuel. Fuel injector pumps, fuel pumps, piston rings and valves are all lubricated by the fuel. Vegetable based fuels are better lubricants than petroleum diesel and increase engine life due to lessened engine wear. Additionally, engine deposits are decreased due to lack of sulfur and a complete combustion is achieved [12].

Biodiesel has some drawbacks that diesel fuel does not have. The alcohol used to remove the glycerin from the vegetable oil is not completely removed and reacts with fuel deposits and fuel system components. Deposits from diesel fuel are often dissolved by biodiesel and collect on fuel filters. As a result, the fuel filter becomes clogged which necessitates its replacement. Most users of Biodiesel reported the need to change the fuel filter one time, after the initial switch to biodiesel. Of course, the amount of deposits and the purity of the biodiesel impacts filter use [13], [14].

The aim of this work is to find an acceptable alternative for Iraqi diesel fuel that has high sulfur content. This alternative must be clean and abundant in the country. The choice directed toward sunflower oil based biodiesel fuel. This paper represents a part of a continuing Iraqi research effort carried out over the years at the Mechanical Engineering Department-University of Technology, Baghdad, Iraq. The aim is to provide improved knowledge of the combustion characteristics of alternative clean fuels for internal combustion engines that can be used practically and efficiently in the country.

2 EXPERIMENTAL SETUP

2.1 Equipment

The experimental engine used in the recent study is a direct injection, four cylinders, natural aspirated diesel engine type Fiat whose major specifications are shown in Table 1 [15]. The engine is coupled to a hydraulic dynamometer to control the subjected load on it by increasing the torque. The concentrations of nitrogen oxide (NOx), unburned hydrocarbon (HC), CO2 and CO measured by Multigas mode 4880 emissions analyzer. Fig. 1 represents an illustrative scheme diagram of the used engine and its accessories.

Emitted particulate matters (PMs) were collected using a low volume air sampler type Sniffer L-30 and Whatmann-glass micro-filters. The weight of these filters before and after the end of the sampling operation measured and recorded. Sampling process took one hour each time. Then, the particulate matters (PMs) concentrations were determined by the equation [16]:

$$PM\ in\ \left(\mu g/m^3\right)=\frac{w_2-w_1}{Vt}\times 10^6 \qquad (1)$$

TABLE 1. TESTS ENGINE SPECIFICATIONS

Engine type	4cyl., 4-stroke
Engine model	TD 313 Diesel engine rig
Combustion type	DI, water cooled, natural aspirated
Displacement	3.666 L
Valve per cylinder	two
Bore	100 mm
Stroke	110 mm
Compression ratio	17
Fuel injection pump	Unit pump 26 mm diameter plunger
Fuel injection nozzle	Hole nozzle 10 nozzle holes Nozzle hole dia. (0.48mm) Spray angle= 160° Nozzle opening pressure=40 Mpa

Where: *PM* = particulate matters concentration in (μg/m^3).
w_1 = filter weight before sampling operation in (g).
w_2 = filter weight after sampling operation in (g).
Vt = drawn air total volume (m^3)
Vt can be found by the equation:

$$Vt = Q_t . t \qquad (2)$$

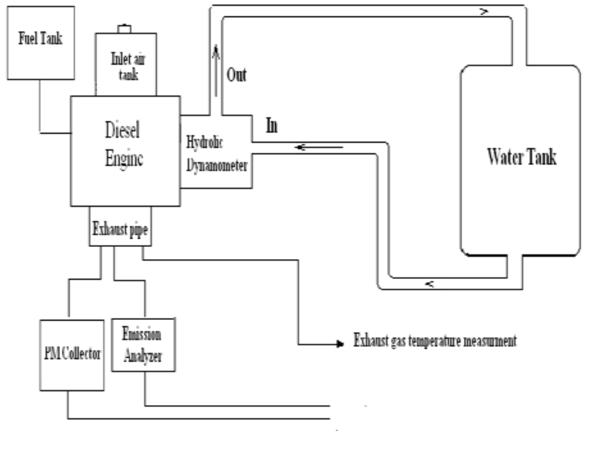

Fig. 1. An elucidative scheme diagram of the experimental rig

Where: Q_t= Elementary and final air flow rate through the device (m^3/sec).
t = sampling time in (min).

The filters separated and preserved in plastic bags temporarily at the end of collecting samples operation until weighted and analyzed the results.

The overall sound pressure measured by precision sound level meter supplied with a microphone type

4615the device was calibrated by a standard calibrator type pisto phone 4220.

The equations used in calculating engine performance parameters illustrated in [17] and many other researches like [15].

2.2 Preparation of the Used Fuel

Transesterification process is the transformation of one type of an ester into another to produce biodiesel. The fuel preparation process of the present work included: adding 200ml of methanol and 3.5 g of sodium hydroxide (lye) in a beaker and mixing them well for 5 min. One liter of Iraqi sunflowers oil (produced by General Company of Vegetable oils-Bagdad- Iraq) added to the mixture and stirred for 15 minute. The total mixture heated to 65°C. After 15 to 25 minutes, the stirring stopped, and the glycerin allowed settling down in the beaker. Finally, the biodiesel (ester) separated, washed and then boiled to remove any residual moisture.

