Alexandria Engineering Journal (2019) 58, 9–17

HOSTED BY

ELSEVIER

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Experimental and simulation study for the effect of waste cooking oil methyl ester blended with diesel fuel on the performance and emissions of diesel engine

Mohamed F. Al-Dawody [a,*], Ali A. Jazie [b], Hassan Abdulkadhim Abbas [c]

[a] *Department of Mechanical Engineering, University of Al-Qadisiyah, Iraq*
[b] *Department of Chemical Engineering, University of Al-Qadisiyah, Iraq*
[c] *Department of Material Engineering, University of Al-Qadisiyah, Iraq*

Received 18 November 2017; revised 29 March 2018; accepted 5 May 2018
Available online 7 January 2019

KEYWORDS

Waste oil;
Transesterification;
Diesel engine;
Performance;
Emissions;
Diesel-rk software

Abstract The methyl ester of waste cooking oil (MEWCO) has been prepared from used cooking oils collected from different restaurants and investigated experimentally and theoretically. The suggested biodiesel is mixed with different percentages (10%, 20%and 100%) on a volume basis together with original diesel fuel and tested on a constant speed diesel engine. The experimental work deals with the impact of the blending ratio on the performance and emission parameters at different load conditions. The experimental side is verified with simulation study done by Diesel-rk software and it reveals that they are in good agreement. The maximum pressure reduced as a result of increasing MEWCO blends due to the reduction in the heating value of the blended fuels. Both sides are reported promising reduction in nitrogen oxides (NO_x) on the behalf of carbon emissions. Mixing 20% MEWCO is the best compromise, mixing ratio and beyond that, dramatic reduction in the outcome of the performance has been observed.

© 2019 The Authors. Published by Elsevier B.V. on behalf of Faculty of Engineering, Alexandria University. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Increasing industrialization, growing energy demand, limited reserves of the fossil fuels and increasing environmental pollution have jointly necessitated for exploration of substitute for conventional liquid fuels. Vegetable oils can be used as alternatives to petroleum fuels for engine operation. These oils are mixtures of free-fatty acid molecules to contain carbon, hydrogen, and oxygen atoms [1,2]. The present day scenario says: there is a not that much attempt makeable to utilize biodiesel from non-edible sources commercially to substitute petroleum fuel. The waste fry oil (WFO) can serve as a substitute for diesel fuel. Esterifies such oils possess acceptable fuel properties and their heat energy is nearly 10 percent less than conventional diesel fuel [3].

* Corresponding author.
E-mail address: Mohamed.aldawody@qu.edu.iq (M.F. Al-Dawody).
Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2018.05.009
1110-0168 © 2019 The Authors. Published by Elsevier B.V. on behalf of Faculty of Engineering, Alexandria University.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Nomenclature

10% MEWCO	blend ratio of 90% diesel and 10% MEWCO	HC	hydrocarbon emission (%)
20% MEWCO	blend ratio of 80% diesel and 20% MEWCO	l	spray length (meter)
100% MEWCO	blend ratio of 100% MEWCO	l_m	fuel penetration distance (meter)
BTE	brake thermal efficiency (%)	P	cylinder pressure (pa)
BP	brake power (kW)	PM	particulate emissions (g/kW h)
BSEC	brake specific energy consumption (MJ/kW h)	R	constant of gas (8.3143 kJ/kmol K)
BSFC	specific consumption of fuel (Brake) (g/kW h)	RPM	revolution per minute
BSN	Bosch smoke number	rps	revolution per second
EGT	exhaust gas temperature (C)	TDC	top dead centre
CA°	crankshaft angle (deg.)	Tz	zonal temperature (K)
		U	fuel spray velocity (m/s)
		Uo	Initial spray velocity (m/s)

Several investigations have reported the results of the test engine with waste frying oil without transesterification process and the emission findings are different some researchers reporting reduces of a certain pollutants and other reporting increases [4].

Al-Dawody [5] tested different blending ratios from rapeseed methyl ester (RME) with diesel fuel. It was found that 47.27%, 81.06%, 82.56% and 93.36% reduction in the Bosch smoke number is obtainable with 10% RME, 20% RME, 50% RME and 100% RME respectively, compared with ordinary diesel. The blends of RME are noticed to emit higher NOx emissions. The simulated result signals that 10% RME is the promising ratio of blending which reports less performance variances and reduced carbon emissions as well.

Isigigur et al. [6] tested diesel fuel blended with 10% and 20% MEWCO and reported that even the energy content and cetane number are less than for ordinary diesel, most properties of blended fuels are nearer to those of pure diesel.

Mittelbach et al. [7] investigated the influence of used wastage oil methyl ester on exhaust pollutant emission of a diesel engine. The observations are reduction in carbon emissions and increasing nitrogen oxides on the other hand. Regarding performance parameters, it is recorded lower fuel economy for the biodiesel comparatively to diesel.

Reed et al. [8] converting wasting frying oil to its methyl ester and examined biodiesel and a 30% proportion of biodiesel with 70% diesel in a diesel bus by using a chassis dynamometer. With the use of prepared biodiesel, not that much difference in performance has been noticed with the exception of the dramatic decrease in soot emissions esters of the used oil.

Ashok et al. [9] utilized waste frying oil blended with diesel fuel in a stationary diesel engine. The results point out that NOx emissions reduced below diesel emission level as well as the proposed biodiesel can save 10% of diesel consumption.

