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EXPERIMENTAL INVESTIGATION OF PERFORMANCE AND EXHAUST EMISSIONS OF A GAS TURBINE ENGINE FUELED WITH WASTE COOKING OIL

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ABSTRACT
In this study, the performance and exhaust emissions characteristics of gas turbine engine fuelled with blends of waste cooking oil biodiesel with Jet A-1 is investigated experimentally. The blending ratios define the percentage of biodiesel in the mixture and the used blend ratios were blend 10% (B10), blend 20% (B20) and blend 50% (B50) on volume bases. The biodiesel fuels were produced using transesterification process and characterized according to American Society for Testing and Materials (ASTM) biodiesel specifications. Chemical and physical properties show a good potential of using waste cooking oil biodiesel blends as an alternative for Jet A-1. The gas turbine engine performance parameters and exhaust emissions were measured over a range of throttle setting and compared with the measured parameters of the gas turbine engine when fuelled with 100% Jet A-1. The experimental results show that, the static thrust of the gas turbine engine was reduced when the engine operated with blends of waste cooking oil biodiesel compared to that of 100% Jet A-1. In addition, the engine rotational speed was reduced while operating the engine with waste cooking oil biodiesel blends. The thrust specific fuel consumption (TSFC) for biodiesel blends was higher than that for Jet A-1. On the other hand, the values of carbon monoxide (CO) and Nitrogen oxides (NO_x) concentrations for biodiesel blends were lower compared to that of Jet A-1.

1 INTRODUCTION
Rapid growing in industry, power generation and transportation sectors make the consumption of petroleum fuels increasing rapidly. As the petroleum fuels are limited and depleting, our world confronts two main problems which are shortage of petroleum fuel and environmental degradation. Recently, renewable energy resources such as solar energy, wind energy, hydropower and geothermal can be utilized to fulfil the shortage of conventional fuel in industry and power generation sectors. However, these energy resources are not effective for transportation sector. In addition, these renewable energy resources depend on geographical location and have low energy density compared with conventional energy resources that depend on petroleum fuels. Hence, scientists focus their efforts on development of technologies used for utilization of alternative fuels to compensate the deficiency of petroleum fuel.
Alternative fuels are the fuels that can be used directly in the existing transportation systems without design modifications. Such fuels include biodiesel, bioethanol, biomethanol, biogas, syngas and hydrogen. In recent years, biodiesel has attracted significant attention from researchers, governments and industries as a renewable fuel, biodegradable and non-toxic fuel. Biodiesel is produced from edible vegetable or non-edible oil. However, production of biodiesel from edible vegetable oil will have a negative effect on food security as well as have a high production cost compared with the nonedible oil. It is possible to produce biodiesel from waste cooking oil instead of edible vegetable oil. Waste cooking oil is obtained after using edible vegetable oils, such as cotton, palm, sunflower and corn several

times for frying. It is though that utilization of waste cooking oil in biodiesel production is less expensive than edible oil and solves the environmental problem of waste oil disposal.
Biodiesel is defined as mono-alkyl ester of long chain fatty acids derived from vegetable oil or animal fats and it conform to ASTM D6751 specifications. The main reaction for converting the raw vegetable oil to biodiesel is known as transesterification. Transesterification is a chemical process of transforming large, branched, triglyceride molecules of vegetable oils, animal fat to straight chain free fatty acids alkyl ester.
In the research line of using biodiesel for gas turbine engines, there are two types of gas turbine engines, those used in aviation and stationary gas turbines used for power generation. Few research studies were conducted in the use of biodiesel and alternative fuels in aircraft gas turbine engines [1]-[12]. Alternative aviation fuels are required to be liquid fuels and compatible with conventional kerosene based jet fuels. It can be added to conventional jet fuels as a substitute without a need to modify the engine and fuel system. These alternative aviation fuels should have no or trivial amount of aromatic hydrocarbons and sulfur, which are an advantage over conventional kerosene based fuels because of its benefits on the reduction of exhaust emissions. Blakey et al. [1] concluded that the biodiesel fuel is not suitable for aviation gas turbine engines due to the carryover of metal contaminants from the raw feedstock. Also, it have an adverse effect of the hot end materials on the engine and causing issues in pipelines and is treated as a major contaminant of aviation Jet fuel. In addition, they cited that Bio-Synthetic Paraffinic Kerosene (Bio-SPK) is the recommended alternative aviation fuel. Daggett et al. [2] and [3] cited that challenges of using biodiesel in aviation is its pour point and freeze point at normal operating temperatures of the aircraft gas turbine engines in addition to its storage stability as it is advised that the biodiesel should be used within 6 months of manufacture. Chunck et al. [4] cited that biodiesel can be used for aviation if it contains short chain esters rather than long chain to achieve low temperature behavior and calorific value of JetA-1 aviation kerosene. Mendez et al. [5] studied the effect of using butanol/JetA blends (Bxx) on the performance and emission of small scale aviation gas turbine engines. They reported that the use of butanol blends resulted in lowering the maximum operational rotational speed by about 5000 rpm, compared with JetA fuel. Also, under the same test conditions, the butanol/JetA blends produced higher thrust compared with JetA. With respect to emissions, they reported that the NO_x and CO emissions for the butanol blends were significantly lower than those with Jet-A. Habib et al. [6] investigated the performance and emissions of a small scale gas turbine engine operated with biodiesel produced from soybean, canola and recycled rapeseed. For the gas turbine engine performance, they reported that using pure biodiesel achieves the same static thrust, lower thrust specific fuel consumption TSFC and higher thermal efficiency compared with JetA. While, operating the gas turbine with biodiesel blend of B50 did not show significant differences compared with JetA. For CO_2 emissions, they reported that B100 biodiesel fuels have higher CO_2 compared with JetA while, for B50 no significant change from JetA. For CO and NO_x emissions, they concluded that using biofuel reduces CO and NO_x emissions compared with JetA fuel. Tan et al. [7] and [8] studied the effect of biodiesel on micro turbojet engine. They reported that using biodiesel fuel increase the produced static thrust and decrease the TSFC compared to kerosene. Also, they concluded that using biodiesel decrease HC and NO_x emissions significantly. On the other hand, they reported that CO and CO_2 emissions increase with biodiesel fuel. Corporan et al. [9] studied the performance and emissions of T63 helicopter engine operated with blends of JP-8 and biodiesel. They reported that there was no change in the overall engine performance using biodiesel concentrations up to 20%. They added that the test results show biodiesel can produce a noticeable reduction in particulates emissions at higher power settings. Talib and Ahmad [10] investigated the performance of small scale turbojet engine operated with biodiesel from palm oil. They cited that as the biodiesel blend increase the static thrust decrease and TSFC increase. From the above literature, it is clear that additional research is still needed to investigate the whole effects of using biofuels to operate aircraft gas turbines engines in order to make a better assessment and understanding of its technical possibility.