The resulted biodiesel was used in this work in three volumetric percentages: 100% biodiesel (called B100), 50% biodiesel + 50% diesel fuel (called B50) and 20% biodiesel + 80% diesel fuel (called B20). The performance and emissions of the engine fueled and operated with these blends, compared to neat diesel fuel operation characteristics.

Fuel properties of diesel fuel and the constitutions of three blends demonstrated in **Table 2**. These properties measured at Chemical Engineering Department, University of Technology, Baghdad, Iraq. The oxygen fraction in the fuel blends ranged from 5.87 to 11.1 which agree with many researchers [8], [11], [13]. So, it is reasonable to regard the effect of oxygen increment in the blends with the biodiesel addition. In the other hand, biodiesel heat value is low, and its cetane number is small compared to diesel fuel. B100 appears to have the lowest heating value and the largest kinematic viscosity and specific gravity. In contrast, the diesel fuel had the largest heating value and the lowest kinematic viscosity and specific gravity.

TABLE 2. TESTED FUELS SPECIFICATIONS

Fuel type	Calorific value (kJ/kG)	Density (g/dm^3)	Viscosity (mm^2/s at 27^{o}C)	Cetane No.	Flame point (^{o}C)	Cloud point (^{o}C)	Pour point (^{o}C)
Diesel fuel	44227	810	4.23	49	59	-13.8	-29
Biodiesel (B100)	39873	906	65	38.6	239	-3.7	-12.4
B50	40368	877	44.7	40.6	179	-10.2	-17.833
B20	41654	829	14.38	42.9	112	-11.78	-24.68

2.3 Error Analysis

Measurement accuracy represents the reliance potential extent of the study results. The error sources were defined by calibrating the used measuring equipment, and the uncertainty in this study determined. **Table 3** shows the measuring device and its calibration accuracy. The uncertainty defined as [17]:

$$e_R = [(\partial R/(\partial V_1)\, e_1)^2 + (\partial R/(\partial V_2)\, e_2)^2 + \cdots + (\partial R/(\partial V_n)\, e_n)^2]^{0.5}$$

(11)

Where:

eR : results uncertainty.

R=function consists of variables or R=R (V1, V2, …, Vn).

ei: variable uncertainty range.

The partial derivative $\frac{\partial R}{\partial V_1}$ represents the results sensitivity of a single variable. Hence, the uncertainty for the present study results was:

$$e_R = [((.6)^2 + (1)^2 + (2)^2 + (1.3)^2 + (2.4)^2 + (0.67)^2 + (.82)^2 + (1.034)^2 + (.003)^2)]^{0.5} = \mp 3.873\ \%$$

TABLE 3. MEASUREMENT TYPE AND ACCURACY FOR THE PRESENT STUDY

Measurement	accuracy
Temperature measurement	±0.6%
Fuel mass flow measurement	±1%
Air mass flow measurement	±2%
Engine speed measurement	±1.3%
Engine torque measurement	±2.4%
Sound pressure level measurement	±0.67%
Exhaust gases concentrations measurement	±0.82%
PM collection measurement	±1.03%
Sensitive weighting measurement	±0.0034%

This result confirms an uncertainty of less than 5% in the measurement of the present study achieved. For each condition, three tests were conducted to minimize random errors in the experiments. From the results of these experiments for each condition, the average value is reported along with more than 95% confidence intervals.

2.4 Tests Procedure

In the experiments, the three biodiesel blends (B20, B50 & B100) with different biodiesel proportions were used to operate the engine. Meanwhile, the combustion characteristics and emissions measured and analyzed at the same load and engine speed. Furthermore, these engine characteristics were compared to those resulted from fueling the engine with pure diesel in order to define the effects of the biodiesel fuel on the combustion.

3. RESULTS AND DISCUSSIONS

The biodiesel is the only renewable alternative fuel that can be used directly in any diesel engine without the need for conducting some modification. As its properties are similar to those of the diesel fuel derived from petroleum. Both can be blended in any proportion without any inconvenience.

Fig. 2 shows the comparison of the brake specific fuel consumption (bsfc) with brake mean effective pressure for the used blends. It is evident from the curvthat as the load increases the bsfc decreases for all fuels as expected. In the same time, the bsfc increased with the rise in the concentration of biodiesel fuel in the blends. The engine consumes more fuel with biodiesel that has the lowest heating value. A slightly higher fuel feeding rate is needed to attain the same engine torque as the other three fuels. The increments in brake specific fuel consumption (bsfc) were 23, 27 and 35.7% for B20, B50 and B100 respectively compared to neat diesel.

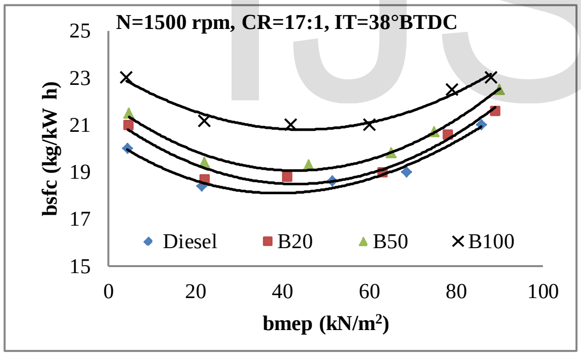

Fig. 2. Load effect on bsfc for the tested fuels at constant engine speed.