Sanli et al. [10] used methanol and ethanol to produce two biodiesels from used fry oil. Pure biodiesel and 20% blended with diesel fuel have been tested in direct injection diesel engine under three different speeds (1100, 1400, 1700) rpm. The BSFC and thermal efficiencies of ester fuels were higher than diesel fuel. Better engine performance is recorded with ethyl ester rather than methyl ester biodiesel.

Vinoothan et al. [11] conducted experimental study to investigate the emissions parameters and performance of waste cooking oil methyl ester, diesel and ethanol blends in a diesel engine. The work is carried out on diesel fuel and blends B20, B20 with E10 and B15 with E5. CO and NOx emissions for B20 with E10 is lowered by 18.91% and 13.95% respectively compared to diesel fuel at higher loads.

As most of the listed literature related to use waste cooking oil as biodiesel is based on experimental findings, hence the current work focuses on both experimental investigation as well as simulation study using Diesel-rk software. Both performance and emission parameters of the engine for various loads using different blends of MEWCO with diesel fuel have been studied.

2. The experimental work details

Different samples from various restaurants are collected and subjected to cleaning and filtering prior to transesterification process as remaining food particles and oil deposits have tremendous impact on combustion characteristics. The preparation of biodiesel under study was in the chemical engineering department, college of engineering, university of Al-Qadisiyah using transesterification process in addition to methyl alcohol that is catalyzed by NaOH. This method is influenced by several factors such as: reactive mode, the proportion of alcohol/oil, alcohol kind, catalyst quantity, reactive time and reactants pureness as well. The general equation of preparation is demonstrated in Fig. 1. The properties of biodiesel along with standard properties of diesel and biodiesel are shown in Tables 1 and 2 respectively.

The MEWCO is blended with pure diesel fuel on different ratios (10%, 20% and 100%) by volume and being tested using the research engine available in the IC. Engines lab at the University of Babylon as shown in Fig. 2. The observed data are collected with variable load and the necessary calculations are completed successfully to measure the required data of the engine. The technical design of the test rig is shown in Table 3.

The experiments were conducted with a constant ratio of compression (17.5) through the experimental work. Initially, it is fueled with diesel fuel to generate the baseline data, and then MEWCO was tested as B10%, B20 % and as a pure biofuel B100% on a volume basis. These blends were subjected to performance and emission tests on the engine. All tested fuels were conducted at four loads of engine (0, 0.925, 1.85, 2.75 and

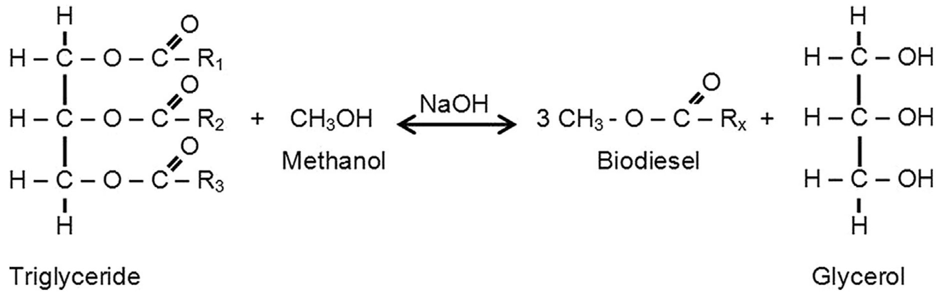

Fig. 1 Biodiesel production by the transesterification process [10].

Table 1 Properties of diesel and MEWCO.

Property	Diesel	10% MEWCO	20% MEWCO	MEWCO
C%	87	86	85	77
H%	12.6	12.55	12.5	12.1
O%	0.004	0.0145	0.025	0.109
Density at 15 °C (kg/m^3)	830	835	839	870
Viscosity at 40 °C (cst)	3.0	3.19	3.4	4.9
Calorific value (MJ/kg)	42.5	42.27	42.04	40.20
Flash point (°C)	76	81.4	87	130
Cetane number	48	48.3	48.6	51
Molecular weight	190	200.6	211.2	296

Table 2 Standard Properties of diesel and biodiesel [12].

No.	Fuel properties	Diesel	Biodiesel
1	Fuel standard	ASTM D 975	ASTM D 6751
2	Composition	$C_{10–21}$	$C_{12–22}$
3	Density @15 °C (kg/m^3)	840	880
4	Kinematic viscosity (CST) at 30 °C	4.59	1.9–6.0
5	Flash point (°C)	52–96	273
6	Cetane number	45	37
7	Lower heating value (MJ/kg)	42.49	39.6
8	Auto ignition temperature (°C)	260	300

3.7 kW) respectively at a constant engine speed of 1500 RPM. During the experiments the values of torque, exhaust temperature and pollutants such as, CO, HC, NOx and CO_2 were measured through the gas analyzer attached to the engine. The tests were 3 times repeated, hence the value depended on this work was the mean of the 3 results. The accuracies of the measured parameters are listed in Table 4.

3. Theoretical simulation

In RK-model of combustion, the spray is classified into seven regions, as illustrated in Fig. 3. Each region had a separate condition of evaporation and burning. These are:

1. Free spray core.
2. Front of the free spray.
3. Outer sleeve of the spray.
4. Near wall flow (NWF) nucleus.
5. NWF on the piston surface.
6. The dense front of the NWF and
7. NWF Outer zone.