Accordingly, the current study aims to investigate experimentally the performance and emissions of small scale aircraft gas turbine engines fueled with blends of waste cooking oil biodiesel and JetA-1. The performance and exhaust emissions of gas turbine engine are investigated at different waste cooking oil biodiesel blends of B10, B20 and B50 with JetA-1. All experiments were conducted under the same operation conditions. The results were compared with 100% JetA-1 data as a baseline at different throttle settings.

2 EXPERIMENTAL SETUP

A gas turbine engine type Olympus E-start HP which generates up to 230 N of thrust is used in this study. The basic gas turbine engine specifications are given in Table 1. The engine is equipped with pressure, flow, temperature, thrust and speed sensors in addition to data acquisition system and control unit (ECU). Five k-type thermocouples and pressure sensors are fixed at different positions to measure temperature and pressure at the compressor inlet, compressor exit, combustion chamber exit, turbine exit and nozzle exit. Also, the engine is equipped with load cell and shaft speed sensor to measure, static thrust and engine rotational speed respectively. Liquid turbine flow meter is fixed to the fuel line to measure the fuel volume flow rate. The detailed sensors specifications are given in Table 2. The exhaust gases are passed after engine exit through water cooled sampling probe that is fixed at the exit of engine nozzle to enable sudden cooling for exhaust samples to freeze the reactions. The probe catches the cooled exhaust sample that transferred to exhaust gas analyzer E-Instruments E8500 by long hose. The exhaust gas analyzer E8500 specifications are provided in Table 3. The schematic diagram shown in Fig. 1 indicates the layout of the measuring system. The gas turbine engine test facility allow to measure static thrust, fuel consumption, engine efficiency, exhausts gas speed and intake air speed in addition to exhaust gas composition (O_2, CO, CO_2, NO_x, SO_2 and HC). A fuel manifold was added to the gas turbine fuel delivery system to allow the engine to start with Jet A-1, switch to the test biodiesel fuel for the experiment, and then end experiments with Jet A-1 to purge the biofuel from the system and this prevents the damage of the fuel delivery system.

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 Exhaust Gas Temperature (EGT)	700 ^oC
Max. EGT	750 ^oC

Table 1. Olympus E-start HP gas turbine engine specifications

Sensor Type	Specification	Error
Temperature sensors	K-Type thermocouples	± 0.75% of reading
Pressure sensors	0-15 psi Honeywell manufacture	± 1% of reading
Fuel Flow meter	0.1 to 2.5 l/min turbine flow meter and measures up to 15 CST viscosity fluids	± 3% of reading
Speed sensor (rpm)	0-130,000 rpm Armfield shaft speed sensor	± 3% of reading
Thrust (force) sensor	0-20 kg thrust cell	± 3% of reading

Table 2. Engine equipped sensors specifications

Emission	Sensor Type	Measuring Range
CO_2	NDIR	0 - 20 %
CO (Low range)	Electrochemical	0 - 8000 ppm
CO (High range)	NDIR	0 - 15 %
O_2	Electrochemical	0 - 25 %
C_xH_y	NDIR	0 - 3 %
NO	Electrochemical	0 - 4000 ppm
NO_2	Electrochemical	0 - 1000 ppm
SO_2	Electrochemical	0 - 4000 ppm

