Experimental Investigations on the Performance and Exhaust Emissions of a Diesel Engine Using Waste Frying Oil as Fuel

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Abstract---- Experiments were conducted on a single cylinder direct injection diesel engine using low sulfur diesel, biodiesel and their blends converted from waste frying palm oil to investigate performance, exhaust emissions and combustion characteristics of diesel engine under four engine loads at an engine speed of 1500 rpm. Different blended fuels containing 10% (B10) and 20% (B20) by volume of biodiesel and diesel fuel were used. The properties of waste frying oil such as viscosity, density, calorific value and flash point were determined. The experimental results of the study reveal that the waste cooking oil biodiesel has similar characteristics to that of diesel oil and diesel engine can perform satisfactorily on biodiesel and its blends with the diesel fuel without any engine modifications. It is also observed that there is significant reduction in CO, HC and smoke emissions for biodiesel and its blends compared to diesel fuel. However, NOx emission of WCO biodiesel is marginally higher than petroleum diesel. On an average, HC emission reduced by 25%, smoke emission reduced by 22 %, CO emission reduced by 13% and NOx emission increased by 8.2% at full load operating conditions for B20 compared to diesel oil. With an increase of biodiesel in the fuel, brake specific fuel consumption increases with simultaneous reduction in the engine thermal efficiency compared to conventional diesel oil. The results indicate that the combination of diesel and biodiesel from waste frying oil gives similar results to those in the literature and could be used as a diesel fuel substitute for short term engine operation.

Index Terms— Waste frying oil; diesel engine; Performance; Emissions; combustion characteristics.

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1 INTRODUCTION

The search for alternative fuels, which promise a harmonious correlation with sustainable development, energy conservation, efficiency and environmental preservation, has become very important today. Biodiesel is an alternative diesel fuel derived from the transesterification of vegetable oils, animal fats, or waste frying oils with alcohols to give the corresponding fatty acid methyl esters [1]. The use and research of biodiesel as an alternative fuel for the diesel engine started because of the reduction of petroleum production by Organization of the Petroleum Exporting Countries (OPEC) and the resulting price rise. In the transportation sector, it can be used blended with fossil diesel fuel and in pure form. The major chemically bound oxygen component in the biodiesel fuel has the effect of reducing the pollutant concentration in exhaust gases due to better burning of the fuel in the engine [2]. Physical and chemical properties of biodiesel fuels have significant effects on the combustion process which will impact engine performance and emissions. For better performance and emissions, the engines should match the biodiesel characteristics Pillay et al. [3] reported that using biodiesel in diesel engines reduces emissions of unburned hydrocarbons, carbon monoxide, sulfur oxide, and particulate matter. In contrast to these decreases, generally, biodiesel increases NOx emissions when used as fuel in diesel engines as shown by Keskin et al., 2010 [4]. Vegetable oil is considered to be nearly a net zero carbon emission fuel because the carbon produced by combustion, typically as carbon dioxide, is absorbed back from the atmosphere by plants [5]. The amount of process energy required to create vegetable oil is minimal, especially when compared to the requirements to produce petroleum diesel or even biodiesel [6]. Biodiesel has higher cetane number than diesel fuel, no aromatics, almost no sulfur, and contains 10 to 11% oxygen by weight. These characteristics of the fuel reduce the emissions of carbon monoxide, hydrocarbon and particulate matter in the exhaust gas. For that reason, numerous emissions studies using biodiesel and its blends shows emissions concentration (CO, CO_2, HC, PM, NOx as well as deposit) varies depend on source of biodiesel and engine combustion system [7-9]. However, during extended operation of the engine with biodiesel, Problems of injector coking, dilution of engine oil, de-

