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Experimental Study on Performance and Emissions of Turbojet Engine Fueled by Alternative Biodiesel

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Abstract

The effect of two different kinds of biodiesel on performance characteristics and emissions of turbojet engine is investigated experimentally and compared with the engine recommended fuel (JetA-1) in this work. Two different kinds of biodiesel that are Cotton Methyl Ester (CTME) and Corn Methyl Ester (CRME) and their blends of 10%, 20% and 50% biodiesel/JetA1 by volume are produced, characterized and investigated experimentally in this study. The turbojet engine used in this work is fully equipped with pressure, flow, temperature, thrust and speed sensors in addition to data acquisition system and control unit. Exhaust gas analyzer is used at turbojet engine exit to measure the exhaust gases composition that are O₂, CO, CO₂, HC, NO_x, and SO₂. The performance characteristics of the engine are identified by engine speed, static thrust, thrust-specific fuel consumption (TSFC) and thermal efficiency. The results show that biodiesel fuels have a higher density, kinematic viscosity, flash point and pour point than JetA-1 fuel, while, their calorific value, carbon and hydrogen contents is close to JetA-1 fuel. Moreover, the results show that the performance parameters for biodiesel are close to those for JetA-1. The static thrust for JetA-1 and all tested biodiesel fuel are very close while the TSFC for biodiesel fuel blends is lower than JetA-1. As expected the engine efficiency of biodiesel was higher than Jet A-1 because of the oxygen content on biodiesel chemical composition which leads to a leaner and more complete combustion. JetA-1 fuel has higher combustor exit temperature and exhaust gas temperature compared with biodiesel fuel blends. Biodiesel fuels and its blends have higher O₂ concentration in the exhaust compared

with JetA-1 fuel while JetA-1 has a higher CO and HC concentration compared with other biodiesel fuels. Biodiesel fuels have higher CO₂ and NO_x emissions and a lower SO₂ compared to JetA-1. Biodiesel is more environmental friendly than JetA-1 fuel.

1. Introduction

Biodiesel is a renewable fuel source, comprised of mono-alkyl methyl esters of long chain fatty acids derived from vegetable oils and considered as nontoxic, biodegradable fuel, and reduces serious air pollutants. Blending biodiesel with petrol and fossil fuels makes it possible to be used directly in the combustion engines without any engine modifications and reduces the emissions of CO, HC and SO₂ that exhausted from the engine. However, as the biodiesel blend amount increases those gases emissions decreases. Testing the effect of biodiesel fuels on diesel engine performance and emissions has been widely covered by many researchers unlike the performance of the gas turbine engines fueled by biodiesel fuels. Habib et Al. [1] studied the performance and emission of a 30 kW gas turbine engine using Jet A of 100% (B100) and 50% (B50) blends of Soy Methyl Ester (SME), Canola Methyl Ester (CME) and Recycled Rapeseed Methyl Ester (RRME). They reported that the CO₂ emissions values for the B50 for all biodiesel fuels didn't change significantly from Jet A correspondence value. However, the CO₂ concentration in the exhaust for pure biofuels (B100) was slightly higher than that for Jet A and this may returns to that the equivalence ratios for biofuels were lower than Jet A, while the equivalence ratio " Φ " is defined as the ratio between actual air to fuel ratio to the stoichiometric air to fuel ratio and it defines the deviation of the mixture from stoichiometric conditions as following: $\Phi < 1$ for lean condition and as the value of Φ become smaller than 1 the combustion process become leaner, while $\Phi = 1$ for stoichiometric condition, however $\Phi > 1$ for rich condition. Therefore, a leaner combustion achieved and resulting in higher CO₂ concentration in the exhaust and consequently lower CO emissions for all biofuels. Also, B50 for all tested biodiesel fuels produced lower CO thrust specific emission index than the B100 blends, while the thrust specific emission index is defined as the mass of pollutant emitted per unit time per unit thrust generated. Moreover, Habib et Al. [1] cited that NO emissions form Jet A fuel was higher than NO emissions for all biofuels blends fuels, in addition, NO formation was not dominated by the thermal mechanism as the turbine inlet temperatures were comparable for all fuels. Also, they added that the B50 of different biofuels produced lower NO per unit thrust than biofuels of B100. Nascimento et al. [2] investigated the performance and emissions of a 30kW diesel micro-turbine engine at full and partial loads for steady state operating conditions.

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They used different blends (B5-B100) of castor biodiesel. They cited that the NO_x emissions for pure biodiesel were lower than the emissions for diesel fuel and as known NO_x emissions have three formation mechanisms: thermal NO_x , Prompt NO_x and Fuel NO_x . Thermal NO_x formed due to high temperature oxidation of the atmospheric nitrogen atom founded in the combustion air, while, prompt NO_x formed by the reaction of atmospheric nitrogen with radicals such as HC that derived from the fuel and the Fuel NO_x is generated mainly by oxidation of the nitrogen atom founded in the chemical composition of the fuel and as there is no nitrogen atoms founded in the fuel chemical composition so the generated NO_x emissions are from thermal and prompt mechanisms. Also, they cited that, no SO_2 emissions for the case of biodiesel fuel were found in the engine exhaust gases as the biodiesel fuels have no sulfur in their composition. For CO emissions, Nascimento et al. [2] pointed that CO for pure biodiesel was higher than the emissions for conventional diesel and this due to the poor atomization and evaporation characteristics of biodiesel fuels. For the same injection system and different fuels with different viscosities, as the viscosity of the fuel become higher the efficiency of the atomization process of the fuel become lower and the size of fuel droplets become larger in the fuel spray and consequently the air and fuel mixing process become harder and a rich mixture is formed and consequently a rich combustion process happened which is the main reason for CO and HC formation. Due to that castor biodiesel presents higher viscosity than diesel and there were no modifications with engine fuel injection, the size of the droplets and the primary-zone equivalence ratio must be different for biodiesel and diesel. Rehman et al. [3] used Jatropha oil blended with diesel fuel in a gas turbine engine used for power generation. They indicated that CO emissions for different blends of biodiesel were lower than diesel. The cited that this is due to higher oxygen content of jatropha oil which improves combustion process, therefore, CO emissions for B25 are lower than that of B15 due to more oxygen content in B25 than in B15. Moreover, HC emissions for the case of B15 and B25 are lower when compared with the case of diesel fuel due to higher fuel oxygen content of biodiesel. Also, the HC emissions for the case of B25 are lower than that for B15 again and this is due reason related to the percent of oxygen in fuel. In their study, NO_x emissions (thermal NO_x and prompt NO_x) for B15 and B25 were higher than that obtained with diesel fuel. This is due to that the cetane number for the biodiesel is higher than diesel fuel and the NO_x emission for B25 is higher than that of B15 which can again be attributed to the same reasons combined with higher cycle temperature achieved during the combustion process. Lee et al. [4] simulated a combustor of 60KW industrial gas turbine and compared the combustion performance of DME (dimethyl ether) with