Table 3. Specifications of exhaust gas analyzer E8500

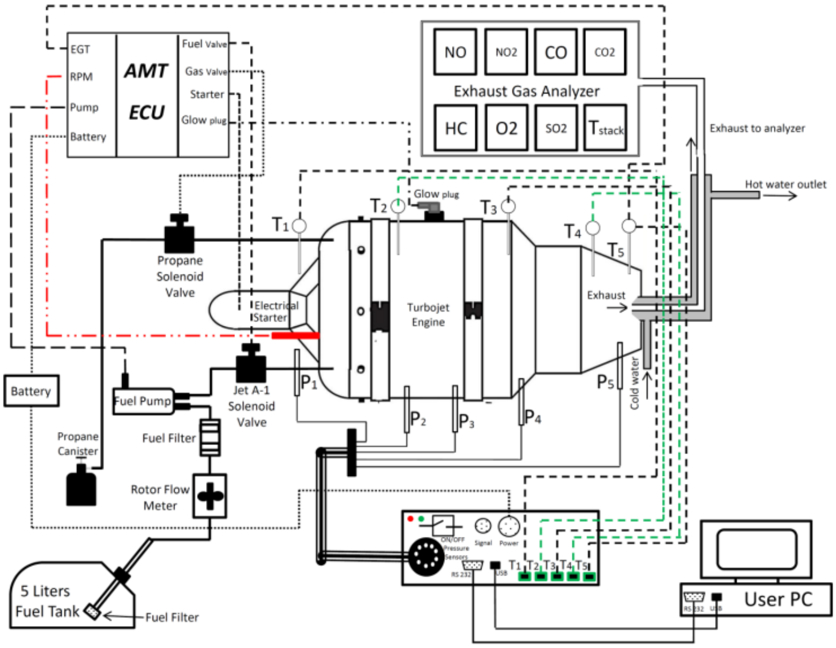

Figure 1. Schematic diagram of the experimental setup

3 RESULTS AND DISCUSSION

For each experiment runs with alternative fuel, the engine performance reference parameters were obtained by using 100% JetA-1 as a baseline. This is in order to compare the performance parameters and emissions with those obtained when the engine runs with different biodiesel fuels at different blends. Before each experiment with alternative fuel, the engine is operated with jet A-1 fuel in order to make sure that the engine fuel system is clean of any residuals from the previous biodiesel tested fuel. Here, performance parameters and exhaust emissions are discussed for fuel throttle valve position of 10%, 20%, 40%, 60%, 80% and 90%. The waste cooking oil biodiesel fuel used in this study is produced using transesterification process and characterized according to ASTM D6751. The fuel properties are shown in Table 4.

Properties	Method	Waste cooking oil biodiesel	JetA-1
Density at 15.5°C	ASTM D-1298	0.8755	0.797
Kinematic Viscosity, cSt, at 40°C	ASTM D-445	5.3	1.08
Pour Point °C	ASTM D-97	-16	-43
Flash Point °C	ASTM D-93	90	39
Sulfur Content, ppm	ASTM D-4294	5	50.3
Higher Calorific Value (kJ/kg)	ASTM D-240	41533	46329
Lower Calorific Value (KJ/kg)	ASTM D-240	38242	43465

Table 4. Physical and chemical properties of pure waste cooking oil biodiesel and JetA-1

3.1 Fuel Mass Flow Rate

The effect of fuel throttle valve setting on the fuel mass flow rate is shown in Fig. 2. The results shown are for waste cooking oil biodiesel blends of B10, B20 and B50. At 10% and 20% throttle valve settings, the difference between the values of fuel mass flow rate for all the tested blends is ranged from -4.2% to 3% compared with the mass flow rate of JetA-1. However, most of these differences are within the error limits of the fuel flow meter given in Table 2. Consequently, throttle valve settings of 10% and 20% could not reflect significant differences between the tested fuels. In the range from 40% to 90% of throttle valve setting, the difference between the fuel mass flow rate for waste cooking oil biodiesel blends and JetA-1 are clear. As shown in Fig. 2, for 40% to 90% of throttle valve setting, the fuel mass flow rate for waste cooking oil biodiesel blends is decreased with values ranged from 5.3% to 23.2% compared with values of JetA-1. From the data presented in Fig. 2, as the blend of waste cooking oil biodiesel increases, the fuel mass flow rate is decreased. This inversely affects engine speed and output static thrust. These results are due to the higher viscosity and lower calorific value of waste cooking oil biodiesel fuels as shown in Table 4.