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posits in various parts of engine have been reported. The major drawback with the vegetable oils as fuel is its higher viscosity [10]. Higher viscosity of oils is having an adverse effect on the combustion in the existing diesel engines. Esterification is one of the methods to reduce viscosity of plant oils and produces biodiesel. Several researchers have used biodiesel as an alternate fuel in the existing diesel engines without any modification [11]. In addition, biodiesel is over double the price of petroleum diesel oil. The high price of biodiesel is mainly due to the high price of the feedstock as investigated by Demirbas, 2007 [12]. One of the ways to reduce the price of biodiesel fuel is to use waste fats of animal and vegetable origin as shown by Lebedevas et al., 2009 [13]. It has also been reported by Zhang et al., 2003[14] that the use of waste cooking oil instead of food grade oil to produce biodiesel is an effective way to reduce the raw material cost because it is estimated to be about half the price of food grade oil. Therefore, researchers are searching for low-cost feed stocks such as inedible or waste feed stocks for biodiesel production to reduce the production costs. Low cost feed stocks as biodiesel source have been investigated, and some of them are described below. The key issue in using waste cooking oil (WCO) based fuel is oxidation stability, stoichiometric point, biofuel composition, antioxidants on the degradation and much oxygen with comparing to diesel gas oil [l5]. Repeated frying for preparation of food makes the edible vegetable oil, no longer suitable for consumption due to free fatty acid (FFA) content [16]. In addition waste cooking oil also brings many disposal problems all around the world by polluting river water and choking of drainage. So, use of WCO may bring in many benefits if it is used as a fuel source. Thus production of biodiesel from waste cooking oil is one of the better ways to utilize it efficiently and economically eliminating the disposal related problems [17]. Waste cooking oil cannot be used directly in diesel engines as it has higher viscosity, free fatty acid and moisture content with low volatility leading to severe engine deposits, injector coking and piston ring sticking [18, 19]. These undesirable effects can be removed by transesterification of waste cooking oil. Biodiesel from WCO was tested by Meng et al. (2008) [20] on an unmodified diesel engine, and the results showed that under all conditions, the dynamical performance remained normal. Moreover, B20 and B50 blend fuels (which includes 20 and 50% crude biodiesel, respectively) created unsatisfactory emissions, while the B′20 blend fuel (which includes 20% refined biodiesel) reduced PM, HC and CO emissions significantly. Muralidharan, K. et al, conduct an experimental work to evaluate performance, emission and combustion characteristics of a variable compression ratio engine using methyl esters of waste cooking oil and diesel blends. Authors concluded that 40% blending with the compression ratio of 21 produces higher efficiency [21]. In another study, wasted cooking oil from restaurants was used to produce neat biodiesel through transesterification, and this converted biodiesel was then used to prepare biodiesel/diesel blends. Lin et al., 2007 [22] concluded that B20 and B50 are the optimum fuel blends in terms of emissions. K. Nanth Gopal et al. [23]. Studied in-depth research and comparative study of blends of biodiesel made from WCO and diesel oil is carried out to bring out the benefits of its extensive usage in diesel engines. The experimental results of the study reveal that the WCO biodiesel has similar characteristics to that of diesel oil. The brake thermal efficiency, carbon monoxide, unburned hydrocarbon and smoke opacity are observed to be lower in the case of WCO biodiesel blends than diesel fuel. On the other hand, specific energy consumption and oxides of nitrogen of WCO biodiesel blends are found to be higher than diesel oil. In addition combustion characteristics of all biodiesel blends showed similar trends when compared to that of conventional diesel fuel. Abu-Jrai et al [24] studied the combustion characteristics and engine emission of a diesel engine fuelled with diesel and treated waste cooking oil blends. Results indicated an increase in brake specific fuel consumption with simultaneous reduction in the engine thermal efficiency compared to conventional diesel oil.

The motivation of this present study is to investigate the influences of the biodiesel derived from waste cooking oil blended fuel in small engine on performance, combustion characteristics and exhaust emissions and the obtained results were compared with that of regular diesel. Testing was undertaken with a four-stroke single cylinder compression ignition engine at variable loads and constant engine speed at 1500 rpm. WCO methyl ester blended with diesel fuel in ratios of 10% (B10) and 20% (B20).

2. MATERIALS AND METHODOLOGY

A. Conversion of Waste Cooking Oil into Biodiesel

Huge quantities of waste cooking oil can be collected from restaurants and food item industry. Waste cooking oil has sufficient potential to run diesel engines. It is available in the local market at cheaper rate. Waste cooking oil used to produce biodiesel has been obtained from different sources such as hotel, restaurants, canteen, cafeterias and food item industry. In present work, biodiesel is produced by using transesterification process. As prior preparation, unnecessary solid impurities present in waste cooking oil (WCO) such as food residue were removed using vacuum filtration and the traces of water present in the oil are removed before transesterification process by initial heating. WCO is heated up to 60^{o}C for 20 min. on magnetic stirrer with heater in order to avoid soap formation due to water present in that and to ensure the minimal presence of water in the oil and to use it for further transesterification process. The process of converting vegetable oil into biodiesel is called transesterification, it is a chemical process that removes the glycerine stem from the molecule, resulting in a much smaller molecule, called an ester, which improves its characteristics for use as an engine fuel. Transesterification is the method in which the vegetable oils are reacted with alcohol in the presence of a suitable catalyst at specific temperature. It is a series of reversible reactions in which the triglycerides are converted into diglycerides and diglycerides are converted into monoglycerides as shown below Neyda et al., 2008 [25].