Fig. 3 presents the volumetric efficiency for the four blends; the biodiesel fuel has the highest efficiency due to its high oxygen content, as well as its blends that increase the volumetric efficiency.

Fig. 4 shows the comparison of the brake thermal efficiency with brake means effective pressure for the examined blends. The thermal efficiency of diesel fuel was 30.45% at full load. While the efficiencies of B20, B50 and B100 were 28.8%, 27.9%, and 27% respectively. The thermal efficiencies of biodiesel blends are lower compared to diesel fuel. This reduction may be due to its lower heating value. Reduction in thermal efficiency by about 3.45% is noticed at full load for B100 compared to diesel fuel.

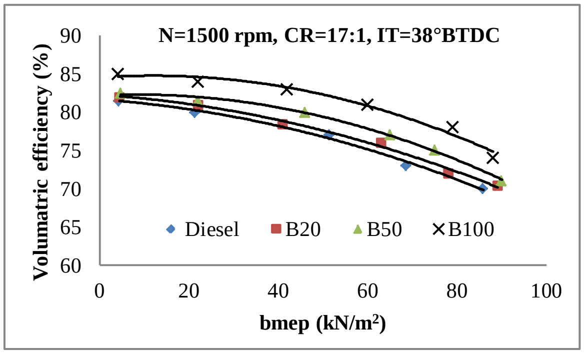

Fig. 3. Load effect on volumetric efficiency for the approved fuels at constant engine speed

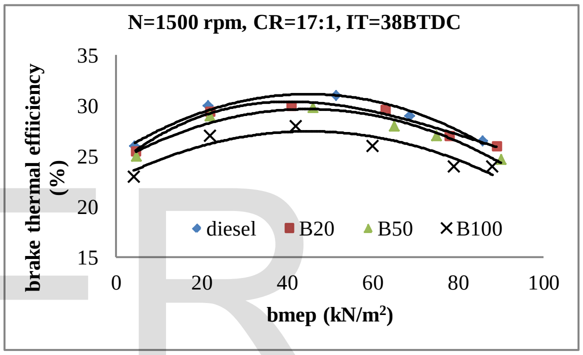

Fig. 4. Load effect on brake thermal efficiency for the tested fuels at constant engine

Fig. 5 compares between the exhaust gas temperatures for the four blends. The amount of fuel injected into the combustion chamber of the diesel engine increased with engine torque increase. Hence, the exhaust gas temperature rose with increasing engine load. The burning of the diesel fuel appears to have slightly larger exhaust gas temperatures, particularly at higher engine loads because of its higher heating value. The biodiesel blends had lower exhaust gas temperatures slightly. The lower heating value of the biodiesel blends caused less burning gas temperatures inside the combustion chamber.

Fig. 6 shows the comparison between brake powers (bp) of the four blends at variable engine speeds. The bp of the biodiesel fuel is slightly less than that of diesel at all speeds.

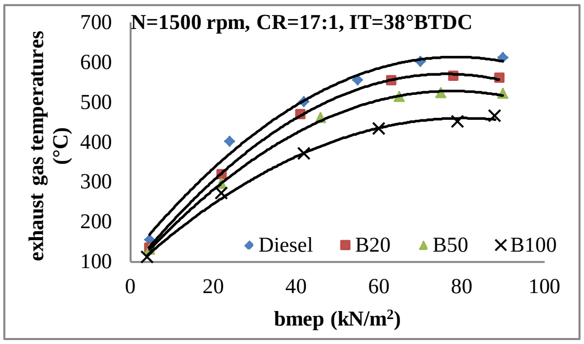

Fig. 5. Load effect on exhaust gas temperatures for the used fuels at constant engine speed.

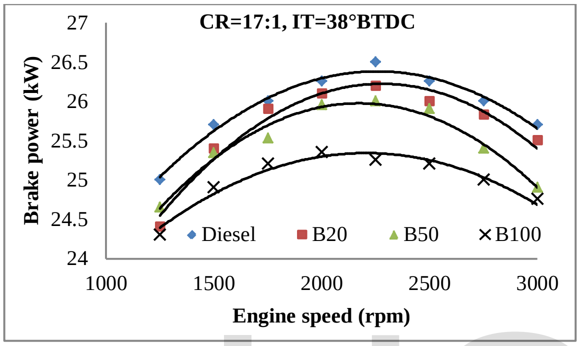

Fig. 6. Engine speed effect on brake power for the tested fuels at constant engine load

The effects of fuel type and engine speed on brake specific fuel consumption (bsfc) under constant engine torque as Fig. 7 reveals. The increase of engine speed raised the bsfc of the diesel engine. Because the biodiesel has a lower heating value, its bsfc must have been larger than diesel fuel. The diesel fuel, which has a higher heating value among the four blends, has the lowest bsfc.