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methane in terms of NO_x emissions, CO emissions and the combustion chamber outlet temperature. They reported that, low NO_x and CO emissions were found during the test of DME. Also, low flue gas temperature at the combustion chamber outlet was found of DME combustion, therefore reduces the thermal failure of turbine blades. Krishna [5] tested biodiesel blends as a fuel in unmodified 30kW power generation micro gas turbine. Through his experiment, the biodiesel was added to the blend to reduce the sulfur contents of the fuel, consequentially the emission of sulfur dioxide. For CO and NO_x emissions, Krishna [5] reported that the CO emission for biodiesel was lower than the case of diesel fuel and the NO_x level was lower with the increase of biodiesel in the blend and it is lowest value with pure biodiesel of B100. Purssi et al. [6] measured the emissions concentration of different blends of biodiesel fuels at different injection temperature on micro gas turbine engine. They cited that, the higher the injection temperature, the lower the CO and NO_x concentration in the exhaust stream. Also, the CO emissions for vegetable oil at nominal condition were almost same for the case diesel fuel. While at higher load CO emissions for SVO were higher than the case of diesel fuel. Moreover, they reported that higher NO_x emissions were observed for SVO than for the case of diesel fuel and this may be due to existence of a small amount of nitrogen in the vegetable oil leading to the possibility of fuel NO_x formation. Nascimento et al. [7] investigated 30KW diesel micro gas turbine engine using palm biodiesel, castor biodiesel and soybean biodiesel fuels. They reported that palm and castor Biodiesel fuels produced larger CO emissions than for the case of diesel fuel with quantitative values of 4 and 3 mg/(kW.hr) respectively at full load. This unlike the soybean biodiesel fuel case which produced CO emissions with value lower than 2 mg/(kW.hr). For NO_x emissions, they reported that the NO_x reduction was about 26.60% for castor biodiesel, 12.66% for soybean biodiesel and 22.78% for palm Biodiesel compared to diesel fuel for the case of the engine operated at the full load and there was no significant reduction at partial or medium engine loads. Allouis et al. [8] measured the ultrafine particles at the exhaust of a power generation micro gas turbine fueled by liquid fuels including diesel fuel, a mixture of the diesel fuel with a biodiesel and kerosene. They reported that an increase of the turbine load combined with addition of 50% of biodiesel lead to do no changes in the size of the ultrafine particles in the exhaust, however, it leads to decrease of the amount of formed particles while for the case of kerosene it produces larger amount of ultrafine particles in exhaust. Throughout their study the particle sizes were measured with the diesel fuel and compared with the results on a diesel engine operated at the same conditions and using the same fuel and producing the same power, diesel engines emits larger amounts of ultra-fine particles compared to the gas turbine engine and the

emitted particles have the same size of the particles produced by the gas turbine. Nascimento and Santos [9] presented overview for experiments done by seven researchers during eleven years from 1995 to 2006. Those researchers utilized biodiesel to drive gas turbine engines mostly used for power generation. Throughout their studies, they used castor biodiesel, biogas, rapeseed biodiesel, soybean biodiesel, sunflower biodiesel and animal fats. They concluded that using castor biodiesel fuels and preheat it to 40 °C leads to reduction in emissions of CO and NO_x in the exhaust gases compared with conventional diesel, in addition to CO₂ emissions were reduced for the case when the engine was fueled by biodiesel. Moreover, biodiesel fuels didn't show a noticeable increase in emissions of particulate matter compared to the jet fuel. However, sometimes an increase of CO content in the exhaust gases with the increase in the percentage of biodiesel in the blend and that was due to the reduction in combustion efficiency. They cited that burning biodiesel from rapeseed, sunflower and animal fats showed a significant increase in emissions of CO and CO₂ at full load and reduction in NO_x emissions.

Through the literature review, clearly the performance and emission of gas turbine engines operated with biodiesel were widely covered; however, most of the tested gas turbine engines in the literature are industrial type that used for power generation. While, there are limited research work in the literature investigating both the performance and emission of a turbojet engines used for aviation and military applications when its fueled with biodiesel. Moreover, there are still some types of biodiesel fuels such as corn and cotton biodiesel have not been investigated for performance and emissions of turbojet engines.

Therefore, this study aims to investigate experimentally the performance and emissions of turbojet engine when fueled by two different types of biodiesel fuels named Cotton Methyl Ester (CTME) and Corn Methyl Ester (CRME) and their blends of B10, B20 and B50 with JetA-1 fuel compared with JetA-1 fuel at different throttle valve position of 10%, 30%, 50%, 70% and 90% of the full open respectively.

2. Biodiesel Production and Characterization

In this study, biodiesel fuels are produced through a chemical process called transesterification. The aim from the production process is to reduce the high viscosity of the used oils. Through transesterification process the large branched triglyceride molecules of vegetable oils and fats transformed into smaller straight long chain molecules which are almost similar in size to the molecules of the species present in diesel fuel and glycerin. At first, the oil should be warmed up to 40°C and filtered to remove solid particles. The second step is to prepare the catalyst which is

sodium methoxide by adding 5.5 (g/l oil) of NaOH to 250 (ml/l oil) of methanol and mixing them together until the NaOH is completely dissolved in the solution. After that, the oil should be heated up to 110-120°C and then the oil should be removed away from the heater and adding sodium methoxides as drops and mix it strongly for 15-20 min with a good mixing device. After 2-5 hr., the biodiesel is float on top of the mixture, while, the denser glycerin is congealed on the bottom of the container, the biodiesel can be separated easily by draining it out of the container. Then, wash the biodiesel for 2 or 3 times with water to ensure removal of any glycerin and soap. After washing biodiesel, the last step is to remove residual water in the biodiesel by heating the washed biodiesel up to 100°C to ensure the complete removal of the residual water from washed biodiesel. The produced biodiesel fuels are characterized according to ASTM D6751, ASTM D97 and ASTM D240 standards as shown in Table 1. It is clear from Table 1 that biodiesel fuels have a higher density, kinematic viscosity, flash point and pour point than JetA-1 fuel, while, their calorific value, carbon and hydrogen contents is very close to JetA-1 fuel. However, the JetA-1 fuel has higher sulfur content than other biodiesel fuels. Blending biodiesel with JetA-1 can be a suggestion to overcome the problem of the higher viscosity of the pure biodiesel fuels.

Table 1. Physical and Chemical Properties of Pure Biodiesel Fuels and Jet A-1

Properties	Test Code	JetA-1	CTME B100	CRME B100
Density at 15.5°C	ASTM D-1298	0.797	0.8938	0.8924
Kinematic Viscosity, cSt, at 40°C	ASTM D-445	1.08	7.34	6.92
Pour Point °C	ASTM D-97	-43	-3	-12
Flash Point °C	ASTM D-93	39	175	173
Sulfur Content, ppm	ASTM D-4294	50.3	15.2	10.2
Higher Calorific Value (kJ/kg)	ASTM D-240	46329	44649	44914
Lower Calorific Value (KJ/kg)	ASTM D-240	43465	42189	42376
Hydrogen Content (%mass)		13.48	11.58	11.6
Carbon content (% mass)		86.51	88.42	88.4

3. Experimental Setup

A turbojet engine test facility that fully equipped with the required measuring sensors is used in this study to investigate the performance and emissions of different types of biodiesel fuels. The test facility contains turbojet engine which generates up to 230 N of thrust and equipped with pressure, flow, temperature, thrust and speed sensors in addition to data

acquisition system and control unit (ECU). The exhaust gases are passed after engine exit through water cooled sampling probe that is fixed at the engine nozzle exit. The probe catches the cooled exhaust sample that transferred to exhaust gas analyzer by a long hose. The basic turbojet engine specifications are given in Table 2. The fuel throttle valve is controlled using ECU unit and consequently control the engine speed. A 4.5% of lubricating oil is added to fuel tank and mixed with the used fuel as there is no separate oil tank, also, the engine is supplied with two fuel filters one is placed inside the fuel tank at the start of the suction line and the other is placed before the fuel pump. Propane canister is used in the engine start up in order to make engines reaches its operating temperature rapidly.

Table 2: Olympus E-start HP gas turbine main data

Engine Type	Turbojet – Single spool
Engine Name	Olympus E-start HP gas turbine
Diameter	131 mm
Length	384 mm
Turbine weight	2850 g
Compressor	Single stage radial compressor
Combustion Chamber	Annular combustion chamber
Turbine	Single stage axial flow turbine.
Pressure ratio at max. rpm	3.8 :1
Maximum RPM	108,500 rpm
Thrust at max. RPM	230 N
Thrust at min. RPM	13 N
Mass flow at max. rpm	450 g/sec
Fuel consumption at max. rpm	640 g/min
Normal EGT	700 °C
Max. EGT	750 °C
Fuel Type	Liquid fuel (Kerosene or JetA-1)

The engine is equipped with five k-type thermocouples and pressure sensors to measure temperature and pressure at the compressor inlet, compressor exit, turbine inlet, turbine exit and thrust nozzle exit. Also, the engine is equipped with turbine flow meter, thrust cell and shaft speed sensor to measure fuel flow rate, static thrust and engine rotational speed respectively. The detailed sensors specifications are shown in Table 3. The schematic diagram shown at figure 1 indicates the layout of the connection between engine, sensors, control unit and user pc. Sensors and equipment allow to measure and calculate static thrust, thrust-specific fuel consumption (TSFC), engine efficiency, exhausts gas speed and intake air speed. A fuel

manifold is added to the gas turbine fuel delivery system to allow the engine to start on Jet A-1, switch to the test fuel for the experiment, and then end experiments with Jet A-1 to purge the biofuel from the system and this prevent the damage of the fuel delivery system.