The important parameter affecting transesterification process was analyzed such as catalyst concentration, reaction temperature and reaction time. Transesterification reaction was carried out in a water bath. 250 gm of waste cooking oil was taken in a conical flask and it was preheated to a temperature of 60°C for 90 min. In a separate flask, 1.25% of NaOH works as a catalyst which increases the rate of reaction and yielding of biodiesel and 20% of methanol (alcohol) by weight of waste cooking oil was mixed and then this mixture was poured into preheated oil sample. The reaction was carried out in water bath at temperature of 60°C for 60 min at constant stirring after which the two phase product formed as result of transesterification was separated using a separating funnel. Upper layer consists of biodiesel, alcohol and moisture. Lower layer consists of Glycerin, Catalyst and traces of un reacted oil. After separation, waste cooking oil methyl ester washed with hot water several times until the washing was neutral. The ester was filtered in order to blend with diesel. For this research study, two types of biodiesel blends from WCO have been used for engine testing namely B10 and B20 and all of them were compared with diesel oil. B10 comprises of 10% WCO biodiesel and 90% diesel oil and B20 comprises of 20% WCO biodiesel and 80% diesel, while D100 is 100% diesel oil without any addition of biodiesel. The measurement of the fuel properties was conducted in order to ensure that all biodiesel complied with ASTM biodiesel standard. Experiments were repeated to optimize the catalyst concentration, reaction temperature and reaction time.

B. Characterization of Biodiesel from Waste Cooking Oil

Biodiesel produced from used cooking oil was characterized for its fuel properties like flash point, fire point, pour point, cloud point, kinematic viscosity, density, calorific value and cetane index [19]. Viscosity was measured by using Redwood viscometer. Flash point and fire point were measured by closed cup apparatus. Cloud point and pour point were measured using cloud and pour point apparatus whereas calorific value was determined using bomb calorimeter. Table 1 shows the equipments used to determine fuel properties. The properties of waste cooking oil biodiesel (methyl esters) were quite comparable to that of diesel fuel as transesterification improves the desirable fuel properties of oil like density, kinematic viscosity, flash point, fire point, cloud point, pour point and calorific value. The comparisons show that the biodiesel has fuel properties relatively closer to diesel fuel, as shown in Table 2, flash point and fire point were higher than diesel this confirmed the safety of biodiesel storage. Cloud point and pour point were higher than diesel this may be due to the presence of saturated fatty acids in biodiesel produced from used palm oil. Kinematic viscosity and density were higher than diesel this may result in improper spray characteristics. Cetane index was found out using saponification value and iodine value [20]. Cetane index was higher than diesel and it would have positive impact on combustion quality of biodiesel. After preparation of biodiesel it is mixed with diesel fuel with some proportion. We cannot use 100% biodiesel in an engine because of some problem. One of them is viscosity. It is seen that the viscosity of biodiesel from waste cooking oil is 12 cSt which is greater than petroleum diesel. It effect on fuel injection system of diesel engine. So that biodiesel is mixed with diesel with definite proportion and proper homogenous mixture is prepared. This prepared mixture is called blending of biodiesel. The fuel properties of biodiesel blended fuels as compared to diesel are shown in Table 3.

Table 1: Different apparatus and standard used for fuel characterization

Fuel property	Method/ Standard
Kinematic Viscosity	Redwood Viscometer, IS:1448[P:25] 1976
Flash point and	
fire point	Closed cup flash and fire point apparatus IS:1448[P:32] 1992
Cloud point and	
pour point	Cloud and pour point apparatus
	IS:1448[P:6] 1970
Calorific value	Bomb Calorimeter, IS: 1448[P:6] 1984
FFA content	Titration with 0.1N NaOH

Table 2: Fuel properties of waste cooking oil biodiesel as com-

Properties	ASTM Standard	Diesel oil	Waste cooking oil biodiesel
Density, gm/cm^3	0.88	0.84	0.887
Viscosity@ 40^{o}C, cSt	1.9-6.0	2.71	4.4
Flash point, ^{o}C	Min.130	78	177
Fire point, ^{o}C	Min. 53	82	184
Cloud point, ^{o}C	-3 to12	<10	-1
Pour point, ^{o}C	-15 to10	-6	-7
Calorific Value, kJ/kg	Min. 33000	43433	39375.6

pared to diesel oil

Table 3: The Fuel properties of blends along with diesel oil

Parameter	ASTM D6751	Diesel fuel D100	Waste cooking oil(WCO)Blends	
			B10	B20
Density, gm/cm^3	0.88	0.84	0.862	0.882
Kinematic viscosity at 40 °C, mm^2/s	1.9-6.0	2.71	3.732	4.282
Calorific Value, MJ/kg	Min 33.0	43.433	39.08	35.02
Cetane Number	46	46.4	49.9	57.7
Acid Number, mg/KOH/g	Max 0.5	0.27	0.27	0.32

