Renewable Energy 216 (2023) 119134

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Evaluation of engine characteristics of a micro-gas turbine powered with JETA1 fuel mixed with Afzelia biodiesel and dimethyl ether (DME)

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ARTICLE INFO

Keywords:
Micro-gas turbine
Dimethyl ether
Jet fuel
Biodiesel
Emissions

ABSTRACT

The use of Jet fuels in micro gas turbines results in high fuel consumption and increased gaseous emissions which in turn causes environmental pollution. In this study, a fixed proportion of Afzelia-Africana biodiesel (A) was mixed with dimethyl-ether (B) and Jet A1 (J) fuel of varying proportions, A10B10J80 (10% biodiesel, 10% dimethyl-ether, 80% Jet fuel), A10B15J75 (10% biodiesel, 15% dimethyl-ether, 75% Jet fuel), and A10B20J70 (10% biodiesel, 20% dimethyl-ether, 70% Jet fuel) in a bid to produce a fuel of improved properties. Their properties were compared with those of their pristine forms by testing the fuels in the gas turbine in order to ascertain the resulting engine emissions, thrust and thrust specific fuel consumption. Compared to the JETA1 fuel, the A10B10J80 fuel gave the best results in terms of engine speed, thrust (37 N) and thrust specific fuel consumption (4.3/h vs 5/h); the CO_2, NO_x, and CO emissions were lower for the blended fuels compared to those of the JET fuel. The A10B15J75 and A10B20J70 fuels gave 3 and 4.5% lower thrusts respectively, while the A10B10J80 fuel gave 3% increase in static thrust with a 14% reduction in its thrust-specific fuel consumption over the JET A1 fuel.

1. Introduction

In the past decade, there has been a consistent rise in global energy consumption, with a resultant annual growth rate of 2.6% recorded in 2018 [1]. Large volumes of petroleum-based fuels are used in MGT engines, such as those used in stationary power units and aircrafts, thus resulting in enormous air pollution [2]. The use of fossil fuels pollutes the environment severely. Excessive use of fossil fuels results in global warming [1] and the release of greenhouse gases [2]. As a result, using an environmentally friendly and renewable fuel source reduces pollution levels. Since fossil fuels are rapidly depleting, researchers have the mandate to develop alternative fuels that have zero/reduced potential for polluting the environment and have no effect on human health [3]. The alternative fuel should not only meet the demands for electricity but also induce high performance, conversion, and engine efficiency with minimal/no negative environmental consequences [4]. Biofuels account for 75% of the world's renewable energy and 13% of its global primary energy, whereas bio-energy contributions, particularly those of liquid biofuels, are expected to account for up to 30% of the global energy supply by 2050 [5].

In recent times, researchers have considered the possibility of using biodiesel in gas turbines. Owing to their availability and reliability, micro gas turbines (MGTs) are becoming increasingly popular in demand [6]. MGTs can be made to run on Jet A-1 [7] and biodiesel [8] by advanced techniques. Researchers have demonstrated that methyl esters have flaws that must be addressed before using them in MGTs [9,10]. According to Jagtap et al. [11], biodiesel has a higher viscosity and density than conventional diesel, thus resulting in poor atomization of the fuels and the potential for clogging fuel nozzles. Viscosity, density, and surface tension of a liquid fuel can influence its atomization [4]. Luo et al. [12] examined the effects of soybean oil-based biodiesel in a MGT, and the results showed that the gas turbine's efficiency and power were poor, with no significant increase in its performance characteristics. However, the resulting emissions were found to reduce significantly. Their results showed a 42% reduction in CO and a 53% reduction in NOx

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https://doi.org/10.1016/j.renene.2023.119134
Received 8 March 2023; Received in revised form 11 June 2023; Accepted 7 August 2023

Nomenclature

A10B10J80	10% biodiesel-10% dimethyl ether −80% Jet fuel
A10B15J75	10% biodiesel-15% dimethyl ether −75% Jet fuel
A10B20J70	10% biodiesel-20% dimethyl ether −70% Jet fuel
RPM	Revolution per minute
CO_2	Carbon dioxide
DME	Dimethyl ether
TSFC	thrust-specific fuel consumption
MGT	Micro gas turbine
TIT	Turbine inlet temperature
EI	emission indices
EGT	Exhaust gas temperature
η	Thermal efficiency
NO_x	Oxides of nitrogen
CO	Carbon monoxide
TP	Thrust Power