Table 3: The engine quipped Sensors and their specifications

Sensor Type	Specification
Temperature sensors	K-Type thermocouples
Pressure sensors	0-15 psi Honeywell manufacture
Fuel Flow meter	0.1 to 2.5 l/min turbine flow meter and measures up to 15 CST viscosity fluids
Speed sensor (rpm)	0-130,000 rpm Armfield shaft speed sensor
Thrust (force) sensor	0-20 kg thrust cell

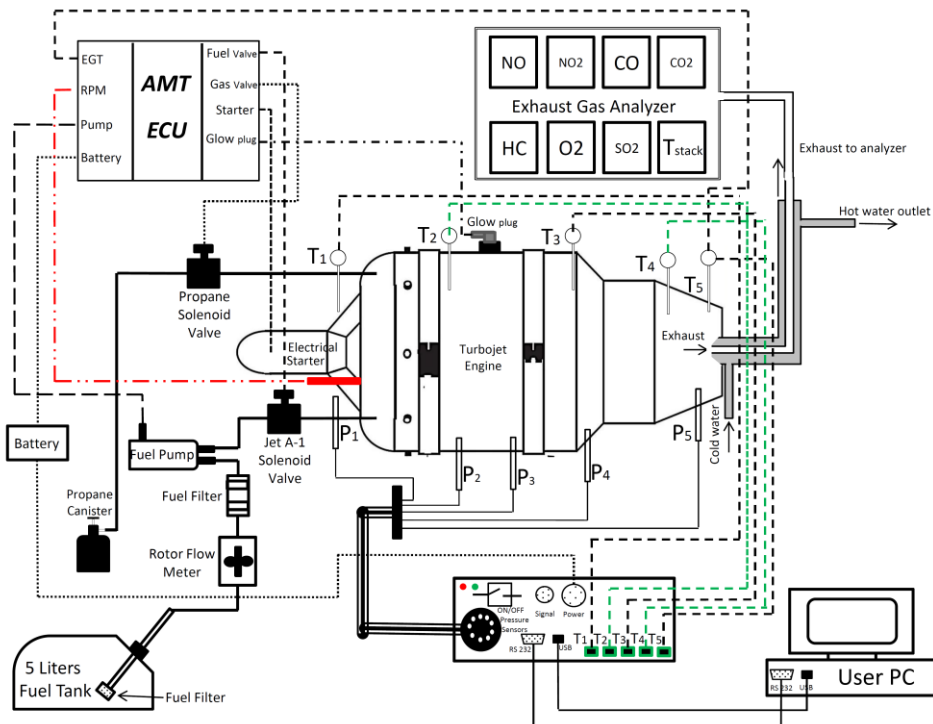


Figure 1. Turbojet Engine schematic diagram with measuring sensors.

The E-Instrument industrial combustion and emissions analyzer E8500 is used to measure the exhaust concentrations of O₂, CO, NO, NO₂, C_xH_y and CO₂. A fabricated water cooled probe is fixed to the outlet of nozzle of the engine to enable the sudden cooling of the exhaust sample for emissions measurements. The gas samples were pretreated to remove particulate and moisture before deliver into the analyzers. The Exhaust gas analyzer specifications are provided in Table 4.

Table 4: The measuring ranges of E-Instrument Industrial Combustion and Emissions Analyzer E8500

Emission	Sensor Type	Range	Least Count
CO ₂	NDIR	0 - 20 %	0.1 %
CO (Low range)	Electrochemical	0 - 8000 ppm	1 ppm
CO (High range)	NDIR	0 - 15 %	0.01 %
O ₂	Electrochemical	0 - 25 %	0.1 %
C _x H _y	NDIR	0 - 3 %	0.01%
NO	Electrochemical	0 - 4000 ppm	1 ppm
NO ₂	Electrochemical	0 - 1000 ppm	1 ppm
SO ₂	Electrochemical	0 - 4000 ppm	1 ppm

4. Presentation Parameters

4.1 Engine Efficiency

The engine efficiency represents the energy conversion within the turbojet engine itself and sometimes is called as internal energy. The efficiency for the turbojet engine is defined as the ratio between the power imparted to engine airflow and the rate of energy supplied in the fuel. Also, it defines how efficiently the chemical energy stored in the fuel is converted to kinetic energy of the exhaust gases and accounts for both combustion efficiency and thermodynamic cycle efficiency [1]. The efficiency is calculated as follows:

$$\eta = \frac{\text{Power imparted to engine airflow}}{\text{Rate of energy supplied in the fuel}}$$

$$\eta = \frac{\text{Thrust power} + \text{Kinetic energy imparted to engine airflow}}{\text{Rate of energy supplied in the fuel}}$$

$$\eta = \frac{Tu + \frac{1}{2}\dot{m}_a[(1+f)(u_e - u)]^2}{\dot{m}_f \cdot CV} \quad (1)$$

Where T is the thrust and it is measured using the load cell, u is the air inlet velocity and it can be calculated from the air mass flow rate and cross section area of the inlet duct, u_e is the exhaust velocity and it calculated from the exhaust mass flow rate and cross section area of the nozzle, m_f is the fuel mass flow rate and its measured by a rotor flow meter, f is the fuel to air ratio is calculated from mass flow rate of the fuel and mass flow rate of the air, also, CV is the fuel calorific value and it measured according to ASTM D-240.

4.2 Exhaust Emissions

Equivalence ratio " Φ " is defined as the ratio between the actual air to fuel ratio to the stoichiometric air to fuel ratio and it is used to define the deviation of the mixture from stoichiometric conditions and given by:

$$\Phi = \frac{A/F)_{actual}}{A/F)_{stoichiometric}} \quad (2)$$

5. Results and Discussion

The turbojet engine performance and emissions when fueled by CTME and CRME biodiesel fuels and their blends of B10, B20 and B50 with JetA-1 fuel are characterized at different engine throttle valve position of 10%, 30%, 50%, 70% and 90% and compared with the case of 100% JetA-1 and the results as shown through figures (2-13) respectively. In the following results discussion, the throttle valve position of 50% is taken as the normal operating condition for the turbojet engine. Therefore, the performance parameters and emissions for different fuels are compared at 50% throttle valve position. Moreover, the effect of increasing biodiesel percentage in the blend on the engine performance and emissions of the engine has been discussed through the following sections.

5.1 Engine Performance

5.1.1 Effect of Biodiesel Fuel Blends on Engine Static Thrust

The measured engine static thrust as a function of the fuel mass flow rate is shown in figure 2. Clearly from the figure, it can be seen that as the fuel mass flow rate increased the engine rotational speed increases, consequently both the rate of intake air and exhaust gases are increased too which resulted in higher static thrust value. For the presented results in the figure, the fuel mass flow rate is ranged from 9.06 kg/hr to 41.41 kg/hr and the correspondence engine static thrust is ranged from 24.02N to 194N, respectively. For the throttle valve position of 50%, which represent the normal operating conditions of the turbojet engine, the engine static thrust is ranged from the lowest value 123.17N for CRME B50 to the highest value of 139.18N that recorded for JetA-1 fuel. Therefore, the maximum deviation in the engine thrust value for CRME B50 from that of JetA-1 value is lower by about 11.5%. While, increasing the biodiesel fuel percentage in the blend have no significant effect on the engine static thrust. However, based on the fact that the biodiesel fuels has higher viscosity, therefore, a the percent of biodiesel fuel increase in the blend leads to decrease the fuel mass flow rate followed by the decrease in both engine rotational speed ant the static thrust. Therefore, for all runs the JetA-1 fuel has the highest static thrust at most of throttle valve positions and static thrust decreases by increasing the blend ratios. From these results it can be concluded that the static thrust value for

biodiesel fuel is not lower than 11.5% as well as and not higher than 1.62% compared with standard engine JetA-1 fuel. Moreover, at throttle valve position of 50%, the biodiesel fuels CTME blends have higher static thrust compared to CRME fuel blends.