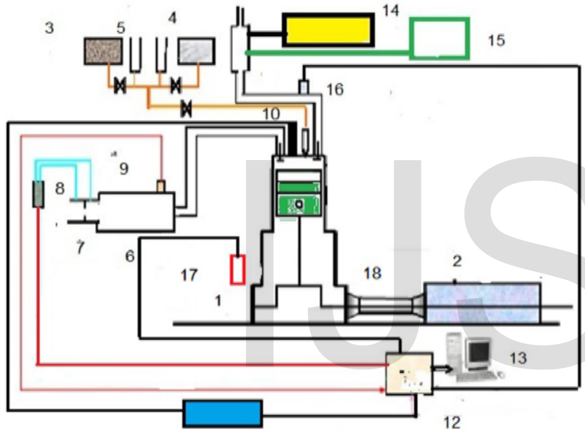
3. EXPERIMENTAL SET UP

A. Engine Setup

The experimental program was carried out using a single cylinder, four stroke, air cooled, direct injection (DI), naturally aspirated, constant compression ratio, diesel engine with a developing power of 5.775 kW at 1500 rpm. The technical specifications of the engine are given in Table 4, and the schematic diagram of the experimental arrangement is shown in Fig. 1. AC generator of maximum electric power output of 10.5 kW equipped with a load controller and other auxiliary items have been coupled directly to the test engine to determine the engine brake power. The intake airflow was measured by a sharp edged orifice mounted in the side of an air box, coupled to the engine inlet to dampen the pulsating airflow into the engine. A U tube manometer was used to measure the pressure drop across the orifice. Calibrated thermocouple probes of type (K) were used for temperature measurements at different locations in the experimental set up; including: intake air manifold and exhaust gas. A selecting switch is used to switch among these thermocouples and the signals are readout by a digital thermometer. The crankshaft rotational speed was measured using speed tachometer. Two fuel tanks of 10 Liters capacity were mounted for storing the fuels on the rear side of the panel at highest position. One burette with stopcock and two way valves was mounted on the front side of the panel for fuel flow measurements and selecting between both diesel and biodiesel fuels. The fuel consumption was determined by measuring the time for the consumption of fixed fuel volume (20 ml). For recording, the instantaneous in cylinder pressure a water cooled Kistler piezoelectric pressure transducer (model 601A) measure from 0 to 250 bar as pressure range with sensitivity of 16.5 pc/bar and accuracy of 1.118% connected with Nexus charge amplifier (2692-A-0S4) were used. The piezoelectric pressure transducer was flush mounted with the cylinder head to measure the combustion pressure. The flush mounting was preferred to minimize the lag in the pressure signal and avoid pipe connecting passage resonance. The instantaneous position of the piston top dead center (TDC) was determined using a proximity switch (Type LM12-3004NA) fixed on the output shaft of the engine. In order to guarantee confidence in the combustion diagnosis results, the combustion pressure data were averaged over 120 consecutive engine cycles. In all the cases, the pressure crank angle diagrams were recorded and processed, to get the combustion parameters by the data acquisition system. High speed data was acquired using LABVIEW software and national instruments data acquisition system (NIUSB- 6210) for later analysis. OPA 100 smoke meter and MRU DELTA 1600-V Gas Analyzer were used for the measurements of various exhaust gas parameters. The accuracy and reproducibility of the instrument was ±1% of full scale reading. The measurement principle for CO, HC, CO_2 was infrared measurement and for NO and O_2 it was electrochemical measurement. Digital readouts of CO and NO_X, HC, CO_2 and O_2 are available through the analyzer screen after steady state conditions and the average was taken for fifth minutes. Tests were executed without carrying out any modification on the engine or its fuel injection system (mass injected or injection timing). The experiment was carried out by varying load from zero to full load by maintaining constant speed of 1500 rpm throughout the experiment. The injection timing was 24° BTDC at an injection pressure of 175 bar and compression ratio was 17.5:1. The engine trial was conducted as specified by IS 10,000. In each test, the performance and emission measurements were triplicated. All the equipment's were calibrated in accordance to the respective manufacturer's specifications, prior to conducting the tests. All the tests are carried out for three times under steady state condition and the observed uncertainties for NO, unburned HC, CO, Smoke opacity and BTE are ±1 ppm, ±1 ppm, ±0.01 % Vol, ± 1 % and ± 1.5 % respectively. The maximum uncertainty in measurement of brake power, brake specific fuel consumption, and engine speed are found to be 0.85 %, 2.2 % and 0.15 % (± 2 rpm), respectively. At the end of the test, the engine is made to run with neat diesel to blush out the WCO -blended diesel fuels from the fuel line systems.

Table 4: Engine specifications

Engine parameters	Specifications
Type	DEUTZ F1L511
Number of cylinders	1
Number of Cycles	Four stroke
Cooling type	Air cooled
Bore (mm)	100
Stroke (mm)	105
Compression ratio	17.5:1
Fuel injection advance angle	24º BTDC
Rated brake power (kW)	5.775 @ 1500 rpm
Number of nozzle holes	1
Injector opening pressure (bar)	175



1- Diesel engine
2- AC generator
3- Diesel tank
4- Biodiesel tank
5- Burette
6- Air surge tank
7- Orifice
8- Pressure differential meter
9- Intake air temperature thermocouple
10- Piezo pressure transducer
11- Charge amplifier
12- Data acquisition card
13- Personal computer
14- Exhaust gas analyzer
15- Smoke meter
16- Exhaust gas temperature thermocouple
17- Proximity switch
18- Cardan shaft

Fig.1: Schematic diagram of the experimental setup.