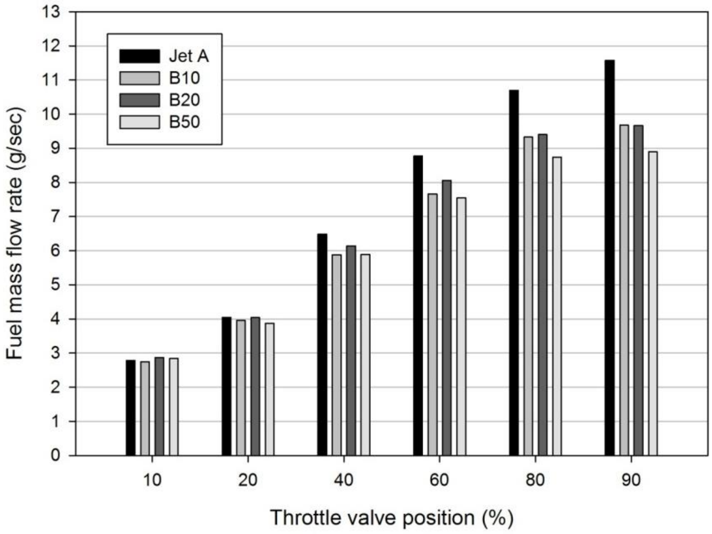

Figure 2. Fuel mass flow rate for waste cooking oil biodiesel blends and JetA-1 at different throttle valve settings

3.2 Engine Rotational Speed

The results of studying the effect of waste cooking oil biodiesel blends on engine rotational speed at different fuel throttle valve settings compared with JetA-1 are shown in Fig. 3 and Fig. 4. As shown, the engine speed increases as fuel throttle valve opening increase because more fuel is injected into the combustion chamber for all tested fuels. For the same throttle position, the engine speed is higher when the engine fueled by JetA-1 compared with all tested biodiesel fuels and their blends. This effect is not appearing at throttle valve setting of 10% and 20% as it ranged from -2.5% to 0.7% compared to values of JetA-1. The measured engine speed data at throttle valve setting of 10% and 20% are within the speed sensor error limits as shown in Table 2 and as a consequence of that different in fuel mass flow rate at these settings is quite small. However, at fuel throttle valve setting of 40% to 90%, the different between the tested biodiesel fuel blends and JetA-1 in terms of engine speed is noticeable and decreased for the tested biodiesel blends with a ratio ranged from 3% to 8% compared to the results of JetA-1. From these results, it is clear that the engine speed is decreased while the percentage of waste cooking biodiesel in the blend increases and this is attributed to the decrease of fuel mass flow rate and increase of fuel viscosity in addition to the reduction in fuel calorific value. The higher biodiesel viscosity leads to decrease the engine fuel gear pump outlet pressure; consequently, the fuel mass flow rate. As the fuel mass flow rate decreased, the engine output power is decreased and is reflected on the measured gas turbine engine speed. It can be concluded the gas turbine engine speed is slightly affected inversely when fueled with waste cooking oil biodiesel blends due to the higher viscosity and lower calorific value.

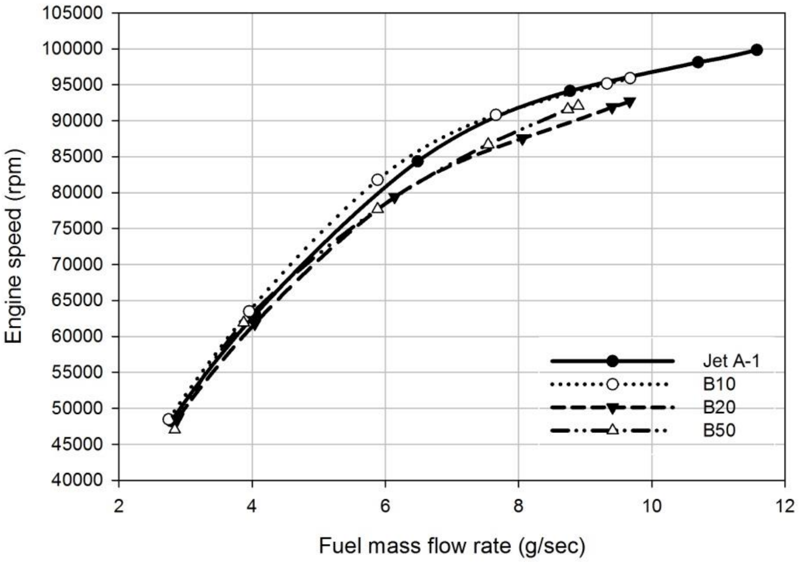

Figure 3. Engine speed for waste cooking oil biodiesel blends and JetA-1 at different fuel mass flow rate