5.1.2 Effect of Biodiesel Fuel Blends on Engine Speed

The effect of different blends of biodiesel fuel on engine rotational speed as a function of the fuel mass flow rate is shown in figure 3. As can be seen from the figure, in general the engine speed is a direct function of fuel mass flow rate, from the figure as the fuel mass flow rate changed from 9.06 kg/hr to 41.41 kg/hr the engine speed is increased from 46072.5 rpm to 103066 rpm. Comparing different blends of biodiesel fuels with JetA-1 fuel at throttle valve position of 50%, the highest engine speed is recorded for JetA-1 with a value of 90931.64 rpm while the lowest engine speed is recorded for CRME B10 with a value 86214.33 rpm which is about 5.18% lower than the JetA-1 fuel case. In basic, the engine speed is a function of fuel mass flow rate, at throttle position of 50% the JetA-1 has the highest value of the fuel mass flow rate of 26.74 kg/hr while CTME B50 and CRME B50 achieve the lowest fuel mass flow rate with a values of 24.27 kg/hr and 24.12 kg/hr respectively, that are lower than JetA-1 by about 9.45%. This was explained in the previous section due to higher biodiesel fuels viscosity. Since biodiesel fuels have higher viscosity compared to JetA-1, the engine fuel gear pump outlet pressure is decreased when operated with biodiesel fuels and that leads to decrease in fuel mass flow rate. When the fuel mass flow rate decrease, the energy input to the engine decrease and engine output power decrease and leads to decrease in engine speed by 5.18% compared with JetA-1. Generally, the highest engine rotational speeds is counted for JetA-1 fuel at any operating condition. Comparing biodiesel fuels with JetA-1, the engines speed for biodiesel fuel is changing from -6.5% to 1.78%. However, it can be concluded the turbojet engine speed is slightly affected inversely when fueled with CTME and CRME biofuels and their blends due to their higher viscosity.

5.1.3 Effect of Biodiesel Fuel Blends on Thrust Specific Fuel Consumption (TSFC)

The engine thrust specific fuel consumption (TSFC) defines the mass of fuel required to provide the net thrust for a given period of time in addition to it defines the fuel consumption efficiency within the turbojet engine. Figure 4 shows the fuel TSFC as a function of fuel mass flow rate (different throttle valve positions) for different biodiesel fuels blends. Comparing biodiesel blends results with JetA-1 at throttle position of 50%, the highest TSFC is recorded for CTME B20 with value of 0.2 kg/N.hr

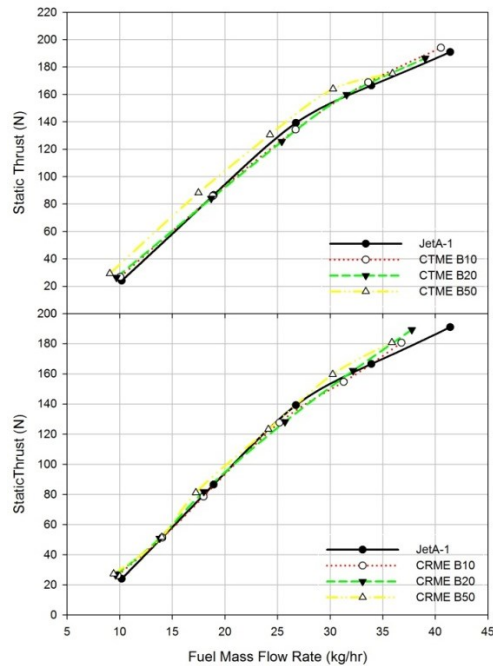


Figure 2. Effect of biodiesel fuels blend on engine static thrust at different fuel mass flow rate
(a) CTME (b) CRME

while the lowest value is recorded for CTME B50 with value of 0.18 kg/N.hr with changes by ratios ranged from -3.22% to 5.25% compared with JetA-1. However, the lower value of TSFC for biodiesel fuels and blends compared with the case of JetA-1 for experiment runs shown in figure 4 are in agreement with similar results presented in Habib et al. [4]. Also it can be seen from figure 4 that, as the blend of biofuel increases the value of TSFC is decreases. This due to that the viscosity and density of the fuel are increase with the increase of blend of the biofuel (see table 1). Therefore, it can be concluded that the decrease in the value of TSFC is attributed to the increase in both fuel viscosity and density. On the contrary, it was expected that the TSFC of biofuels will be higher than that of JetA-1 fuel as the calorific value of biofuels is lower than JetA-1 (see table 1). Based on the fact that for same power as the calorific value of the fuel decreases, the fuel consumption will increase. However, the obtained result reveals that the fuel consumption of biofuels is lower than that of JetA-1 which means that the effect of fuel both density and viscosity of fuels overcomes the effect of the calorific value and leads to increase in fuel consumption.

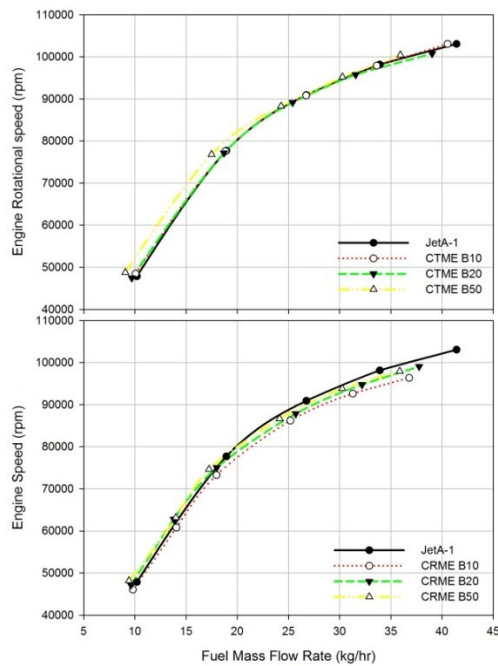


Figure 3. Effect of biodiesel fuels blend on engine speed at different fuel mass flow rate (a) CTME (b) CRME

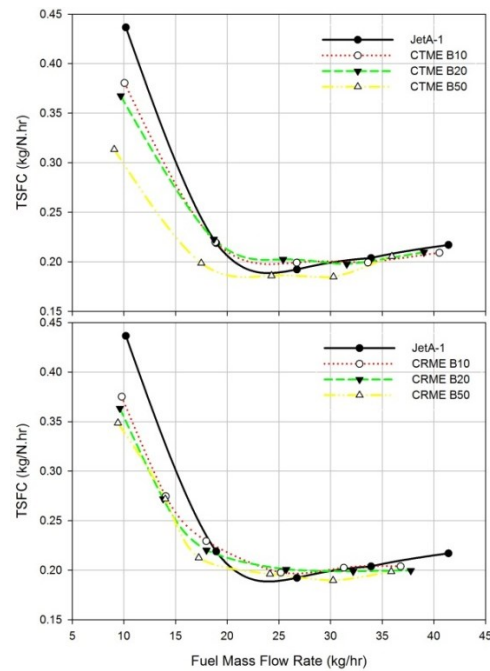


Figure 4. Effect of biodiesel fuels blend on engine TSFC at different fuel mass flow rates (a) CTME (b) CRME

5.1.4 Effect of Biodiesel Fuel Blends on Engine Efficiency

The effect of different biodiesel blends on engine efficiency at different fuel mass flow rates compared with JetA-1 fuel is shown in figure 5. Engine efficiency is calculated for different blends by eq. (1) for CTME and CRME with B10, B20 and B50 respectively.