4. RESULTS AND DISCUSSION
A. Engine Combustion Characteristics

In-Cylinder Pressure: Pressure variation using different fuel is important in the analysis of performance characteristics. Figure 2 shows the variation of cylinder gas pressure with crank angle for all blends of WCO and with diesel fuel at an engine speed of 1500 rpm and full engine load. Cylinder pressure characterizes the ability of the fuel to mix well with air and burn. All biodiesel blends of B10 and B20 follow similar cylinder gas pressure trends to that of diesel fuel under full load condition. The peak cylinder pressures are 6.9, 6.7 and 7.1 Mpa for B10 and B20 with diesel fuel, respectively at full load conditions. It can be observed from Fig. 2, that peak cylinder gas pressure occurred at crank angle within the range of 8–10 crank angle degree ATDC for all biodiesel blends. Unlike diesel, the viscosity of biodiesel blends are greatly higher and thus causes poor atomization, slower air fuel mixing and increment of spray penetration. These conditions will bring about a shorter ignition delay of biodiesel at the lowest speed and produce lower in-cylinder pressure [26]. The other factors that contribute to the lower peak pressure of biodiesel are the higher cetane number and higher oxygen content that leads to an improved combustion process. On the other hand, the in-cylinder pressure for B10 is closer to diesel due to their closer properties to diesel oil.

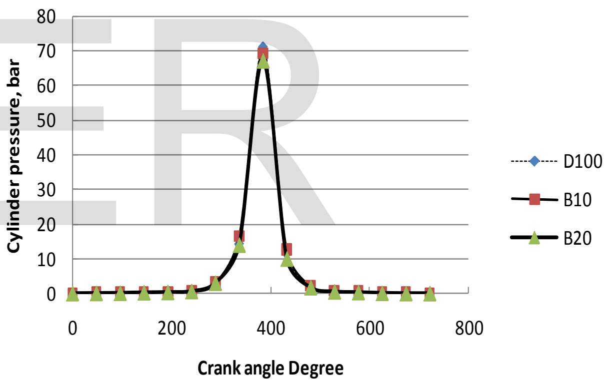


Fig.2: Comparison of cylinder pressure with crank angle at full engine load for biodiesel blends.

Rate of Heat Release (HRR): The comparison of heat release rate variations for biodiesel and its blends with diesel fuel at full load is shown in Fig. 3. Heat release pattern of a fuel is helpful to get some valuable information about the combustion process in an engine such as start of combustion timing and heat release rate at different crank angles. It can be observed that WCO and its blends experience similar combustion stages as diesel fuel at full load condition. But the premixed combustion rate of all biodiesel and its blends are slightly lower than diesel fuel and main combustion rate of diesel fuel is marginally lower than all biodiesel and its blends. The peak heat release rates are 0.69, 0.67 and 0.71 kJ/Degree for B10 and B20 with diesel fuel, respectively at full load conditions. This is due to the accumulation of small amount of diesel fuel in the combustion chamber at the time of premixed combustion phase, which resulted in lower heat release rate at full load condition [22].

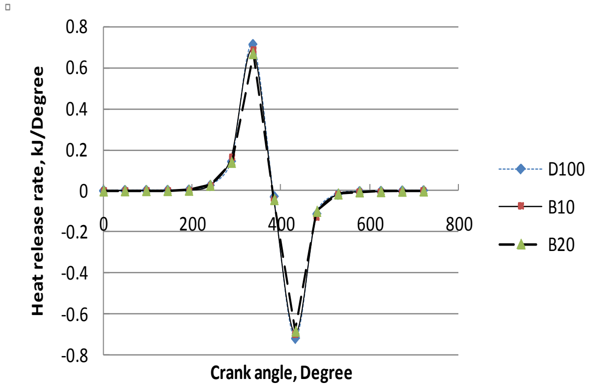


Fig.3: Comparison of heat release rate at full load for biodiesel blends with diesel oil.

B. Engine Performance Analysis

Various engine performance characteristics such as, BSFC, BTE, EGT, A/F and engine out emissions such as CO, UBHC, NOx and smoke opacity besides engine combustion characteristics were analyzed for all blends of biodiesel along with fuels with petroleum diesel at different engine loads.

Brake Specific Fuel Consumption (BSFC)

The effect of blending WCO biodiesel with diesel fuel on the estimated values of the specific fuel consumption at different engine loadings is illustrated in Fig.4. It is clear that brake specific fuel consumption decreased with increasing engine load and it was lower in case of all WCO biodiesel blends compared to regular diesel and exhibited similar profile under various loading conditions. At full load, brake specific fuel consumption of B10 and B20 was observed to be higher by 4.29% and 8.8% than neat diesel fuel operation, respectively. Brake specific fuel consumption (BSFC) increases as the percentage of biodiesel in blend increases. This is quite expected since the heating value of WCO biodiesel was lower than that of regular diesel oil. As a result, to produce the same power output, more amount of biodiesel is required [27].