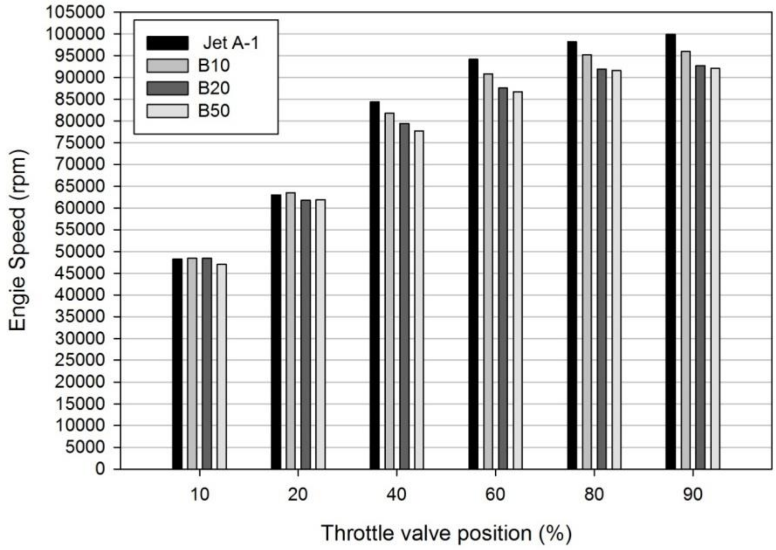

Figure 4. Engine speed for waste cooking oil biodiesel blends and JetA-1 at different throttle valve settings.

3.3 Static Thrust

Fig. 5 and fig. 6 show the effect of waste cooking oil biodiesel blends on engine static thrust at different fuel mass flow rate and throttle settings compared with JetA-1. At the same operating conditions, the results show that, using waste cooking oil biodiesel blends lead to a change in engine static thrust ranged from -21.3% to 13.2 % compared with that of JetA-1 at throttle valve settings of 10% and 20%. For the case of the fuel throttle valve opening is ranged from 40% to 90% the engine static thrust is decreased while using biodiesel blends with ratio of 7.4% to 30.9% compared with the values of JetA-1. The decrease in the measured static thrust of the engine for the case when the engine fueled with biodiesel fuel is mainly attributed to the lower heating value of waste cooking oil biodiesel compared with JetA-1. Moreover, lower fuel mass flow rate of the waste cooking oil biodiesel blends compared with JetA-1 at the same throttle valve opening due to the higher viscosity lead to the decrease in the engine output power and consequently the produced thrust. In addition, by increasing of the waste cooking oil biodiesel percentage in the blend, the static thrust decreases at the same operating conditions.

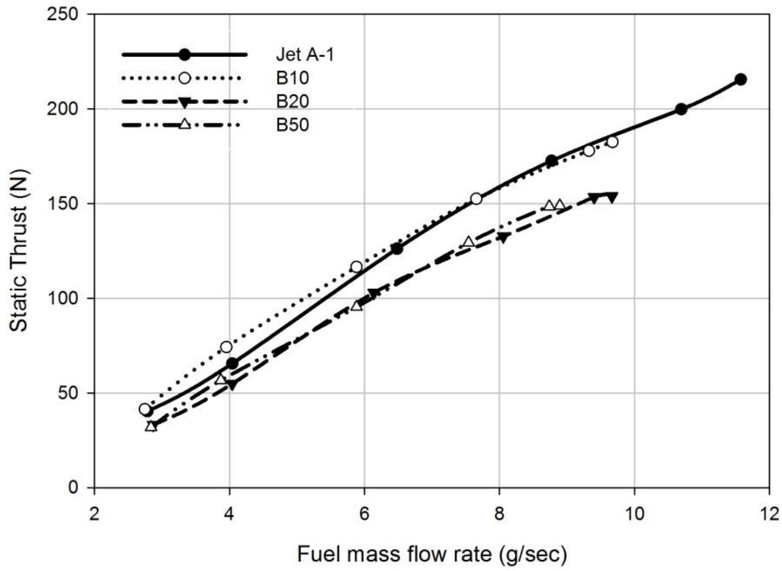

Figure 5. Static thrust for waste cooking oil biodiesel blends and JetA-1 at different fuel mass flow rate.

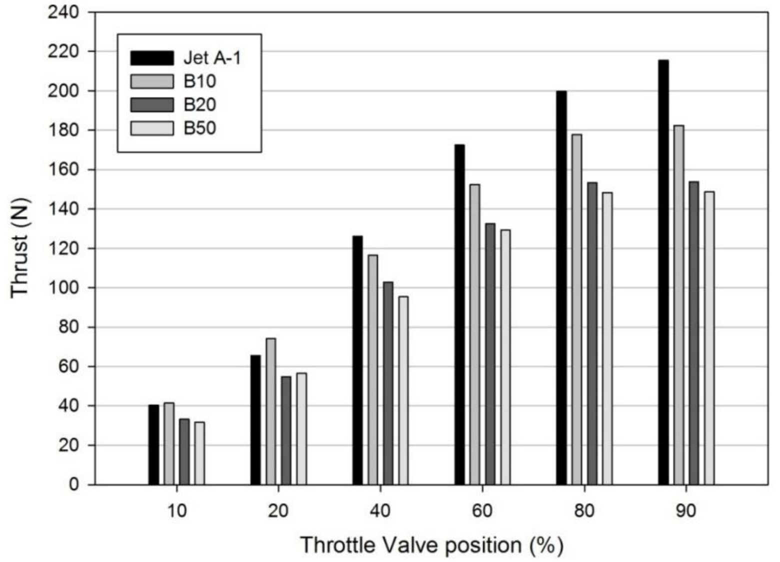

Figure 6. Static thrust for waste cooking oil biodiesel blends and JetA-1 at different Throttle valve settings.