As shown in figure 5, the efficiency increases from 1.43% to 8.65% while the fuel mass flow rate increased from 9.06 kg/hr to 41.41 kg/hr. As the fuel mass flow rate increased the engine rotational speed increased and consequently the air suction rate (air mass flow rate) increases. In quantitative values at the throttle valve opening of 50% of full open, the engine efficiency is ranged from 6.98% for CRME B20 to 7.7% for CTME B50 and comparing this results with the values of efficiency when using JetA-1 fuel the variation in the efficiency is ranged of -4.25% to 5.62% compared with JetA-1 fuel value. From the presented results, the highest engine efficiency value is obtained for CTME of B50 and it is higher than the JetA-1 by about 13.74%. In general, the efficiency of biodiesel is higher than JetA-1 in most of the turbojet engine operating conditions. It can be concluded that the engine efficiency increases with the increase of the biofuel percent in the blend. Increasing in engine efficiency with biofuels is attributed to the presence of oxygen molecule in biodiesel composition

which leads to leaner combustion process and consequently closes to complete combustion process.

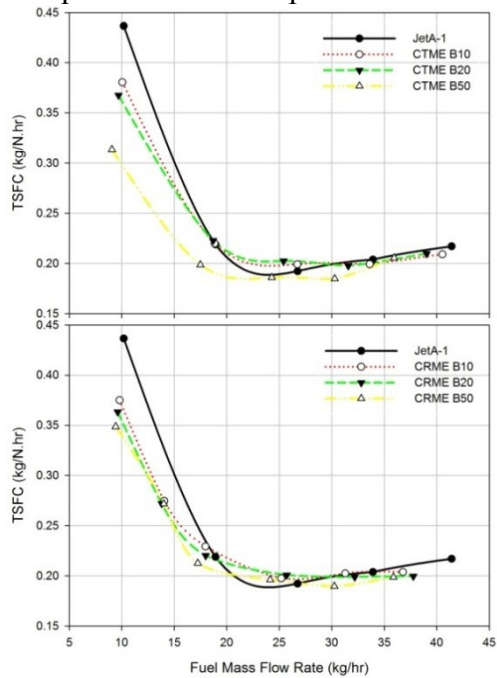


Figure 4. Effect of biodiesel fuels blend on engine TSFC at different fuel mass flow rates (a) CTME (b) CRME

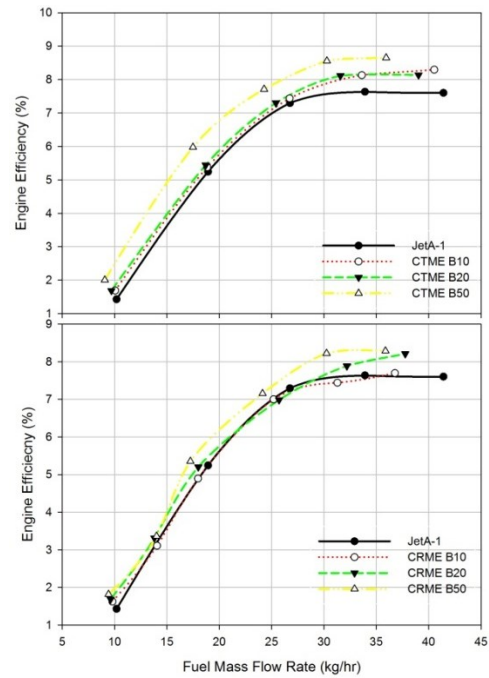


Figure 5. Effect of biodiesel fuels blend on engine efficiency at different fuel mass flow rate (a) CTME (b) CRME

5.1.5 Effect of Biodiesel Fuel Blends on Combustor Exit Temperature and Exhaust Gas Temperature

The temperature at the combustor exit (T_3 in Figure 1) is shown in figure 6 as a function of fuel mass flow rate for Jet-A1 and CTME and CRME and there blends of B10, B20 and B50 fuels. As shown at the experimental setup section, the combustor exit temperature (CET) is measured after the stage of combustor and before the turbine stage (in some literatures it called as turbine inlet temperature (TIT)). The values of CET were ranged from 638.9 K to 976.9 K, as the fuel mass flow rate changed from 9.06 kg/hr to 41.41 kg/hr respectively. At the throttle valve setting of 10% and 30% the CET values are decreased until it reaches the minimum at throttle valve opening of 30%, then it start to increase again with the increase of throttle valve opening. The results in quantitative values are given at the throttle valve opening of 50% of full opening, the CET values are varied from 672.41 K to 820.56 K while the value of 672.41 K is counted for CRME B10 which is lower than the value of JetA-1 with about 18.05% and the highest value of CET at 50% throttle valve position which is 820.56 K is achieved by JetA-. It is clear from figure 6 that the CET for

JetA-1 is higher than biodiesel fuel blends for most of the throttle valve opening positions. This may be due to that the biodiesel fuel blends mass flow rate is lower than that of JetA-1 in addition to lower calorific values of biodiesel fuels as shown in table 1. The values of exhaust gas temperature (EGT) for CTME and CRME and their blends of B10, B20 and B50 as function of the throttle valve opening are shown in figure 7. The EGT is measured at the nozzle exit point T5 in figure 1. The values of EGT are changing from 711.64 K to 874.16 K while the fuel mass flow rate changes from 9.06 kg/hr to 41.41 kg/hr. The difference in temperature between CET and EGT is indication for amount of losses of thermal energy in the engine at the different fuel flow rates and engine speeds, for the presented ranges of CET, EGT and fuel mass flow rate. The increases in EGT at the same value of the CET is due to the percentage of heat loss is decreased at higher fuel mass flow rate. In quantitative values at the throttle valve opening of 50% of full open, the EGT changed from 740.57 K to 779.72 K while the lowest value is counted for CRME B20 which is lower than the value of JetA-1 with about 5.02% and the highest value is achieved by JetA-1. The presented results show that the value of EGT for different CTME biofuels is close to the EGT value for JetA-1 fuel at most of throttle valve setting position. While, for CRME fuel blends JetA-1 fuel has higher EGT than that of biodiesel fuels this may be due to that the biofuels mass flow rates are at most of the throttle valve positions lower than that of JetA-1 fuel and the calorific value of biodiesel fuels are lower than that of JetA-1.

5.2 Exhaust Emissions

5.2.1 Effect of Biodiesel Fuel Blends on Oxygen O₂

The amount of oxygen in the exhaust plotted as function of the equivalence ratio at different throttle position settings of (10%, 30%, 50%, 70% and 90%) for different fuels like JetA-1, CTME and CRME and their blends of B10, B20 and B50 are shown in Figure 8. As shown in the figure 8, increasing the percentage of biodiesel in the blend leads to lower ranges of the equivalence ratios of the blend and leads to a leaner combustion process. The ranges of equivalence ratios calculated from equ.2 for this turbojet engine indicate that a very lean combustion process as they are (0.13-0.19) for jetA-1, (0.1263-0.1872) for CTME B10, (0.1239-0.1835) for CTME B20, (0.1135 – 0.1661) for CTME B10, while for CRME B10 is (0.127-0.183), CRME B20 is (0.123 – 0.181) and (0.1187-0.1736) for CRME B50. From these values, the equivalence ratio range for B50 of any fuel is lower than ranges for B20, and the equivalence ratio range for B20 is lower than B10. While the highest range of the equivalence ratio is achieved by JetA-1 fuel. The lower the range of the equivalence ratio, the

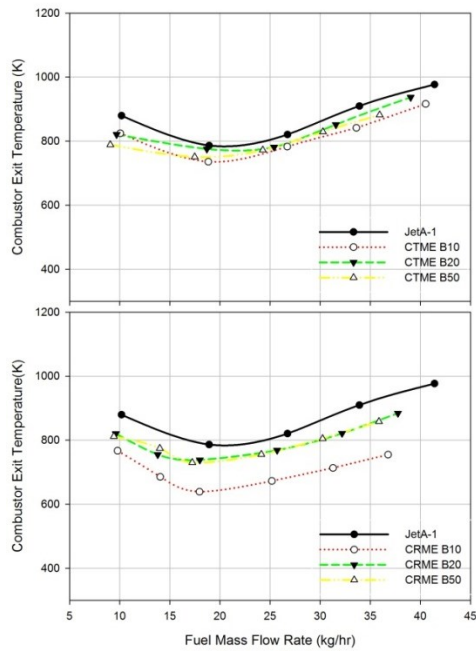


Figure 6. Effect of biodiesel fuels blend on combustor exit temperature at different fuel mass flow rate (a) CTME (b) CRME