Brake Thermal Efficiency (BTE)

Figure 4 represents the variation of brake thermal efficiency of the test fuels with respect to engine load. Brake thermal efficiency of all test fuels increased as the load increased. This could be explained as the load increases, suction pressure developed will be higher which might have resulted in efficient combustion [28]. At full load, the maximum attained BTE are 25.2% and 24.7% when running on WCO biodiesel blends of B10 and B20, respectively. However, the maximum BTE of pure diesel is 26.2%. The estimated brake thermal efficiencies using diesel- biodiesel blends as fuels for diesel engine were close to that of diesel fuel and gradually reduced with the increase of biodiesel in the fuel, which could be attributed to lower heating value, higher density and increased viscosity, which leads to poor atomization and fuel vaporization. Similar results were also reported in [29].

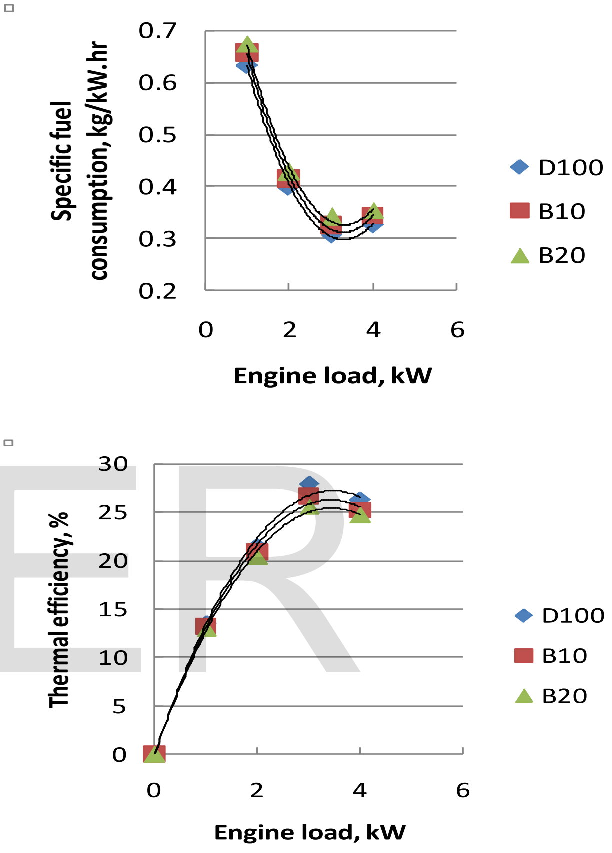


Fig.4: Variation of brake specific fuel consumption and brake thermal efficiency for biodiesel blends with brake power.

Exhaust Gas Temperature (EGT)

The variations in the temperature of the exhaust from the combustion of diesel, biodiesel and their blends at different engine loads are shown in Fig.5. Regarding the exhaust gas temperature; in general, there is an obvious increase with engine load due to the increase in the fuel consumption rate and slight increase with the addition of biodiesel percentage. At full engine load, the exhaust gas temperatures for biodiesel blends B10 and B20 were 275 and 290°C, respectively compared to 310°C in case of regular diesel fuel. Thus, there is a slight increase in the maximum exhaust gas temperature for WCO biodiesel blends compared to that of base fuel as WCO biodiesel blends contains constitutes of poor volatility, which burn only during the late combustion phase [30].

Air fuel ratio (A/F)

The changes in air-fuel ratios with engine load for diesel and WCO biodiesel blends are shown in Fig.5. Lower air to fuel ratio that means a mixture richer in the fuel is needed at higher engine loads. Air- fuel ratio decreased with the increase in load due to the increase in mass of fuel and the compensation of load with increasing the amount of fuel injected. It is observed that lower air to fuel ratio is also needed when using biodiesel as alternative to regular diesel fuel. Fuel consumptions were higher for biodiesel blends compared to diesel fuel hence air-fuel ratio decreased. Air- fuel mixing process was affected by the problems appear in atomization of biodiesel due to its higher viscosity. At full load, the maximum decrease in air- fuel ratio for B10 and B20 were about diesel fuel is 4.8 and 9.7%, respectively compared to diesel oil.