The velocity of gas has low values in the environment as compared to the core of spray where it's accelerated rapidly and approaches the droplet velocity. The velocity as well as position of elementary fuel mass (EFM) is referred as:

$$\left(\frac{U}{U_o}\right)^{3/2} = 1 - \frac{l}{l_m} \tag{1}$$

Fig. 4 presents the evolution of jet with respect to time. The solution of equation (1) is found as:

$$3l_m\left[1-\left(1-\frac{l}{l_m}\right)^{0.333}\right] - U_o t_k = 0 \tag{2}$$

t_k – travel time for the fuel to reach the distance l from the injector's nozzle. The detailed of mathematical analysis for evaporation are described in [13].

4. Modeling of NO_x formation

The oxide of nitrogen reaction is depending on the oxygen concentration and it can be calculated as:

$$N + O_2 \leftrightarrow NO + O \tag{3}$$

The NO Concentration can be determined from below equation [14]

$$\frac{d[NO]}{d\theta} = \frac{2.33*10^7 p.e^{-\frac{38020}{T_Z}}[N_2]_e[O]_e\left(1-\left([NO]/[NO]_e\right)^2\right)}{RT_Z\left(1+(2365/T_Z).e^{\frac{3365}{T_Z}}.[NO]/[O_2]_e\right)}.\left(\frac{1}{rps}\right) \tag{4}$$

Fig. 2 Research engine test rig.

Table 3 Specifications of the engine.

Brand of engine	Kirloskar diesel engine
Kind	1-Cylinder, 4-Stroke
Bore (mm)	80
Stroke (mm)	110
Ratio of compression	17.5
Brake power (kW)	3.7 kW
R.P.M	1500
Injection pressure (bar)	220
Injection timing	23 CA BTDC
Spray angle	160°
Fuel injection nozzle	0.16 mm
Inlet valve opening	4.5° BTDC
Inlet valve closing	35.5° ABDC
Exhaust valve opening	35.5° BBDC
Exhaust valve closing	4.5° ATDC
Software	Lab view

Table 4 Accuracies of measured parameters.

Measurement	Accuracy
Speed	±15 rpm
Time	±0.8%
Temperature	±1.5 °C
CO_2	±0.1%
CO	±0.1%
HC	±1 ppm
NO_x	±1 ppm
Calculated results	Uncertainly
BTE	Max. 2.4%
BSFC	Max. 2.4%

5. PM and smoke calculation methods

The Hartidge smoke level is calculated from the following equation;

$$Hartidge = 100[1 - 0.9545.\exp(-2.4226[C])] \quad (5)$$

where [C] current soot concentration in cylinder.

An experimental curve was used to calculate the Bosch smoke number (BSN) as a function of Hartidge equation. Particulate matter emission (PM) is calculated by equation of (Alkidas [15]) as a function of Bosch smoke number:

The PM emission consists of a list of species. Soot has a dominant fraction. There are some formulas to predict PM emissions as a function of soot emission: one of them is Cummins formula [16] as a function of the Bosch smoke number (BSN):

$$PM = A_{PM}(-184BSN - 727.5)\log\left(1 - \frac{BSN}{10}\right) \quad (6)$$

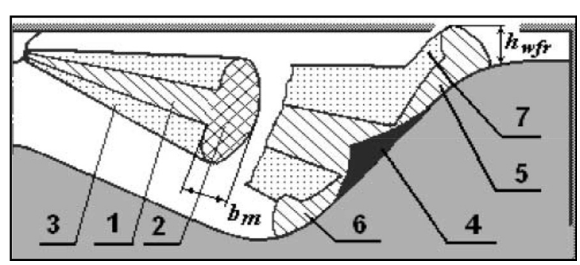

Fig. 3 Spray characteristic [11].

The factor A_{PM} is a correction coefficient for calibrating the PM in a match with measured data. By default $A_{PM} = 1$.

6. Performance calculation

The fuel consumption time indicator is set in automatic mode with required fuel quantity 10 cc (cc) and the time taken for 10 cc of fuel consumption is noted down. From this the total fuel consumption (TFC) can be obtained [17];

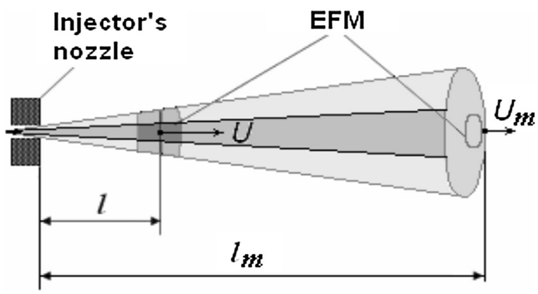

Fig. 4 Growth of spray v/s time.

$$TFC = \frac{q}{t_f}\rho_f \quad (\text{kg/s}) \tag{7}$$

where: q – Volume of fuel consumed equals to 10×10^{-6} (m^3), t_f – Time taken for 10 (cc) of fuel consumption (s).