3.4 Thrust Specific Fuel Consumption

Thrust specific fuel consumption (TSFC) for JetA-1 and waste cooking oil biodiesel B10, B20 and B50 are shown in Figs. 7 and 8. The TSFC is defined as the mass of fuel that is required to provide the net thrust for a given period. The measurements show that at 10% and 20% of the throttle valve setting, the difference of TSFC of JetA-1 and waste cooking oil biodiesel blends is large and ranged from -13.6% to 26.8% compared to that of biodiesel. This difference is gradually decreases with the increase of throttle valve opening from 40% to 90%, and it is found that at throttle position of 40% or higher, the difference between the value of TSFC of JetA-1 and the biodiesel fuels become smaller and ranged from -2% to 20% compared to that of jetA-1. The results show that, as the blend of waste cooking oil biodiesel increase, the value of TSFC get increase. Based on the fact that to attain the same power with lower heating values of the fuel, the fuel consumption will increase. In addition, it is clear that, the viscosity and density of the waste cooking oil biodiesel have a significant effect on TSFC. Therefore, it can be concluded that the increase in the value of TSFC for biodiesel is attributed to the decrease in biodiesel heating value and increase in both fuel viscosity and density.

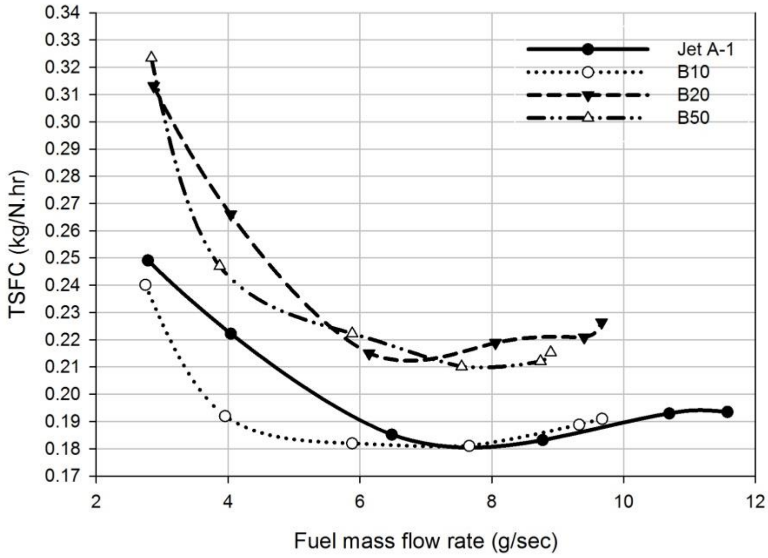

Figure 7. TSFC for waste cooking oil biodiesel blends and JetA-1 at different fuel mass flow rate

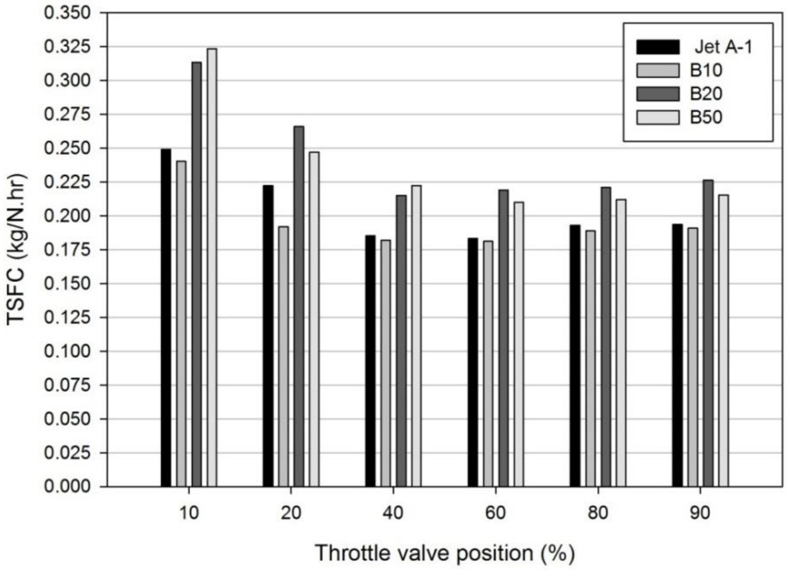

Figure 8. TSFC for waste cooking oil biodiesel blends and JetA-1 at different Throttle valve settings