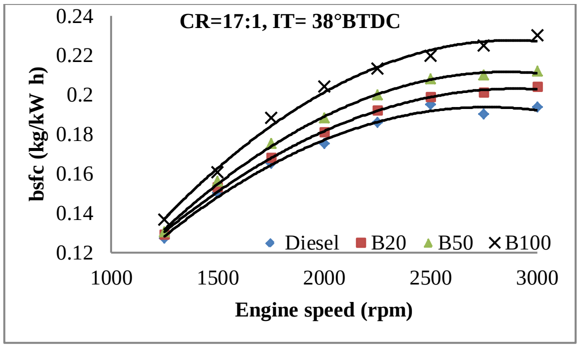

Fig. 7. Engine speed effect on bsfc for the tested fuels at constant engine load

Fig. 8 compares the exhaust gas temperatures for burning the four blends. The amount of fuel injected into the combustion chamber of the engine increased with engine speed to obtain the same engine torque. Hence, the exhaust gas temperature rose with increasing engine speed. The diesel fuel appears to have slightly larger exhaust gas temperatures at higher engine speeds because of its higher heating value. The biodiesel blends had slightly lower exhaust gas temperatures due to its lower heating value.

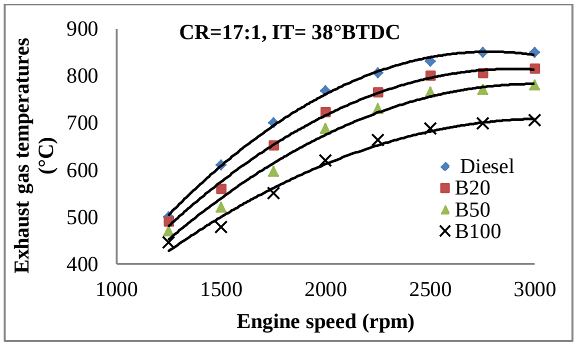

Fig. 8. Engine speed effect on exhaust gas temperature for the tested fuels at constant engine load

Fig. 9 clarifies the trends of CO emissions with the engine load for the tested blends under a constant engine speed (1500 rpm). The CO emissions from burning the four blends appear to decrease with the increase of the engine load. Larger CO emissions at lower load thus observed. However, at higher engine load caused the burning gas temperature inside the combustion chamber to increase. The atomized fuel particles evaporation and mixing with the surrounding air enhanced, resulted in a larger conversion rate of CO to CO_2 emissions, and lower CO emissions. Moreover, the neat biodiesel, which contained oxygen of 9.94 wt. %, could enhance combustion efficiency and reduce the emitted emissions.

Fig. 10 manifests that the CO_2 emissions from burning the biodiesel blends increased with the increase of engine load. Slightly lower CO_2 concentrations compared to diesel imply the reduction in its carbon molecules and the increment in oxygen molecules somewhat.

Fig. 11 illustrates the comparison of hydrocarbon emission in the exhaust for the tested fuels. Unburnt hydrocarbon emission is the direct result of incomplete combustion. The hydrocarbon emission is increasing with the percentage of diesel fuel mixed with the blend. HC varies from 80 ppm at no load to 35 ppm at full load for diesel fuel, and it varies from 29.56 ppm at no load to 10.9 ppm at full load for B100. Similarly for B20, it varies from 64 ppm at small load to 31 ppm at full load. HC is higher at low loads that may attribute to cooler combustion chamber. Also, gaseous hydrocarbons (vapors) remain along the cylinder wall and in the crevice volume unburned.

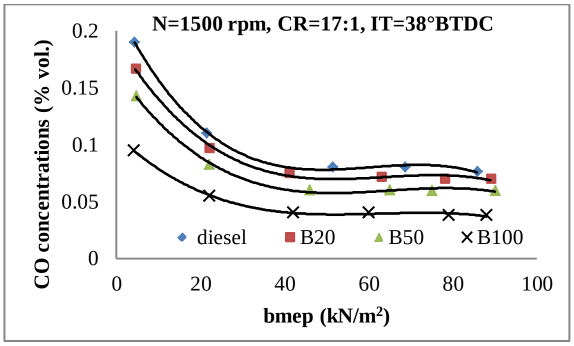

Fig. 9. Engine load effect on CO concentrations for the tested fuels at constant engine speed.

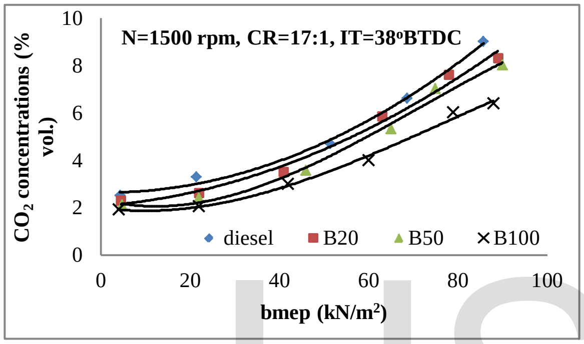

Fig. 10. Engine load effect on CO_2 concentrations for the used fuels at constant engine speed

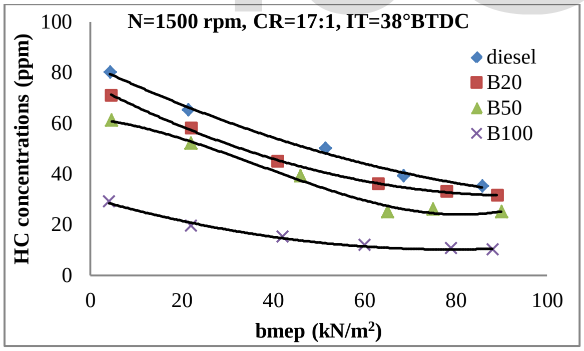

Fig. 11. Engine load effect on HC concentrations for the tested fuels at constant engine speed

Fig. 12 clarifies the comparison of NOx emission with brake mean effective pressure for the examined blends. NOx concentrations increased with increase in biodiesel concentrations in the blends. Two important parameters result in the formation of NOx. First parameter is oxygen availability and the second is in-cylinder temperature. Biodiesel has high oxygen content with about 11% higher than diesel fuel. If the combustion temperature is higher, then higher NOx is formed. In the case of biodiesel blends, high NOx concentrations resulted by fulfillment of these two factors.