From Eq. (7), the brake specific fuel consumption (BSFC) can be calculated:

$$BSFC = \frac{TFC}{BP} \quad (\text{kg/kW h}) \tag{8}$$

Finally the brake specific energy consumption (BSEC) is obtained by multiplying the BSFC with the lower heating value of the fuel.

$$BSEC = BSFC \times ((1 - MEWCO\%)Q_{LHVD} + MEWCO\% \times Q_{LHVWCO}) \quad (\text{MJ/kW.h}) \tag{9}$$

7. Results and discussion

This part of the discussion deals with BTE and BSFC variation with various loads for diesel fuel and MEWCO blends. Fig. 5 shows load v/s BTE for various blends. As percentage of MEWCO increases, BTE decreases because of the reduction in the lower heating content in the blended fuel. 20% MEWCO almost closer to pure diesel fuel and behaves much better than other blends of MEWCO. This is because of cetane number improvement through transesterification process and the change in the chemical structure of the oil which is desirable for diesel engine.

Fig. 6 displays the effect of load variation on the BSFC for MEWCO blends in diesel fuel. It can be observed that BSFC decreased as the brake power of an engine increases because of the rate of increasing brake power is greater than consumption of fuel. The BSFC increased as the blending ratio of MEWCO increased due to the higher viscosity and density MEWCO compared to diesel fuel.

Fig. 7 examines the variety of BTE with MEWCO biodiesel blends at full load condition. Experimental results point put that all blending of MEWCO had lower BTE for the whole load by 6%. The simulation results follow the same way recorded higher BTE than experimental results. Replacing diesel fuel by 100% MEWCO gives nearly 3% lower BTE compared to diesel fuel. Decreasing trend of BTE due to the difference in heating values of the blended fuels.

Fig. 8 shows MEWCO % v/s BSFC. Since BTE in simulation results is slightly higher than experimental results, hence its expected BSFC in theoretical results to be lower than BSFC in experimental results. The BSFC increased, according to the increment in the blending ratio of MEWCO. To obtain same

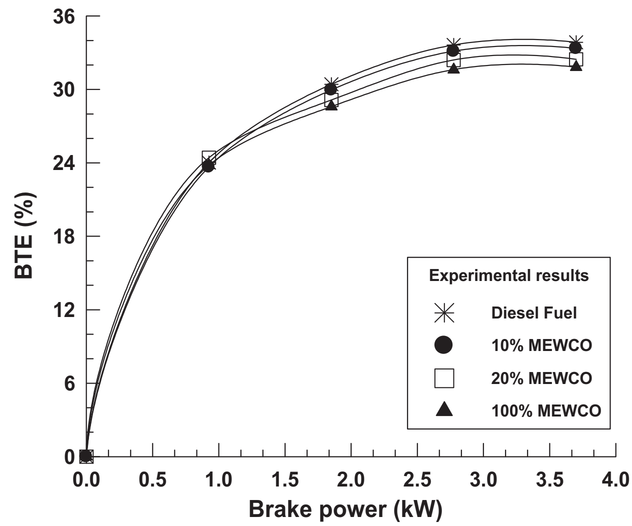

Fig. 5 Load v/s BTE.

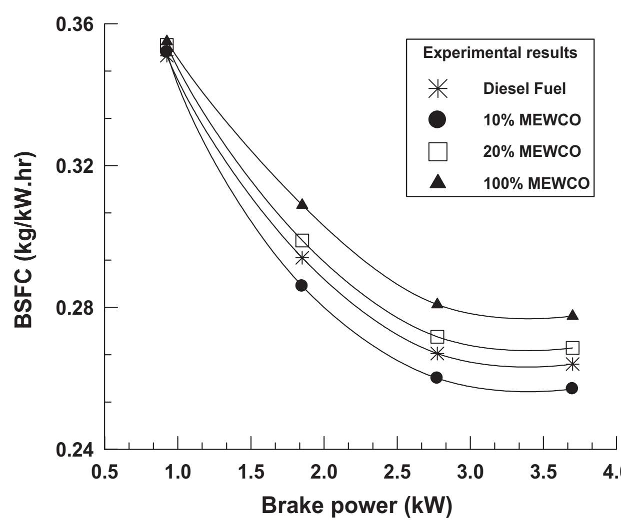

Fig. 6 Load v/s BSFC.

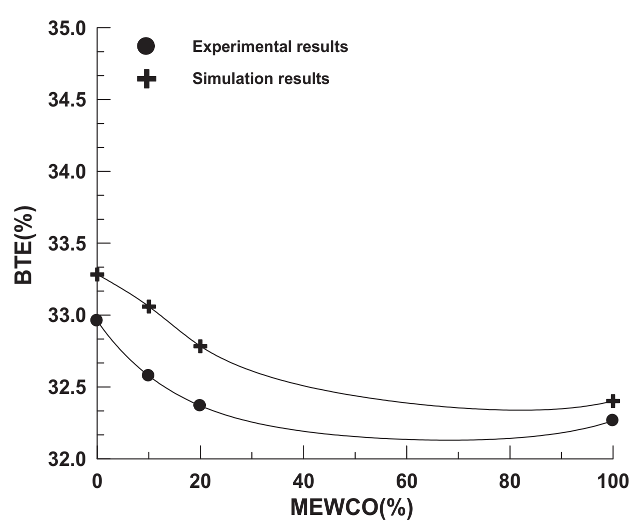

Fig. 7 MEWCO% v/s BTE.