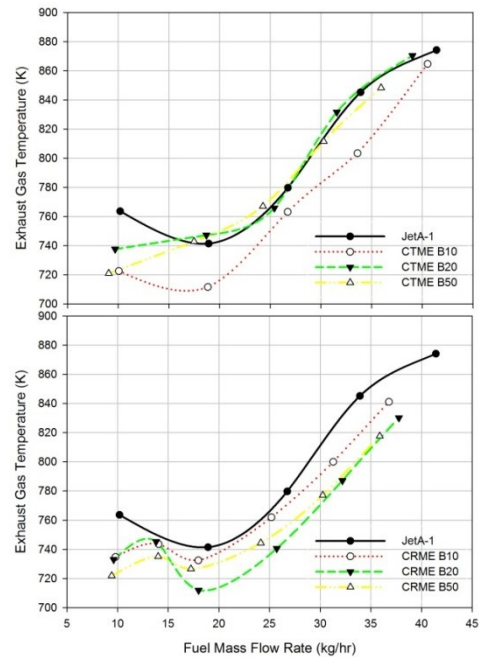


Figure 7. Effect of biodiesel fuels blend on exhaust gas temperature at different fuel mass flow rate (a) CTME (b) CRME

better and leaner combustion process. The amount of oxygen in the exhaust is decreased with increasing of equivalence ratio. At throttle valve position of 50%, the lowest value of O_2 in the exhaust is about 16.7% by volume analysis and achieved by JetA-1. While CTMR B50 has a value of 17.7% by volume analysis for O_2 in the exhaust which is higher than JetA-1 corresponding value by 5.9% and CRME B20 has a value of 17.5% by volume analysis for O_2 in the exhaust which is higher than JetA-1 corresponding value by 4.79%. Generally, it can be concluded that, the more the biodiesel percentage in the blend, the more oxygen emits in the exhaust. This may be attributed to two reasons, the first one is due to the existence of the oxygen molecules in the chemical composition of the biodiesel fuel, and the second reason is due to that biodiesel fuel blends have lower equivalence ratios compared to JetA-1 and consequently leaner combustion process.

5.2.2 Effect of Biodiesel Fuel Blends on Carbon Monoxide CO

For the same injection system and different fuels with different viscosities, as the viscosity of the fuel become higher the efficiency of the atomization process of the fuel become lower and the size of fuel droplets become larger in the fuel spray and consequently the air and fuel mixing

process become harder and a rich mixture is formed at some spots and consequently a rich combustion process which is the main reason for formation of CO. It was expected that the carbon monoxide emission will increase with the increase of the biodiesel percent in the blend as a result of viscosity increase. Figure 9 shows the carbon monoxide emission is plotted versus equivalence ratio at different throttle position 10%, 30%, 50%, 70% and 90% for jetA-1, CTME and CRME and their different blends respectively. From the figure it is clear that at throttle position of 50%, CRME B20 has the highest CO emission with 3.39% higher value than that of JetA-1. Also, CTME B20 achieves the lowest value of CO emission and it is about 4.47% lower than the corresponding value of JetA-1. At throttle positions ranged from 10% to 50%, JetA-1 fuel has higher carbon monoxide emissions than other biodiesel fuels and their different blends and carbon monoxide emissions become lower by increasing the amount of biodiesel in the blend while from throttle position of 50% to 90% CO emission for all fuels has a much closed values. Also, from figure 9, it is clear that CO is decreasing with the equivalence ratio for all studied fuels. This attributed to the amount of air in the combustor, as the equivalence ratio increased, the amount of air inside the combustor decreased and it became difficult to oxidize the carbon monoxide and more CO produced at the exhaust. Generally, comparing the amount of CO emission with JetA-1 to the amount of CO emits by biodiesel blends at all the throttle positions is lower and have better combustion process. For biodiesel fuels, B10 emits higher CO emission than B20 and B20 has a higher CO emission than B50. Therefore, from the figure with assuming the same trend of the curves, using pure biodiesel may lead to significant decrease in CO emission, however, pure biodiesel still not tested in the turbojet engine used in the current study due its higher viscosity. Also, using pure biodiesel may cause some atomization problems and leads to higher CO in the exhaust.

5.2.3 Effect of Biodiesel Fuel Blends on Carbon Dioxide CO₂

The engine CO₂ emission is measured and plotted versus the equivalence ratio at different throttle valve positions of 10, 30, 50, 70 and 90% as shown in figure 10. Comparing the results of JetA-1 fuel with biodiesel blends at 50% throttle valve position, the lowest CO₂ value is achieved by JetA-1 with percent value of 2.8%, while CTME B50 and CRME B50 have CO₂ emissions with percentage of 10.71% and 3.57% higher than that of JetA-1. For all cases shown in figure 10, CO₂ emission is increased with the increase of equivalence ratio. Biodiesel fuels have higher CO₂ emissions than JetA-1 fuel, this is due to lower values of equivalence ratios of biodiesel fuels, therefore a leaner combustion occurs and resulting in a higher CO₂ emission in the exhaust. The CO₂ emission is a good indication

for combustion process efficiency. For biodiesel fuels, B50 has lower range of equivalence ratio and consequently a higher CO₂ emission than B20 while B20 has higher CO₂ emissions than B10. Also, from figures 9 and 10 it can note that JetA-1 fuel has higher CO and lower CO₂ emissions comparing with other biodiesel fuels. After the combustion process, the carbon atom in the fuels is divided into CO and CO₂ in the emissions. For JetA-1, the part of the carbon atom exists in the fuel composition that combusted to form CO₂ is lower than that of biodiesel fuels and consequently the part of carbon atom that used to form CO in jetA-1 is higher than that of biodiesel fuels Table (1) shows that the biodiesel fuels have a higher carbon content than JetA-1 as CTME has (88.42 %) by mass and CRME (88.4 %) by mass and JetA-1 (86.51%) by mass. Therefore, both CO₂ and CO concentrations in the exhaust give indication for complete combustion process. As biodiesel fuel have higher CO₂ concentration and lower CO compared with JetA-1, thus the biodiesel fuels have a more complete combustion process compared to JetA-1 fuel.

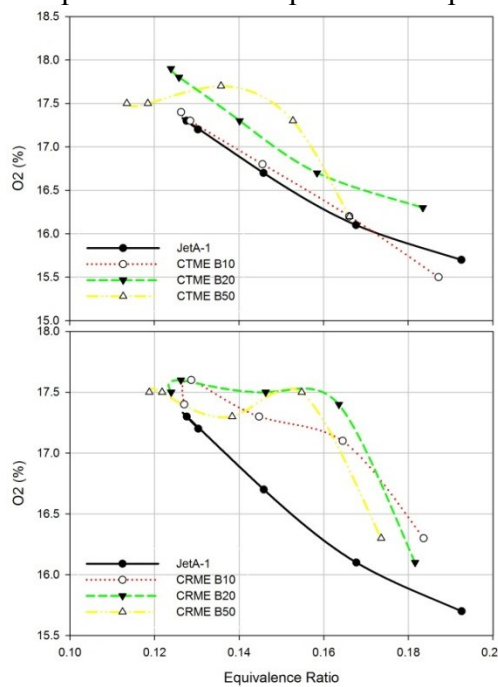


Figure 8. Effect of biodiesel fuels blend on oxygen concentration in the exhaust at different values of equivalence ratio (a) CTME (b) CRME