Fig. 13 represents the PM emissions from the used fuels. The PM contains substantial carbon soot particles generated when the fuel has no enough oxygen to react with all the carbon. Also, it generated in the fuel rich zone of the combustion chamber during the combustion process. From the experimental results, the PM emission from biodiesel fuel and diesel fuel has a few differences in low load level. However, at medium and high loads levels the PM concentrations reduced highly for all biodiesel blends compared to diesel fuel. The maximum reduction achieved in PM concentration was about 34.96 % for neat biodiesel fuel compared to diesel at full load.

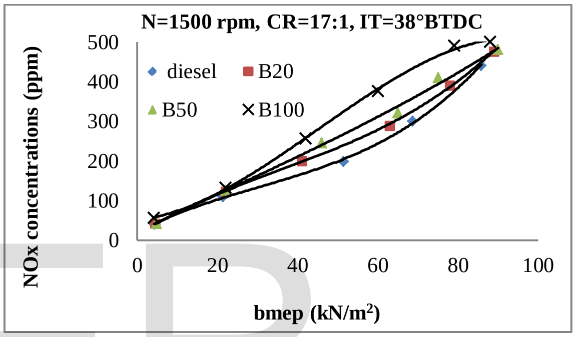

Fig. 12. Engine load effect on NOx concentrations for the tested fuels at constant engine speed

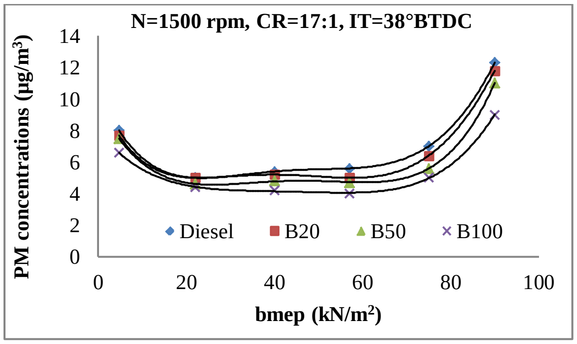

Fig. 13. Engine load effect on PM concentrations for the tested fuels at constant engine speed

There is a significant reduction in smoke emission for all blends of biodiesel at all loads. This soot free and complete combustion is due to the usage of oxygenated fuel (biodiesel blends), which substituted for diesel.

Sound or noise increased with increasing load as Fig. 14 demonstrates. Sound levels for biodiesel blends were found lower about (9-13%) than the sound values of diesel fuel throughout all loads. The minimum reduction (9%) observed in the small loads and the maximum drop (13%) at maximum loads. Combustion improvements due to higher oxygen content in blends reduced noise, although it still higher than accepted limitation, and the rig must be isolated with a proper design and materials to reach acceptable levels.

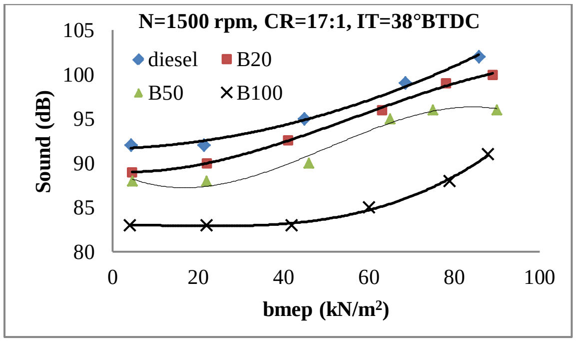

Fig. 14. Engine load effect on noise level for the tested fuels at constant engine speed

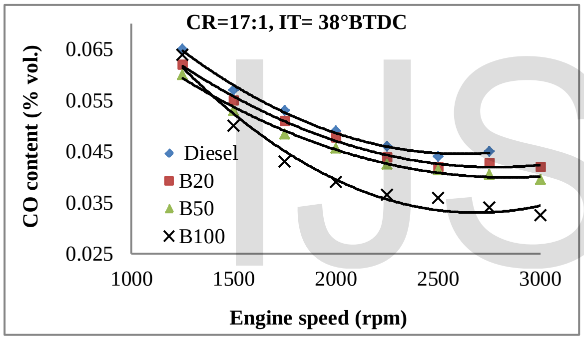

Fig. 15. Engine speed effect on CO concentrations for the tested fuels at constant engine load.

The trends of CO emissions with the engine speed for the four tested blends under a constant engine torque studied, as Fig. 15 presents. The CO concentrations for the examined blends appear to decrease with the increase of the engine speed. In the same hand, larger CO emissions at low engine speeds recorded. However, at higher engine speeds the extent of mixing of the atomized fuel particles and the surrounding air was enhanced, and the burning gas temperature inside the combustion chamber increased. As a result, a larger conversion rate of CO to CO_2 emissions, and lower CO emissions. More complete combustion and lower CO emissions produced by the neat biodiesel and its blends at higher engine speeds. The biodiesel blends, which contained oxygen of about 11wt. %, enhanced combustion efficiency and shorter ignition delay.