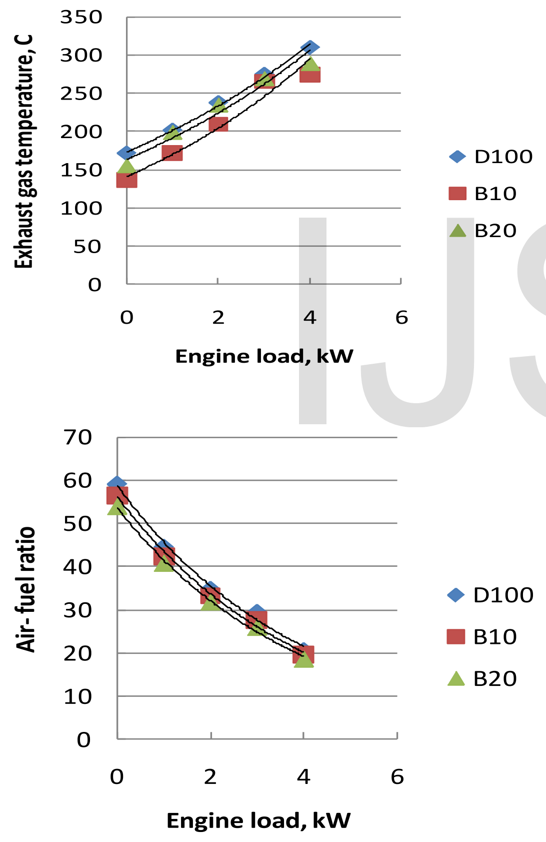


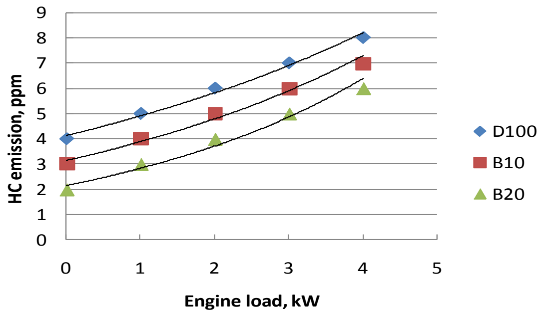
Fig.5: Variation of exhaust gas temperature and air fuel ratio for biodiesel blends with engine load.

C. Engine Emission Characteristics
Unburned Hydrocarbon Emission (UBH)

The predicted UHC amounts for different fuel blends with respect to engine load can be seen in Fig.6. The results demonstrated that UHC emissions decreased when the diesel engine was run with biodiesel blended diesel fuel compared to base fuel that can be clearly seen at full load and 1500 rpm. The maximum obtained concentrations of UBHC are 7, 6 and 8 ppm for B10, B20 and diesel fuel, respectively. Indicating that the maximum UBHC emission declines with the addition of biodiesel blends. The reduction rates were about an average in the order of 12.5 and 25%, respectively for B10 and B20 compared to diesel oil. The reduced UBHC emissions with biodiesel-blended diesel can be accounted for the presence of peroxides due to the biodiesel oxidation process may result in lower UHC emissions [31].

Carbon Monoxide Emissions (CO)

Figure 6 shows the changes in CO emissions for different fuel blends. The fuels have similar trends for the CO formation at the selected engine load range. However, CO emission decreases with the increase of biodiesel percentage in the fuel blend. Experimental results reveal that CO concentration of biodiesel blends is 7.5 and 13% lesser for WCO biodiesel blends B10 and B20, respectively compared to diesel fuels operation. This is due to the additional oxygen content in the biodiesel that allows more carbon molecules to oxidize when compared with diesel oil and the increased biodiesel cetane number. The higher the cetane number, the lower the probability of fuel- rich zones formation usually related to CO emissions. The higher cetane number, which means shorter ignition delay, causes longer combustion duration and increases complete combustion reaction regions. The results for CO emissions are in-line with most of the literature [32–34].



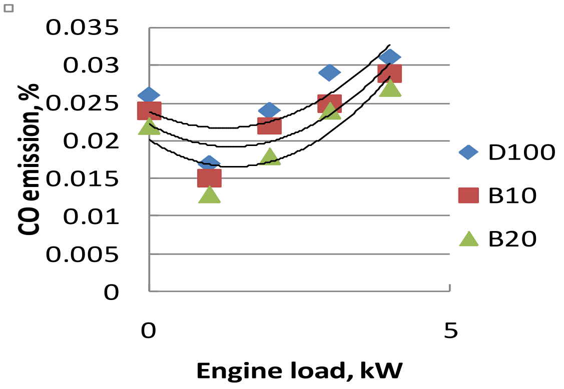


Fig.6: Variation of unburned hydrocarbon emissions and carbon monoxide for biodiesel blends with engine load

Oxides of Nitrogen Emissions (NO$_X$)

Oxides of nitrogen (NOx) are another important emission product for the engines that must be controlled. The variation of oxides of nitrogen (NOx) concentration with load for biodiesel blends and diesel fuel are shown in Fig.7. The formation of NOx in the engine cylinder is affected by oxygen content, combustion flame temperature and reaction time. As seen from the figure that all the fuel blends produced higher NOx emissions relative to diesel fuel for all engine loads as expected. NOx emissions increased with the increasing fraction of biodiesel in the fuel blend. The percentage increase of NOx emissions with B10 and B20 are 2.4 and 8.2% when compared with conventional diesel fuel at full load operating conditions. It is obvious that the higher NOx formations are a result of double bonded molecules that biodiesel typically contains more than petroleum-derived diesel. These double bonded molecules have a slightly higher adiabatic flame temperature, which leads to the increase in NOx production for biodiesel [29]. In addition, the higher oxygen concentration in the biodiesel spray increases the oxidation at high engine loads that were indicated by a reduction of UHC and CO emissions, resulting in increased NOx emissions [35].