3.5 Carbon Monoxide (CO)

Carbon monoxide (CO) emission at different fuel mass flow rates and different throttle valve settings for different fuels are shown in Figs. 9 and 10. The CO emissions for waste cooking oil biodiesel blends are much lower compared to JetA-1 at different throttle valve settings and fuel flow values. The reduction in carbon monoxide emissions is ranged from -29.3% to 2.7% compared with that of JetA-1. However, it was expected that the carbon monoxide emission for biodiesel blends will be higher than that of JetA-1 due to the higher viscosity of the biodiesel blends that leads to poor atomization process compared with JetA-1 and the size of fuel droplets become larger within fuel spray. In this case, the air and fuel mixing process become worse and a rich mixture is formed and consequently a rich combustion process happened which is the main reason for forming CO. On the other hand, the existence of oxygen contents in the biodiesel composition will accelerate the oxidation process for most species as carbon converted to carbon dioxide. The overall effect of waste cooking oil biodiesel blends on CO emission will depend on the compromise between the negative effect of viscosity and the improving effect of oxygen contents. Generally, the CO emissions for biodiesel blends reduced due to the oxygen content in the fuel.

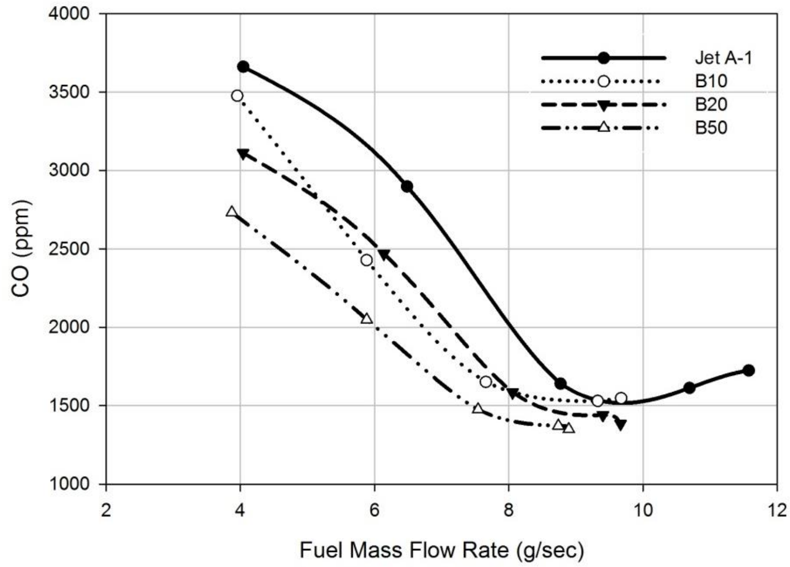

Figure 9. CO emissions for waste cooking oil biodiesel blends and JetA-1 at different fuel mass flow rate.

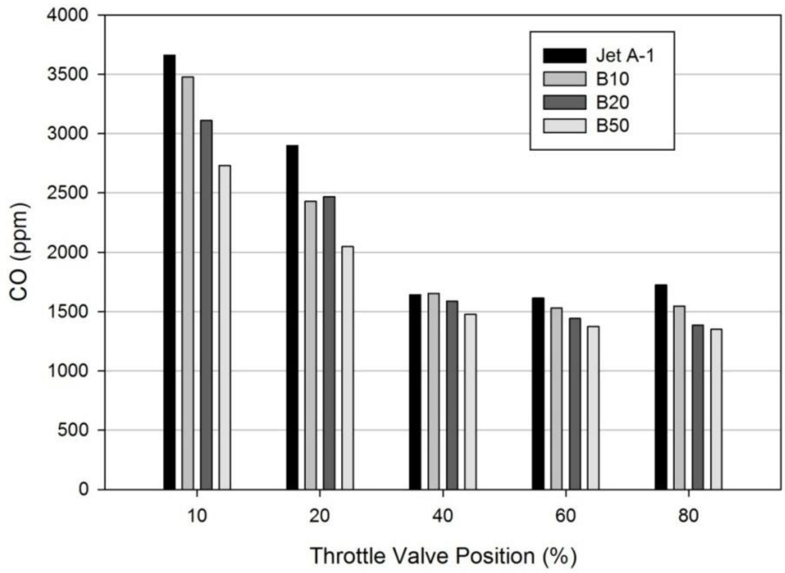

Figure 10. CO emissions for waste cooking oil biodiesel blends and JetA-1 at different throttle valve settings.

3.6 Nitrogen Oxides (NO_x)

Fig. 11 and 12 show the NO_x emission for different waste cooking oil biodiesel blends and JetA-1 and their different blends at different throttle valve settings. At lower throttle valve settings of 10%, 20% and 40%, the NO_x emission for B10 is higher than that of JetA-1 with a maximum difference of 28.5% compared with JetA-1 while the B20 and B50 is lower than that of JetA-1 with a maximum of 50% compared to JetA-1. At higher throttle valve settings of 60%, 80% and 90%, NO_x emissions for waste cooking oil biodiesel blends is lower than that of JetA-1 and by increasing the biodiesel percentage in the blend the NO_x emissions become lower. The reduction in NO_x emissions may be attributed to the lower heating value of the waste cooking oil biodiesel fuels that leads to a lower flame temperature. Generally, NO_x emissions were reduced by increasing of waste cooking oil biodiesel percentage in the blend.