Fig. 16 shows that the CO_2 emissions from burning the neat biodiesel and biodiesel blends increased with the increase of engine speed. This occurred because the engine consumes more fuel to increase its speed, and higher fuel burn to produce CO_2. Slightly lower CO_2 emissions from burning the biodiesel blends imply the effect of less carbon to hydrogen and oxygen atoms percentage.

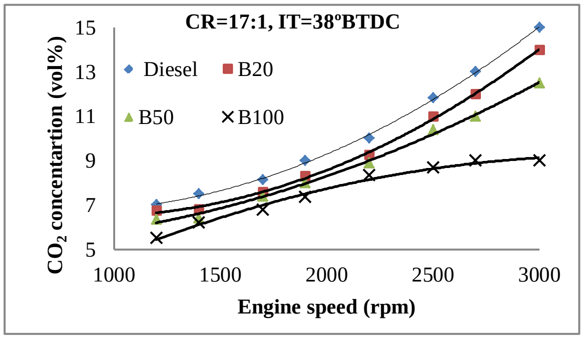

Fig. 16. Engine speed effect on CO_2 concentrations for the tested fuels at constant engine load.

HC concentrations reduced with engine speed increase for tested blends as Fig. 17 represents. At low speeds, HC reduced about 50% with B100, and at high speeds it was reduced about 65%. In addition to complete combustion due to the mixture turbulence increase; the trapping of fuel in crevices and boundary layers reduced. The HC concentration reductions were 20 and 35% for B20 and B50 respectively.

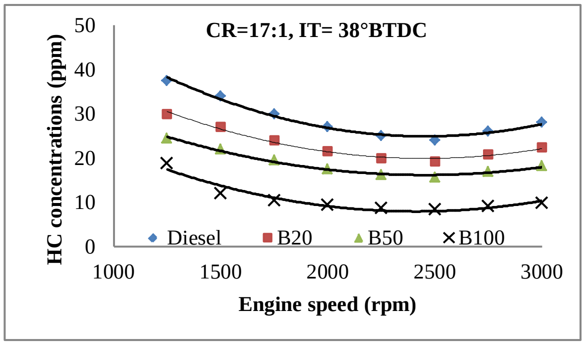

Fig. 17. Engine speed effect on UBHC concentrations for the used fuels at constant engine load

Fig. 18 declares that NOx concentrations from burning tested blends under constant engine torque increased with the increase of engine speed. Primarily because of increments in combustion temperature, due to improvement in volumetric efficiency and flow velocity of the reactant mixture at higher engine speeds. The burning of the neat biodiesel released relatively higher NOx emissions, due to the higher oxygen content in the chemical structure of this fuel. In contrast, the neat diesel produced lower NOx emissions, despite it has a higher heating value compared to biodiesel.

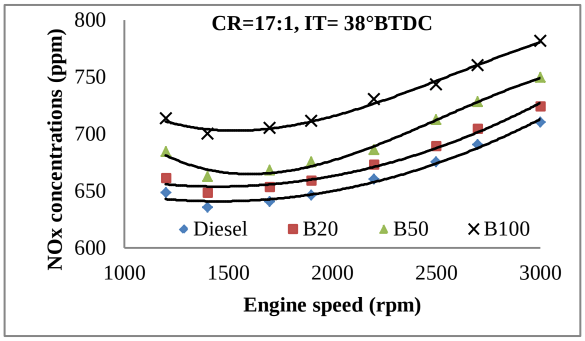

Fig. 18. Engine speed effect on NOx concentrations for the tested fuels at constant engine load

Fig. 19 depicts the effect of variable engine speeds on combustion noise for the examined blends. As the engine speed increases, the combustion pressure raised for most of the output loads. Many valuable studies demonstrated that the combustion noise decreased with the engine speed increases [11], [19].

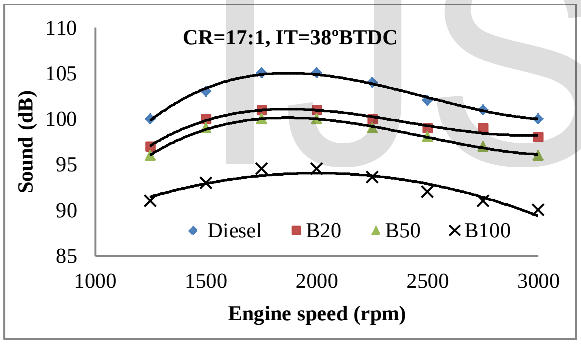

Fig. 19. Engine speed effect on noise level for the used fuels at constant engine load.

The increment in engine speed caused a reduction in the ignition delay period of the air-fuel mixtures. Which results in a decline in the pressure rise rate; therefore, the noise levels were reduced. In general, engine noise levels increased from low to medium speeds then it reduced for high speeds. Compared to other fuels diesel fuel still resulting in higher noise levels at maximum speed.

Fig. 20 represents the engine speed variation effect on the emitted PM concentration at medium load (44 kN/m²). PM concentrations reduced significantly with the biodiesel addition. As the figure indicates, PM concentrations decreased with the addition of biodiesel blends for all tested engine speeds compared to diesel. These results indicated that the engine operation mode has a significant effect on PM concentrations. The measured PM concentrations reductions were 16.847, 28 & 43.34% for B20, B50 and B100 respectively compared with diesel fuel.