Smoke Opacity

Smoke was formed due to incomplete combustion. The smoke opacity for different blends of fuel and that of conventional diesel at different load was reported in Fig.7. It was observed that smoke opacity is low at low and medium engine loads but increases obviously at high engine load for all operations of diesel and WCO biodiesel blends. The predicted results showed that WCO biodiesel blends produced lower smoke opacities at the entire load range. The smoke level in the exhaust decreases with the increasing amount of biodiesel in the fuel blend, especially, at higher engine loads. The difference is particularly obvious at higher engine loads but there is no significant change at lower engine loads. The lower smoke opacity in biodiesel and its blends explained more complete combustion due to higher cetane index and oxygen content [36]. According to Canakci et al., [37] since the smoke is highly dependent on oxygen and sulfur content of the fuel, no wonder that smoke opacity was found to be lower when diesel was blended with biodiesel. Lower smoke opacities of all WCO biodiesel blends is perhaps due to the absence of aromatic compounds in vegetable oils which are known to contribute to soot formation. Also, the presence of oxygen in the chemical composition of vegetable oils was known to enhance combustion and thus contributed to lower soot formation. At the same time, the oxygen in the fuel can assist in reducing smoke formation during the stage of diffusion combustion. The improvement is more obvious at high engine loads when larger percentage of fuel is burned in the diffusion mode [38]. The percentage decrease of smoke emissions with B10 and B20 are 15 and 22 % when compared with conventional diesel fuel at full load operating conditions. HC emission and smoke opacity profile obtained in this test were good in agreement with experimental results of most of the researchers [39, 40 and 41].

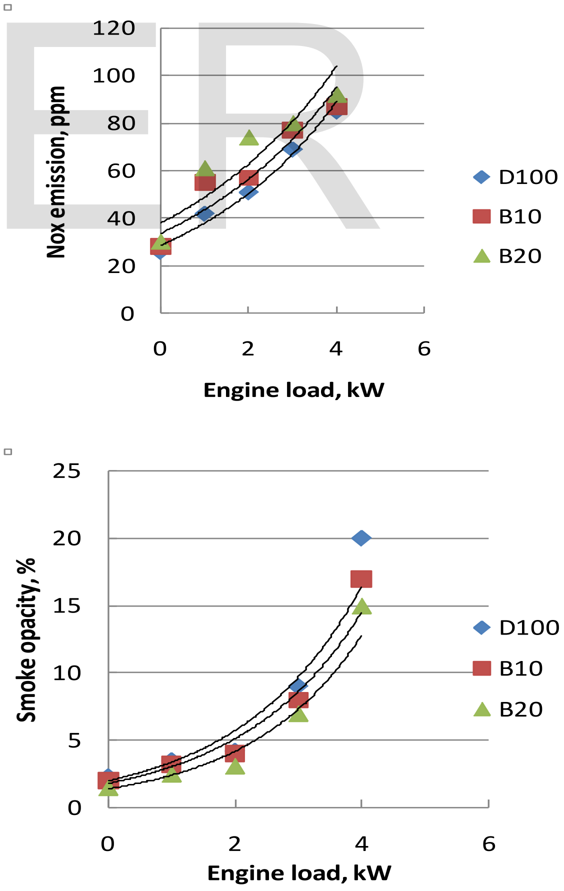


Fig.7: Variation of NOx emissions and smoke opacity for biodiesel blends with engine load.

5.CONCLUSION

In the present investigation, performance, emission and combustion characteristics based on the experimental results obtained while operating single cylinder diesel engine fueled with biodiesel from waste cooking oil methyl esters and their blends have been discussed and compared with diesel fuel. Results of the present work are summarized as follows:

A. Properties of biodiesel from waste cooking oil are comparable with diesel fuel and properties of different blends of biodiesel are very close to diesel oil.
B. Brake specific fuel consumption (BSFC) for biodiesel from waste fried oil is higher because of lower heating values. The BSFC increases with blending proportion for waste cooking oil biodiesel.
C. The brake thermal efficiency of diesel engines tested was reduced when substituting diesel by WCO biodiesel blended diesel fuel. At full load the brake thermal efficiency of B10, and B20 decreased by 3.8 and 9.5% respectively as compared to diesel fuel.
D. It is also observed that there is significant reduction in CO, UBHC and smoke emissions for WCO biodiesel blends compared to diesel fuel. However, NOx emission of WCO biodiesel blended diesel fuel is marginally higher than petroleum diesel. On an average, smoke emission for B10 and B20 decreases by 15 and 22 %, respectively. HC emission reduced by 12.5 and 25%, respectively. CO emission reduced by 7.5 and 13% and NOx emission increased by 2.4 and 8.2% compared to pure diesel fuel.
E. The obtained results are consistent with their counterparts in the literature. It can be stated that waste cooking oil can be used as a suitable feed stock for production of biodiesel fuel that can be successfully used as an alternative fuel for diesel engines.

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