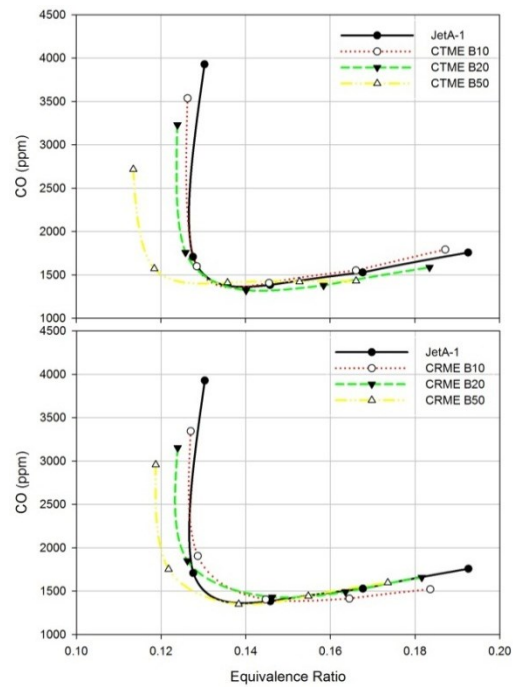


Figure 9. Effect of biodiesel fuels blend on carbon monoxide concentration in the exhaust at different values of equivalence ratio (a) CTME (b) CRME

5.2.4 Effect of Biodiesel Fuel Blends on Unburned Hydrocarbons C_xH_y

Substituting JetA-1 Fuel with biodiesel leads to noticeable decrease in the amount of the unburned hydrocarbons (UHC) in the exhaust gases as

it shown in figure 11. For 50% throttle valve position, the highest UHC value is recorded to JetA-1 fuel with value of 2110 ppm, while the lowest values are recorded for CTME B50 and CRME B50 with 36.49% and 30.8% lower than JetA-1 value. The amount of unburned hydrocarbons increased with the increase of the equivalence ratio. The presence of oxygen molecules in the composition of biodiesel fuel provide more complete combustion process and the data available in figures 9 and 10 as concluded in section (CO₂), the biodiesel fuels have more complete combustion process compared to JetA-1 and consequently this lead to reduce the amount of unburned hydrocarbons emissions in the exhaust and the presented results in figure 11 clearly support this attribution. For biodiesel fuels, B50 emits lower hydrocarbons than B20 this is due to that B50 has higher oxygen content than B20, similarly, B20 emits lower value of unburned hydrocarbons than B10. Although biodiesel is less volatile than JetA-1 fuel due to its higher viscosity, a higher distillation points have been reported for JetA-1 fuel. The final fraction of the JetA-1 may not be completely vaporized and burnt, so that, diesel fuel may has a higher value of unburned hydrocarbons.

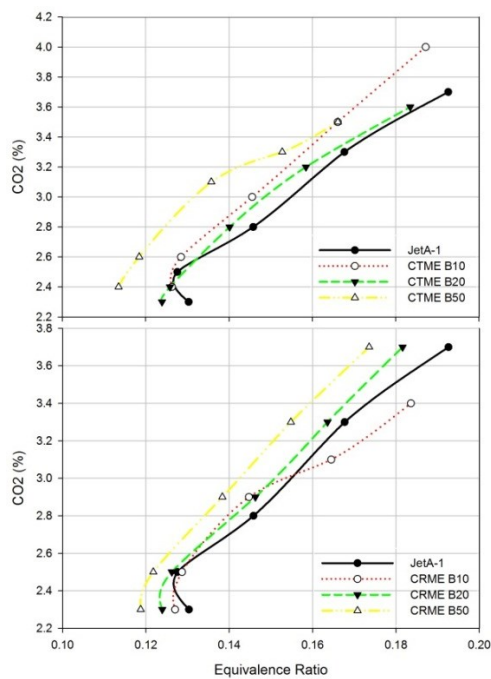


Figure 10. Effect of biodiesel fuels blend on carbon dioxide concentration in the exhaust at different values of equivalence ratio (a) CTME (b) CRME

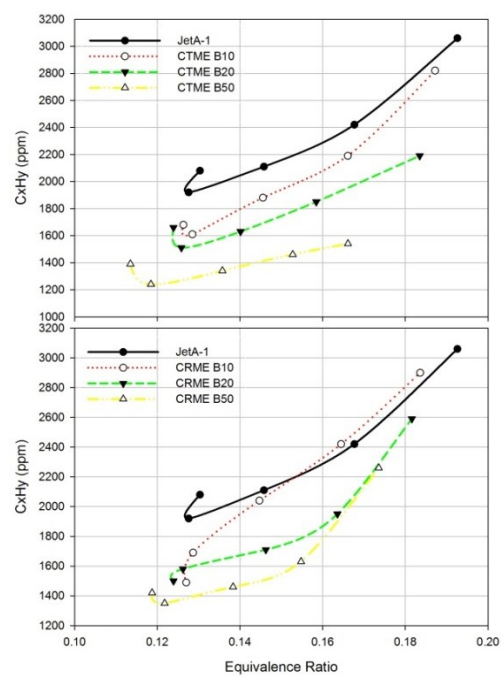


Figure 11. Effect of biodiesel fuels blend on hydrocarbon concentration in the exhaust at different values of equivalence ratio (a) CTME (b) CRME

5.2.5 Effect of Biodiesel Fuel Blends on Nitrogen Oxides NO_x

Fig 12 shows the NO_x emission for CTME, CRME and JetA-1 and their different blends of B10, B20 and B50 at different throttle valve position of 10, 30, 50, 70 and 90% respectively. The highest value is achieved by CTME B10 that higher than JetA-1 with 27.27% while CRME B10, B20 has a value higher than JetA-1 by 18.18%. The lowest value is achieved by CTME B20 with 36.3% lower than JetA-1. The results show that NO_x emissions increase with increasing of equivalence ratio. The NO_x emission for biodiesel fuel is higher than JetA-1 at different values of equivalence ratios. As shown in figure 12, the percent of biodiesel increase in the blend, the amount of emitted NO_x increase too in addition, for biodiesel fuel, B50 have higher NO_x emissions than B20 and B20 has higher NO_x emissions than B10.

5.2.6 Effect of Biodiesel Fuel Blends on Sulfur Dioxide SO₂

Fig 13 shows the variation of sulfur dioxide with different values of the equivalence ratio for different fuels of JetA-1, CTME and CRME and their different blends of B10, B20 and B50 respectively. From the figure, it is clear that SO₂ emissions increased with the increase of equivalence ratio. As shown in the figure 13, the highest level of sulfur dioxide is emitted when the engine is operated with JetA-1 fuel. At the throttle valve position of 50%, CTME B50 have lower SO₂ value with 74.35% lower than JetA-1, while, CRME B50 has lower value than JetA-1 by 61.53%. However, increasing the amount of biodiesel fuels in the blend with JetA-1 fuel, the amount of emitted sulfur dioxide decreases, this is due to that pure biodiesel fuels have very low sulfur content comparing with JetA-1 and blending any percent of biodiesel with JetA-1 will reduces the sulfur content in the fuel and consequently the sulfur dioxide emissions. For example, CRME has a sulfur content of 10.2 ppm while CTME has about 15.2 ppm of sulfur, however JetA-1 fuel has 50.3 ppm as shown in table 1. Thus, the sulfur content of CRME and CTME is lower than that of JetA-1 by 79.72% and 69.78% respectively, and blending CRME B50 fuel reduces the sulfur content to 30.25 ppm which is lower than JetA-1 fuel by 39.86%. As shown in figure 13, for biodiesel fuels, CRME B50 emits lower sulfur dioxide than CRME B20 and CRME B20 emits sulfur dioxide lower than CRME B10 and all of CRME blends have a lower sulfur dioxide comparing to JetA-1. However, the sulfur dioxide emission for CTME is higher than CRME as the sulfur content of CTME is higher than CRME as shown in table 1. Blending JetA-1 fuel with biodiesel reduces the harmful effect of the toxic

SO₂ and consequently reduces the possibility of formation H₂SO₄ which is formed by oxidation of SO₂ in the presence of water.