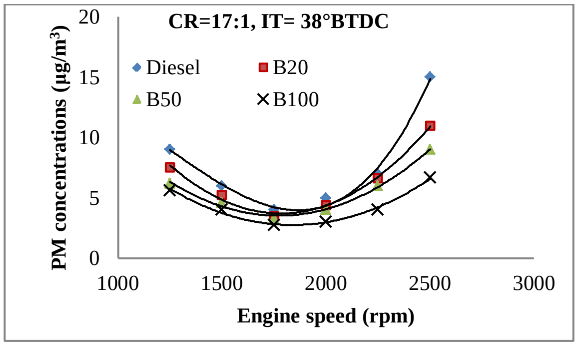

Fig. 20. Engine speed effect on PM concentrations for the examined fuels at constant engine load.

Table 4 represents a comparison between recent study results and the results of some valuable published paper. These studies vary in engine types, volume, power, and the used biodiesel. However, they all have similar results except for [20]. CO and HC concentrations increased in the pre-mentioned reference may be due to the used biodiesel in the tests where the researcher didn't clarify the reason. The other investigations gathered that biodiesel reduces brake thermal efficiency, CO, HC, and PM concentrations and increased bsfc and NOx concentrations.

4. CONCLUSIONS

The biodiesel produced from Iraqi sunflowers oil by transesterification accompanied by peroxidation. Four blends include neat diesel, biodiesel, and blends of the two fuels tested in a direct injection diesel engine. The work conclusions summarized as follows:

1. The brake specific fuel consumption (bsfc) increased with increasing load at constant engine speed, and when using biodiesel with about 23, 27 and 35.7% for B20, B50 and B100 respectively.
2. Engine volumetric efficiency improved with biodiesel blends compared with diesel fuel.
3. Engine brake thermal efficiency reduced when operated with biodiesel blends. The lower percentage was 3.45% when B100 used.
4. Using biodiesel reduces exhaust gas temperatures for all tested loads and engine speed ranges.
5. As a result of higher oxygen content in the biodiesel structure, fewer CO2 emissions obtained from the variable engine tests.

6. CO emissions reduced with biodiesel operation, but high concentrations observed at low engine loads.
7. Unburnt hydrocarbons emissions reduced highly with B100 and by a respective percentage with other biodiesel blends compared with diesel fuel.
8. NOx emissions increased with biodiesel blends utilization and by increasing engine speed.
9. The trend of CO and UBHC emissions with the engine speed was adverse: the emissions decreased with the engine speed for the tested fuels with about 50% in average.
10. Engine noise increases with increasing load. The biodiesel combustion reduced engine noise with about 11% compared with neat diesel fuel.

TABLE 4. A COMPARISON BETWEEN THE RECENT STUDY RESULTS AND OTHER STUDIES

Ref.	Biodiesel origin	Engine type	Blend rate	Brake thermal eff.	bsfc	CO	HC	NOx	PM
Recent study	sunflowers	Fiat 3333cc	100%	-3.45%	+35.7%	-50%	-68.1%	+20.4%	-34.9 %
Liu and Lin, 2012 [21]	Waste-cooking-oil Biodiesel	Cummins Turbocharged 488cc	100%	-	-	-8.65%	-23.4%	+1.14%	-11.6%
Vaneet, 2012 [19]	waste mustard oil	Kirloskar Single c	20%	-16.6	+28.08	+14.11	+111%	+22.2%	-
Altun, 2011 [20]	inedible animal tallow methyl esters	Mitsubishi Canter 4C, 1563cc	100%	-	+6%	-11.8%	-	-18.6%	-
Caichan and Ahmed, 2013 [10]	Disposal Yellow Grease	Fiat 3333cc	100%	-	+23.3%	-43.2%	-46.7%	20.52%	-29.4 %
Kalligeros et al, 2003 [22]	Olive oil	Petter AV1-LAB, single c, 553cc	50%	-	+1.06%	-35%	-49.1%	-14.4%	-18.1%

REFERENCES

[1] Ch. Arapatsakos, D. Christoforidis, G. Sarantitis, and D. Giannopoulos, "Fuel Mixtures of Diesel-Maize Oil," *International Journal of Energy*, vo;. 2, no. 3, pp. 43-50, 2008.

[2] J.A. Yamin, N. Sakhnini, A. Sakhrieh, and M. Hamdan, "Performance of CI Engines Using Biodiesel as Fuel," GCREEDER 2009, Amman-Jordan, March 31st – April 2nd 2009.

[3] N.E. Boulifi, A. Bouaid, M. Martinez, and J. Aracil, "Process Optimization for Biodiesel Production from Corn Oil and its Oxidative Stability," *Hindawi Publishing Corporation, International Journal of Chemical Engineering*, Article ID 518070, pp. 1- 9, 2010.

[4] T. Blades, "BTL – Next Generation Bio-Fuel! IEA Bio-Energy Task 39," Rotterdam, 9-10 January, 2008.

[5] A. Bouaid, M. Martinez, and J. Aracil, "Production of Biodiesel from Bioethanol and Brassica Carinata Oil: Oxidation Stability Study," *Bioresource Technology*, vol. 100, no. 7, pp. 2234-2239, 2009.