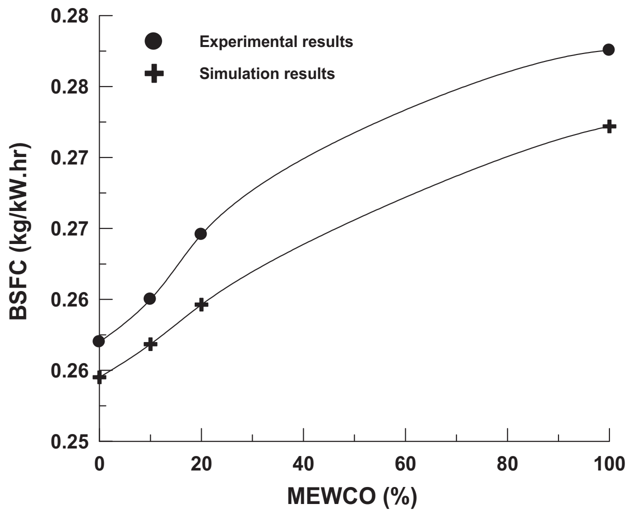

Fig. 8 MEWCO% v/s BSFC.

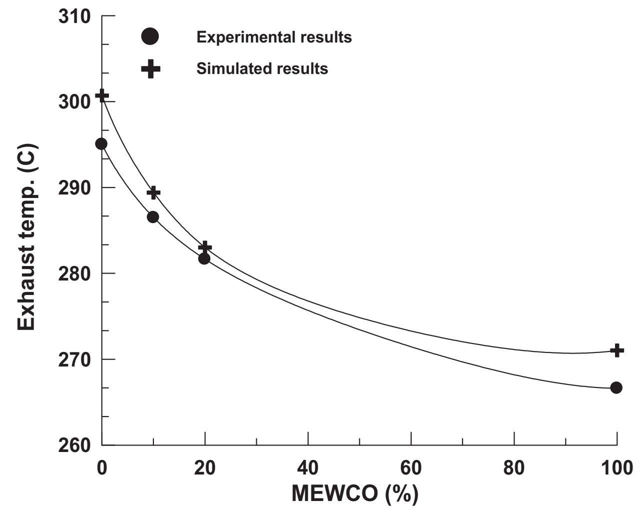

Fig. 10 MEWCO % v/s exhaust temperature.

power output and torque for each fuel examined, the BSFC has to be higher. BSFC for 20% MEWCO reported a 4.28% rise, while it is higher by 7.78% for 100% MEWCO. The difference in density and heating values are responsible for BSFC increment. The results are similar to those of (Mustafa et al. [18] and Monyem [19]).

Fig. 9 presents the relation between BSEC and MEWCO % for. As the load increases up to the full load point, the BSEC decreased due to the improvement in the brake power rather than fuel consumption. The BSEC depends on the BSFC and lower heating value. It can be seen that diesel fuel has least BSEC as compared to other blends of MEWCO due to lower heating values of MEWCO as compared to other fuels tested. When the engine runs on 100% MEWCO biodiesel, there is 2.15% increment in the BSEC according to experimental results, while it was only 1.15% increment in the BSEC according to results of Diesel-rk software.

Fig. 10 displays the effect of MEWCO proportion at full load on the EGT theoretically and experimentally. Generally the EGT detected an increase as a result of increasing load as the input energy increases. Diesel fuel has a higher EGT than all MEWCO blend. In experimental findings, the range of EGT of diesel and MEWCO blends is (295–266.6) °C. The EGT for biodiesel under study is lower than diesel fuel by 10%.

NO_x emissions v/s load in terms of brake power is depicted in Fig. 11. NO_x emissions increased as the engine load increased, due to the increase in combustion temperature. It is the most important emission characteristic of biodiesel and its blends. The reduction of it is always the target for engine researchers and manufacturers. Three conditions which enhance the formation of NO_x are: highly temperature of combustion, a greater quantity of oxygen and quickly rate of reaction [20]. The oxides of nitrogen start reducing as the MEWCO blend increases. The emission of NO_x with 100% MEWCO is decreased because of the decrease in the rate and temperature of combustion which leads to reduced NOx emissions. These results are confirmed by the report of Agarwal [21], and Patterson et al. [22].

Fig. 12 explains the relationship between NO_x and HC emissions with variable percentages of MEWCO. HC emission

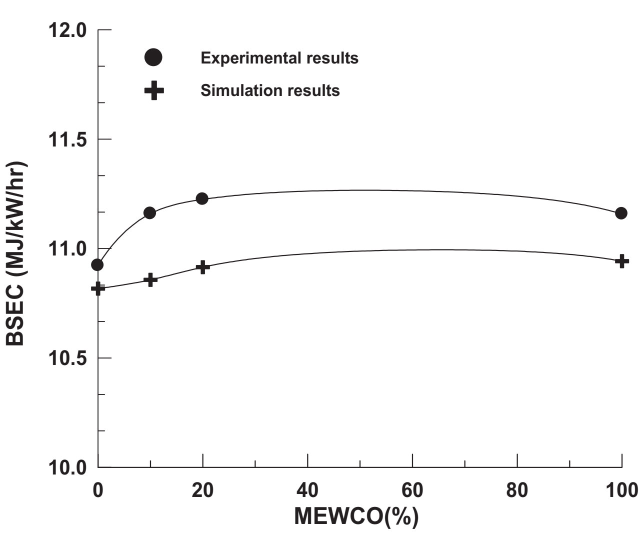

Fig. 9 MEWCO% v/s BSEC.