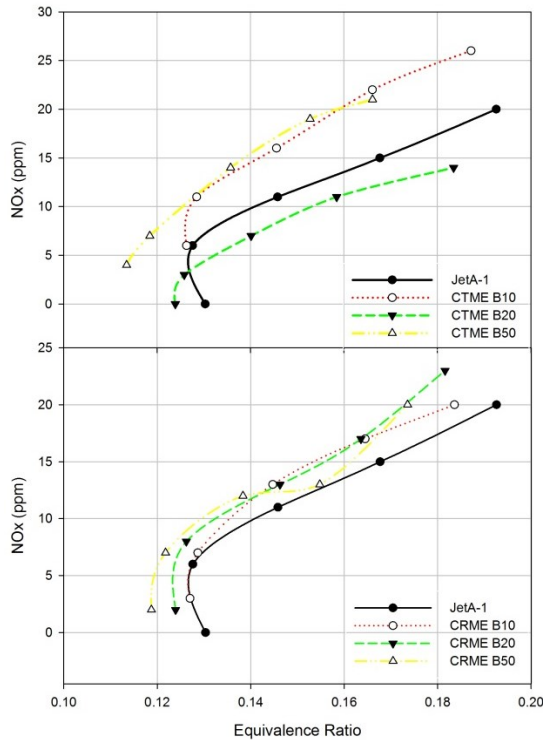


Figure 12. Effect of biodiesel fuels blend on nitric oxides concentration in the exhaust at different values of equivalence ratio (a) CTME (b) CRME

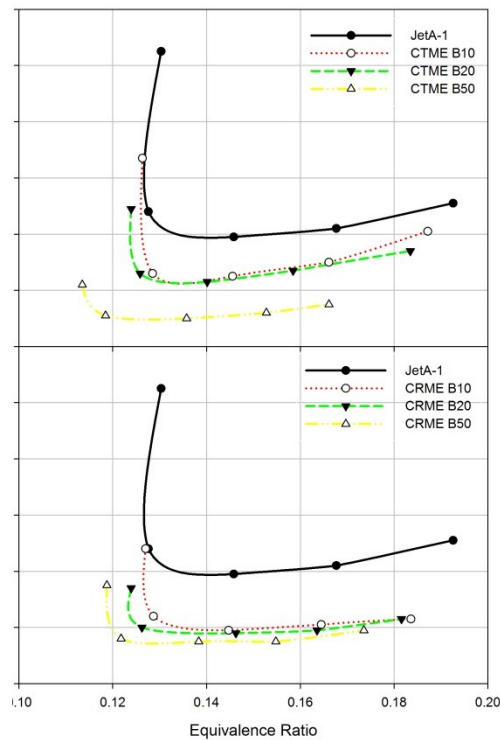


Figure 13. Effect of biodiesel fuels blend on sulfur dioxide concentration in the exhaust at different values of equivalence ratio (a) CTME (b) CRME

6. Conclusions

This study investigated experimentally the performance and emissions of turbojet engine when fueled by two different types of biodiesel fuels named Cotton Methyl Ester (CTME) and Corn Methyl Ester (CRME) and their blends of B10, B20 and B50 with JetA-1 fuel compared with JetA-1 fuel at different throttle valve position of 10%, 30%, 50%, 70% and 90% of the full open respectively. The following can be concluded from obtained results.

- Biodiesel fuels have a higher density, kinematic viscosity, flash point and pour point than JetA-1 fuel, while, their calorific value, carbon and hydrogen contents is very close to JetA-1 fuel. However, the JetA-1 fuel has higher sulfur content than other biodiesel fuels. Blending biodiesel with JetA-1 can be a suggestion to overcome the problem of the higher viscosity of the pure biodiesel fuels.

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- Static thrust value for biodiesel fuel is not lower than 11.5% as well as and not higher than 1.62% compared with standard engine JetA-1 fuel. Moreover, at throttle valve position of 50%, the biodiesel fuels CTME blends have higher static thrust compared to CRME fuel blends.
- TSFC for biodiesel blends is lower than JetA-1 and the decrease in the value of TSFC is attributed to the increase in both fuel viscosity and density. On the contrary, it was expected that the TSFC of biofuels will be higher than that of JetA-1 fuel as the calorific value of biofuels is lower than JetA-1 (see table 1). Based on the fact that for same power as the calorific value of the fuel decreases, the fuel consumption will increase. However, the obtained result reveals that the fuel consumption of biofuels is lower than that of JetA-1 which means that the effect of fuel both density and viscosity of fuels overcomes the effect of the calorific value and leads to increase in fuel consumption.
- The efficiency of biodiesel is higher than JetA-1 in most of the turbojet engine operating conditions. The engine efficiency increases with the increase of the biofuel percent in the blend. Increasing in engine efficiency with biofuels is attributed to the presence of oxygen molecule in biodiesel composition which leads to leaner combustion process and consequently closes to complete combustion process.
- The CET for JetA-1 is higher than biodiesel fuel blends for most of the throttle valve opening positions. This may be due to that the biodiesel fuel blends mass flow rate is lower than that of JetA-1 in addition to lower calorific values of biodiesel fuels.
- The value of EGT for different CTME biofuels is close to the EGT value for JetA-1 fuel at most of throttle valve setting position. While, for CRME fuel blends JetA-1 fuel has higher EGT than that of biodiesel fuels this may be due to that the biofuels mass flow rates are at most of the throttle valve positions lower than that of JetA-1 fuel and the calorific value of biodiesel fuels are lower than that of JetA-1
- The highest range of the equivalence ratio is achieved by JetA-1 fuel and by increasing the fuel blend, the range of the equivalence ratio become lower.
- The more the biodiesel percentage in the blend, the more oxygen emits in the exhaust. This may be attributed to two reasons, the first one is due to the existence of the oxygen molecules in the chemical composition of the biodiesel fuel, and the second reason is due to that biodiesel fuel blends have lower equivalence ratios compared to JetA-1 and consequently leaner combustion process.
- The CO emissions comes from the turbojet engine refers that there is no atomization problem happened when biodiesel fuel is used and blended with jetA-1 up to 50%. But the only problem is counted for the fuel

pump which was needed to be replaced as it was damaged by using a biodiesel fuels with such viscosities.

- Comparing the amount of CO emission for JetA-1 with the amount of CO emits by biodiesel blends at all the throttle positions is lower and has better combustion process. For biodiesel fuels, B10 emits higher CO emission than B20 and B20 has a higher CO emission than B50. In the exhaust, and in this study, the lowest value of Carbon monoxide is counted for B50.
- Carbon dioxide emission for biodiesel fuel is higher than that of JetA-1 due to the lower ranges of equivalence ratios for biodiesel blends.
- The biodiesel fuels have a higher carbon content than JetA-1 as CTME has (88.42 %) by mass and CRME (88.4 %) by mass and JetA-1 (86.51%) by mass. Therefore, both CO₂ and CO concentrations in the exhaust give indication for complete combustion process. As biodiesel fuel have higher CO₂ concentration and lower CO compared with JetA-1, thus the biodiesel fuels have a more complete combustion process compared to JetA-1 fuel.
- Biodiesel fuel blends have lower values of unburned hydrocarbons compared with JetA-1. This is due to higher oxygen content in biodiesel fuels and lower ranges for equivalence ratios which leads to a leaner combustion process. Also, the biodiesel is less volatile than JetA-1 fuel due to its higher viscosity, a higher distillation points have been reported for JetA-1 fuel. The final fraction of the JetA-1 may not be completely vaporized and burnt, so that, diesel fuel may has a higher value of unburned hydrocarbons.
- The NO_x emission for biodiesel fuel is higher than JetA-1 at different values of equivalence ratios. As the percent of biodiesel increase in the blend, the amount of emitted NO_x increase too in addition, for biodiesel fuel, B50 have higher NO_x emissions than B20 and B20 has higher NO_x emissions than B10.
- The highest level of sulfur dioxide is emitted when the engine is operated with JetA-1 fuel. By increasing the amount of biodiesel fuels in the blend with JetA-1 fuel, the amount of emitted sulfur dioxide decreased, this is due to that pure biodiesel fuels have very low sulfur content comparing with JetA-1 and blending any percent of biodiesel with JetA-1 reduces the sulfur content in the fuel and consequently the sulfur dioxide emissions. However, the sulfur dioxide emission for CTME is higher than CRME as the sulfur content of CTME is higher than CRME

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