[6] D.C. Elliott, "Analysis and Upgrading of Biomass Liquefaction Products," Final report, vol. 4, IEA Co-operative project D1 Biomass Liquefaction Test Facility Project, Pacific Northwest Laboratory, Richland, Washington, USA, 87 p., 2007.

[7] J. Kaufman, "Renewable Diesel," SAE Government/Industry Meeting, ConocoPhillips, May, 2007.

[8] M.T. Chaichan and D.S. Al-Zubaidi, "Practical Study of Performance and Emissions of Diesel Engine Using Biodiesel Fuels," *Association of Arab Universities Journal of Engineering Science*, vol. **18, no. 1**, pp. 23-35, 2012.

[9] S. Sivalakshmi, and T. Balusamy, "Research on Di-ethyl Ether as an Oxygenated Additive with Biodiesel in CI Engine," Proceeding to International Conference on Energy and Sustainable Development: Issues and Strategies (ESD 2010), Chiang Mai, Thailand, 2010.

[10] S. Imtenan, H.H. Masjuki, M. Varman, M.I. Arbab, H. Sajjad, F.I.M. Rizwanul, M.J. Abedin and A.S.M. Hasib, "Emission and Performance Improvement Analysis of Biodiesel-Diesel Blends with Additives," *10th International Conference on Mechanical Engineering, ICME 2013, Procedia Engineering*, vol. 90, pp. 472–477, 2014.

[11] M.T. Chaichan and S.T. Ahmed, "Evaluation of Performance and Emissions Characteristics for Compression Ignition Engine Operated with Disposal Yellow Grease," *International Journal of Engineering and Science*, vol. 2, no. 2, pp. 111-122, 2013.

[12] C.Y. Lin and H.A. Lin, "Engine Performance and Emission Characteristics of a Three-Phase Emulsion of Biodiesel Produced by Peroxidation," *Fuel Processing Technology*, vol. **88, pp.** 35–41, 2007.

[13] G.P. Prajapati, P.R. Panchal and T.M. Patel, "Performance and Emission Characteristics of C.I. Engine Fuelled with Diesel-Biodiesel Blends, *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, vol. 11, no. 3 Ver. II, pp. 114-121, 2014.

[14] D. Kodjak, "The Low Carbon Fuel Standard: A Revolutionary New Climate Policy Now Under Development," The International Conference on Transport and Environment: A Global Challenge, Milan, Italy, March 2007.

[15] S.T. Ahmed and M.T. Chaichan, Effect of Fuel Cetane Number on Multi-Cylinders Direct Injection Diesel Engine Performance and Emissions, *Al-Khwarizmi Eng. Journal*, vol. 8, no. 1, pp. 65-75, 2012.

[16] L. McWilliam and T. Megaritis, "Experimental Investigation of The

Effect of Combined Hydrogen and Diesel Combustion on the Particulate Size Distribution from a HSDI Diesel Engine," *International Journal of Vehicle Design, vol.* 50, no. 1-4, pp. 107-123, 2008.

[17] E.L. Keeting, "Applied Combustion," 2nd edition, Taylor & Francis Group, LLC, 2007.

[18] ASHREA GIUDE LINE, Guide Engineering Analysis of Experimental Data, Guideline 2-1986.

[19] E. Elnajjar, M.Y.E. Selim and F. Omar, "Comparison Study of Dual Fuel Engine Performance and Overall Generated Noise Under Different Dual Fuel Types and Engine Parameters," *International Journal of Basic & Applied Sciences*, vol. 11, no. 3, pp. 1-11, 2011.

[20] Vaneet, "Comparative Analysis of the Performance and Emissions Characteristics of a C.I. Engine Fuelled with Three Different Blends of Biodiesel Derived from Waste Mustard Oil," M. Sc. Thesis, Thapar University, Punjab, India, 2012.

[21] S. Altun, "Performance and Exhaust Emissions of a DI Diesel Engine Fueled with Waste Cooking Oil and Inedible Animal Tallow Methyl esters," *Turkish J. Eng. Env. Sci.*, vol. 35, pp. 107-114, 2011.

[22] S.H. Liu, C.Y. Lin and K.H. Hsu, Emissions of Regulated Pollutants and PAHs from Waste-Cooking-Oil Biodiesel Fuelled Heavy-Duty Diesel Engine with Catalyzer," *Aerosol and Air Quality Research*, vol. 12, pp. 218-227, 2011.

[23] S. Kalligeros, F. Zannikos, S. Stournas, E. Lois, G. Anastopoulos, Ch. Teas and F. Sakellaropoulos, "An Investigation of Using Biodiesel Marine Diesel Blends on the Performance of a Stationary Diesel Engine," *Biomass and Bioenergy*, vol. 24, pp. 141 – 149, 2003.

NOTATIONS

bmep	brake mean effective pressure
BTE	brake thermal efficiency
CO2	carbon dioxide
CO	carbon monoxide
CN	cetane number
CR	compression ratio
CA	crank angle
°BTDC	degree before top dead centre
DI	direct injection
N	engine speed (rpm)
T	engine torque
N	engine speed (rpm)
dB	decibel
IT	Injection timing
LCV	Lower calorific value
NOx	nitrogen oxides
PM	particulate matter
Vsn	swept volume
UBHC	unburnt hydrocarbon