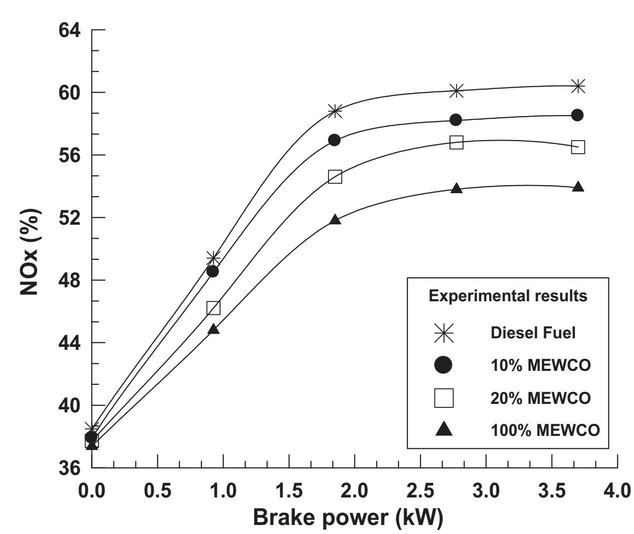

Fig. 11 Load v/s NO_x emissions.

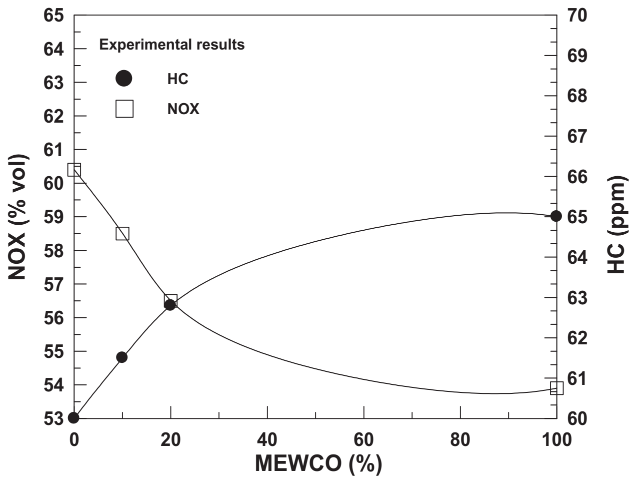

Fig. 12 MEWCO% v/s NOx and HC.

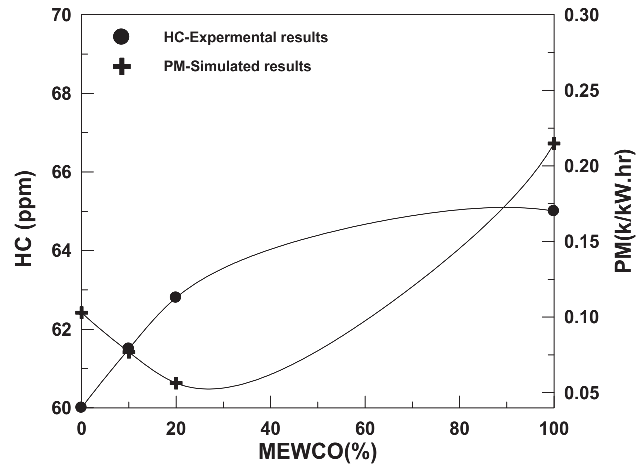

Fig. 14 MEWCO% v/s HC and PM emissions.

for all MEWCO proportions were higher than pure petroleum. Average NOx data for 10% MEWCO, 20%, MEWCO and, 100% MEWCO were fewer comparable with diesel fuel by 3.14%, 6.45%, and 10.76% respectively.

A confirmation comes from Fig. 12 which reports 20% MEWCO as the advisable blending ratio due to intersection of NO_x and HC curves. Even other percentages greater than 20% MEWCO records much reduction in NO_x emissions, on the same way the HC emission is increasing sharply.

Fig. 13 represents a comparison between NO_x emission predicted by the theoretical and experimental study v/s MEWCO %. The theoretical results showed 3.3%, 7% and 9.87% reduction in the NOx emissions as a result of adding MEWCO by 10%, 20% and 100% respectively. The same trend is observed in the experimental results.

Fig. 14 connects the PM emissions calculated by Diesel-rk software with the HC emissions measured by experimental results. Hydrocabron emission increases when percentage of MEWCO is increased. The increased emissions of HC for 100% MEWCO compared with base operation line of diesel because of the bulky structure of molecules and higher viscosity which reduce fuel atomization and increasing carbon emission. Same observations are reported by Devan et al. [23] and [24]. Nevertheless, HC emissions for 10% MEWCO and 20% MEWCO are less compared with 100% MEWCO. The other part of this figure is the variation of PM emissions with MEWCO%. It can be observed that PM decreased as the ratio of MEWCO increased up to 20%. The reduction in PM emission is 25.42% and 45.27% when the engine is running on 10% MEWCO and 20% MEWCO respectively.

Another massage comes from this figure, which says"operating the engine on 20% MEWCO is the best compromise choice to gain the reduction in PM emissions and to avoid the rapid increase in HC emissions that starts after 20% MEWCO.