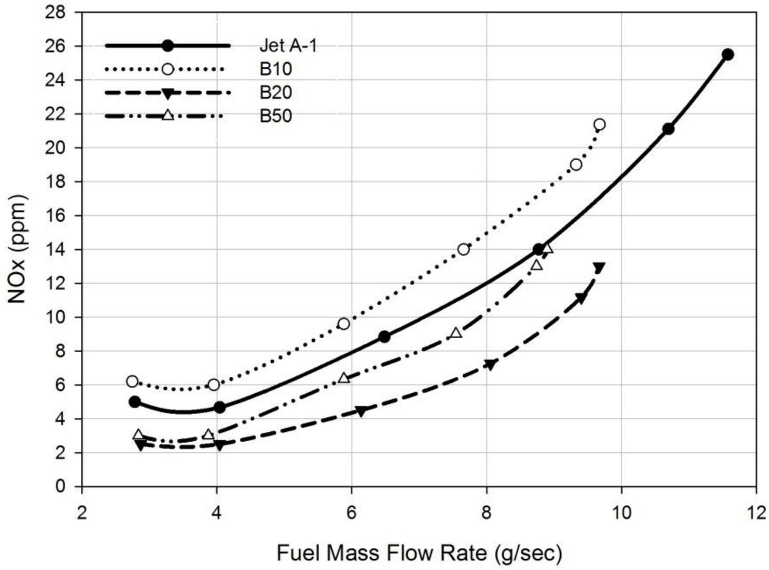

Figure 11. NO_x emissions for waste cooking oil biodiesel blends and JetA-1 at different fuel mass flow rate.

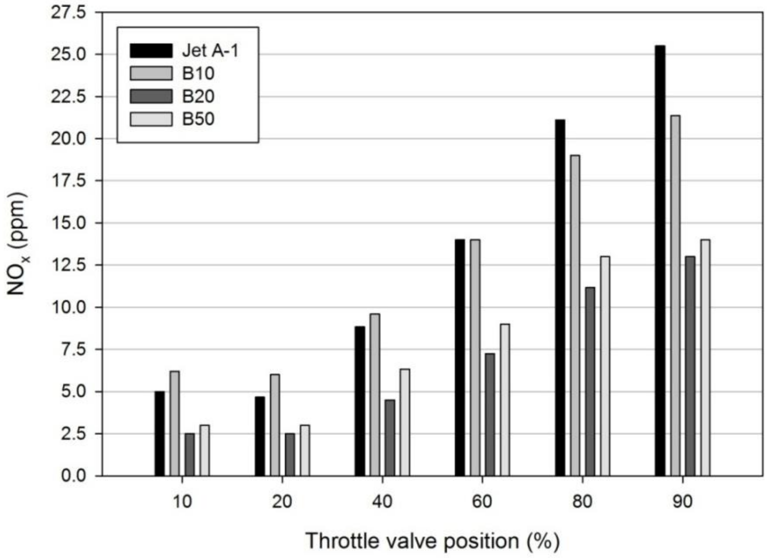

Figure 12. NO_x emissions for waste cooking oil biodiesel blends and JetA-1 at different throttle valve settings.

4 CONCLUSION

The performance and emissions of a gas turbine engine fueled with waste cooking oil biodiesel and JetA-1 blends of B10, B20 and B50 have been investigated experimentally and compared with that of JetA-1 fuel at different throttle valve settings. The experimental results confirm that the engine speed, static thrust and TSFC in addition to CO and NOx emissions of gas turbine engine are functions of biodiesel blend. At the same operating conditions, the gas turbine engine performance reduced with increasing in biodiesel percentage in the blend. However, gas turbine engine emissions improved by using of biodiesel blends. The following points can be concluded from obtained results:

- Waste cooking biodiesel fuel can be used up to blend of 50% with JetA-1 in gas turbine engines without operational problems but with a reduction in engine performance.
- Increasing waste cooking oil biodiesel percentage in the blend leads to a decrease in fuel mass flow rate due to its higher viscosity and consequently the engine rotational speed decreases. In addition, engine static thrust decreased and TSFC increased with

increasing of waste cooking oil biodiesel percentage in the blend. This is due to the lower fuel calorific value by increasing waste cooking oil biodiesel blending ratio.

- Fuel viscosity and calorific value are the two main important parameters of fuel properties which have an effect on the engine performance and emissions and by controlling these two parameters the output performance and emissions will be improved.
- Exhaust gas emissions such as CO and NO_x are reduced by adding waste cooking oil biodiesel for blends of B20 and B50. However, B10 did not show a fixed trend in the emissions.
- Oxygen content in the chemical composition of the waste cooking oil biodiesel is the main player in emissions reduction. The more the biodiesel percentage in the blend, the more oxygen emits in the exhaust.

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