Fig. 15 depicts the variation of full load cylinder pressure for diesel, and MEWCO blends experimentally and theoretically. It is found here that maximal pressure (73.43 bar) for diesel, followed by 20% MEWCO and 100% MEWCO. However, the curve of in-cylinder pressure for 20% of MEWCO is

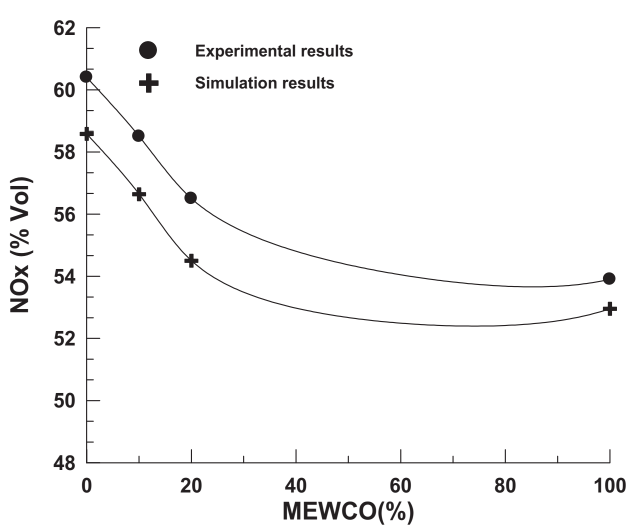

Fig. 13 MEWCO% v/s NO_x emissions.

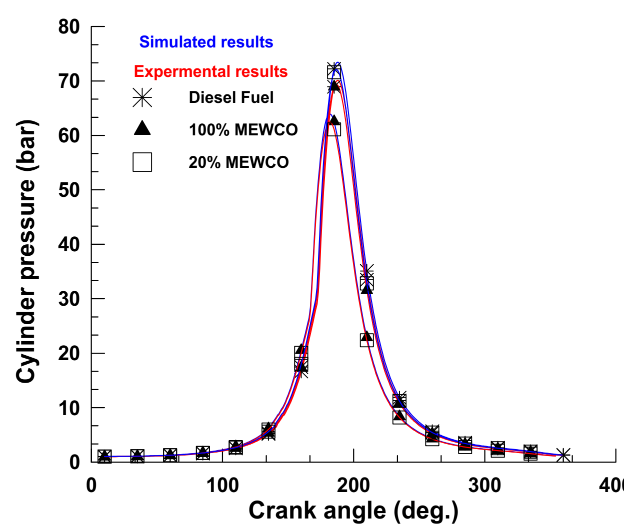

Fig. 15 Crank angle v/s cylinder pressure.

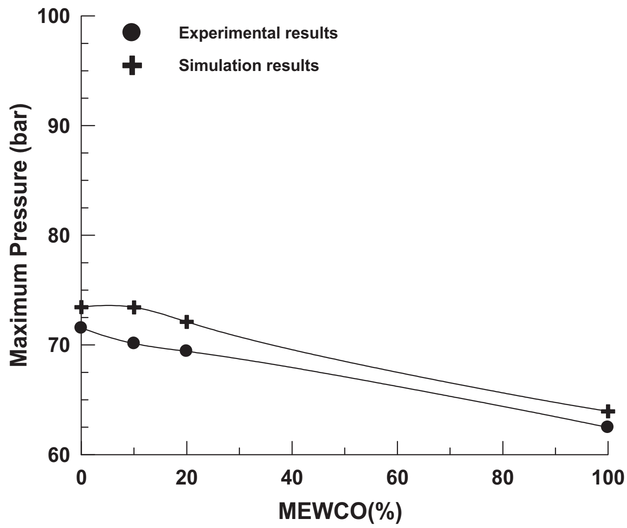

Fig. 16 MEWCO v/s maximum cylinder pressure.

closer to diesel curve. Only 20% MEWCO, 100% MEWCO in addition to diesel are graphed because of the fear from of intersections of curves. The experimental results reported 12.69% reduction in the cylinder pressure as compared with original diesel fuel. One possible explanation for this behavior pressure for 100% MEWCO is reduced heating content and higher levels of viscosity and density compared to original diesel.

Fig. 16 presents the result of peak pressure v/s MEWCO proportion at full load. Peak pressure for all fuels tested decrease as the blending ratio of MEWCO increased The software results come with 13% reduction in the peak pressure when power the engine by 100% MEWCO, while it was 1.85% when 20% MEWCO is used.

8. Conclusions

Based on the present study, the following conclusions are drawn:

1. Used cooking oils, which are no way wasteful, are one of the best efficient selections for production of biodiesel.
2. The prepared biodiesel can be profitably be employed in an existing diesel engine.
3. The performance characteristics follow the same trend for diesel and MEWCO.
4. A reasonable agreement has been detected between experimental work and simulation study.
5. Increasing the substitution of MEWCO came with a reduction in the BTE to a small extent and increased the fuel consumption.
6. MEWCO biodiesel has lower NOx emissions compared with neat diesel.
7. The exhaust temperature decreased by 10% as a result of replacing diesel fuel with MEWCO.
8. Increasing the blending ratio of MEWCO reported increase in the carbon emissions.
9. The present work confirmed 20% MEWCO is the advisable mixing ratio that keeps the outcome of performance, reduces the emissions of NOx as well as a slight increment in the carbon emissions comparable with other examined blends.

References

[1] Mohamed F. Al-Dawody, S.K. Bhatti, Optimization strategies to reduce the biodiesel NOx effect in diesel engine with experimental verification, Energy Convers. Manage. 68 (11) (2013) 96–104.
[2] Y.C. Bhatt, N.S. Murthy, R.K. Dutta, Fuel properties of five non edible vegetable oils and their blends with diesel, SESI J. 13 (1&2) (2003) 31–40.
[3] C. Oner, S. Altun, Biodiesel production from inedible animal tallow and an experimental investigation of its use as alternative fuel in a direct injection diesel engine, J. Appl. Energy 86 (2009) 2114–2120.
[4] K. Naima, A. Liazid, Waste oils as alternative fuel for diesel engine, Rev. J. Petrol. Technol. Alternative Fuels 4 (3) (2013) 30–43.
[5] F. Mohamed Al-Dawody, Theoretical study for the influence of biodiesel addition on the combustion, performance, and emissions parameters of single cylinder diesel engine, J. Babylon Univ. Pure Appl. Sci. 26 (3) (2017) 57–69.
[6] A. Isigigur-Tuna, F. Karaosmanoglu, H.A. Aksoy, Used frying oil as diesel fuel alternative, in: 1990 CIC Congress – Chemical Solutions for the Third Millennium, 40th Canadian Chemical Engineering Conference and Exhibition, 110, Halifax, NS, Canada, 15–20 July 1990.
[7] M. Mittelbach, P. Tritthart, Diesel fuels derived from vegetable oils, III. Emission tests using methyl esters of used frying oil, JAOCS 65 (7) (1988) 1185–1187.
[8] T.B. Reed, M.S. Graboski, S. Gaur, Development and commercialization of oxygenated diesel fuels from waste vegetable oils, in: Energy from Biomass and Wastes, vol. 907–914, The Institute of Gas Technology, IIT Center, Chicago1991.
[9] Y. Ashok, S. Onkar, Investigations on diesel engine performance based on jatropha, karanja and neem biodiesels, Proc. Inst. Mech. Eng. A: J. Power Energy 226 (5) (2012) 674–681.
[10] H. Sanli, M. Canakci, E. Alptekin, A. Turkcan, A.N. Ozsezen, Effects of waste frying oil based methyl and ethyl ester biodiesel fuels on the performance, combustion and emission characteristics of a DI diesel engine, Fuel 159 (2015) 179–187.
[11] K. Vinoothan, R.S. Prajwal, V. Rayan, A. Simmons, B. Sandeep, Rolvin S. D'silva, Investigation on the performance and emissions characteristics of CI engine using different blends of waste cooking oil methyl ester-ethanol-diesel oil, Energy Power 6 (1A) (2016) 28–32.
[12] M.S. Khatun, M.A. Khatun, M.Z.H. Khan, M. Debnath, Methyl ester (biodesel) production from waste cooking vegetable oil by microwave irradiation, Malaysian J. Anal. Sci. 18 (2) (2014) 321–328.
[13] Mahkamov, A. Kuleshov, Multi-zone diesel fuel spray combustion model for the simulation of a diesel engine running on biofuel, Proc. Inst. Mech. Eng. A: J. Automob. Eng. 222 (2007) 309–321.
[14] A.S. Kuleshov, Model for predicting air-fuel mixing, combustion and emissions in DI diesel engines over whole operating range, J. SAE (2005)-01-2119.
[15] A.C. Alkidas, Relationship between smoke measurements and particular measurements, SAE paper No. 840412, 1984.

[16] G.G. Muntean, A theoretical model for the correlation of smoke number to dry particulate concentration in diesel exhaust, SAE paper. – 1999. – No 1999-01-0515.

[17] Mohamed F. Al-Dawody, S.K. Bhatti, Effect of variable compression ratio on the combustion, performance and emission parameters of a diesel engine fuelled with diesel and soybean biodiesel blending, World Appl. Sci. J. 30 (12) (2014) 1852–1858.

[18] Mustafa Canakci, J.H. Van Gerpen, Comparison of engine performance and emissions for petroleum diesel fuel, yellow grease biodiesel, and soybean oil biodiesel. Presented as Paper No. 016050 at the 2001 ASAE Annual International Meeting Sacramento Convention Center Sacramento, California, USA July 30–August 1, 2001.

[19] A. Monyem, The effect of biodiesel oxidation on engine performance and emissions. Ph.D. thesis, Department of Mechanical Engineering, Iowa State University, Ames, IA, 1998.

[20] H. Hiroyasu, T. Kadota, Models of combustion and formation of nitric oxide and soot in DI diesel engines, SAE paper No. 760129,1976.

[21] A.K. Agarwal, J. Bijwe, L.M. Das, Effect of biodiesel utilization of wear of vital parts in compression ignition engine, J. Eng. Gas Turb. Power Trans. ASME 125 (3) (2003) 604–611.

[22] C.L. Peterson, D.L. Reece, B. Hammond, J.C. Thompson, S. Beck Commercialization of Idaho biodiesel (HySEE) from ethanol and waste vegetable oil, ASAE Paper No. 95-6738, 1995.

[23] P.K. Devan, N.V. Mahalakshmi, Study of the performance, emission and combustion caharacteristics of a diesel engine using poon oil-based fuels, Fuel Process. Technol. 90 (4) (2009) 513–519.

[24] Mohamed F. Al-Dawody, Khaled A. Al-Farhany, A comparative analysis of diesel engine fuelled with diesel fuel and methyl ester of waste cooking oil, Int. J. Appl. Eng. Res. 13 (1) (2018) 101–107.