emissions. The high amount of O_2 in the biodiesel improved the thermal efficiency of the engine while lowering its emissions. Fauzan et al. [13] used a gas turbine to study several types of fuel mixtures and found that they emit the same amount of aldehydes as Jet A-1 fuel but with lower emissions. In an investigation involving the demonstration of the spray characteristics of biodiesel, Oni et al. [14], observed that an increase in the viscosity of biodiesel resulted in a corresponding increase in the Sauter mean diameter of the biodiesel-blended fuels relative to those of conventional diesel fuel. Due to the higher surface tension and viscosity of biodiesel, its ineffective atomization and evaporation are very common challenges. To change the physical features of biofuel, a variety of approaches were proposed, as documented in Ref. [10]. They further asserted that the qualities of fuels must be adjusted to meet the needs of the engines in which they will be used. Several researchers [15,16] have attempted to lower the viscosity of biodiesel by preheating it prior to application, while others discovered that distillation can improve the physical qualities of biodiesel [17], which in turn influences its evaporation [16] and atomization properties in MGT [17], along with its surface tension [8], viscosity, and density [18]. Moreover, these processes are both energy- and time-intensive; thus, motivating the need to search for a viable alternative approach of improving JET A1 fuel-properties so as to lower the high tendencies for aldehyde release, alongside NOx, HC, CO emissions and low sulfur, which in turn suffices as a less time-consuming approach. In addition, it is also perceived that since no study has ever reported on testing Afzelia biodiesel-DME-JETA1 fuel blend in a MGT, and considering the sustainable nature of the plant source, the authors then decided to explore blending biodiesel sourced from Afzelia Africana alongside mixing it with DME in order to take advantage of the high oxygen content of DME/the biodiesel, which will in turn improve the combustion potential of the JET fuel. Also, since DME and biodiesel (i.e., methyl ester) are compounds with methyl/ether groups, it is also perceived that their synergistic properties and alkyl-chemistry will offer some measure of methyl- and ether-induced molecular interactions all aimed at improving the final properties of the JET A1 fuel; also, these opportunities have not been explored by previous findings on the subject. Also, according to the investigation by Seljak and Katrašnik [19], the feasibility of a variety of fuels including biodiesel, methanol, and ethanol for use in gas turbines was explored. They observed that incorrect/inappropriate fuel mixtures caused poor combustion, cold starting, nozzle blockages, lubricant contamination, and thermal cracking, which is why DME was considered as a replacement-additive in this study considering its low viscosity at high Reynold's number/increased turbulence.

Based on previous works, DME is an attractive fuel for MGT power plants, diesel engines, and household use. Other reasons for adopting DME as a choice-additive, is due to its similarities with liquefied petroleum gas (LPG); it can be easily liquefied under pressure as well as stored and handled by means of LPG devices, and it does not contain aromatics, metals, and sulfur. A report [19] showed that DME-fueled MGTs gave high performance (thermal efficiency), low emissions (NO_x and HCs), and were sulfur-free when compared to natural gas-fueled turbines. DME is not a mutagen, a carcinogen, or a teratogen, and it does not form peroxides upon exposure to air [20]. DME can serve as substitute for many conventional fuels in diesel engines, power generation plants, and for household use based on its characteristics. Although, recent tests have shown that when DME is used in a gas turbine, it can bring about increased pollutant emissions, dynamic pressures, and combustor metal temperatures that are comparable to those of natural gas-fueled gas turbines, hence the need for consideration for blending it with Afzelia African biodiesel. Its low heating value (LHV) is close to that of ethanol, but it offers some advantages compared to alcohols in terms of stability and miscibility with hydrocarbons. The LHV of DME is less than those of most commercial fuels (methane, propane, butane, and diesel fuel), but it is higher than that of methanol. DME can serve as substitute for diesel fuel in the transportation sector, thus reducing oil dependence. Owing to its high cetane number and low boiling point, DME in diesel engines, provides fast fuel-air mixing, reduced ignition delay, and excellent cold start properties. Furthermore, while numerous studies have been devoted to the combustion of DME in diesel engines, results are scarce as far as boilers and gas turbines are concerned. Therefore, DME is a good alternative fuel for power generation and transportation [19]. Despite its advantages, some works have demonstrated the need to modify the fuel (DME) in consideration of the fuel's combustion properties to enhance its reliability in a fired MGT [21].

In a mini-scale gas turbine, Reksowardojo et al. [22] admixed hog-fat biodiesel, rapeseed, soy, canola, and their blends with Jet-A fuel. The results revealed that an increase in biodiesel in the blends, resulted in a significant decrease in the engine's thrust and emission concentrations (NO and CO). Further investigation revealed that the best blend may be utilized to reduce emissions. They came to the conclusion that MGT engines can run on a range of fuels. Due to the lower calorific value of biodiesel, its addition to Jet A-1 fuel increases fuel consumption and reduces static thrust by as much as 4% and 8%. The presence of oxygen in biodiesel was predicted to result in increased thermal efficiency, decreased NO emissions, and leaner combustion. Because there were few variations in the performance of the different blends/fuels, the information obtained in these works were somewhat insufficient, or the investigators needed to employ more sensitive instruments in their measurements. Biodiesel-butanol mix was blended with Jet A-1 fuel in a micro-gas turbine engine for the first time. The performance and emission characteristics of the blended fuel with Jet A fuel were investigated, including thermal efficiency, static thrust, thrust-specific fuel consumption (TSFC), CO and NOx emissions. Each blend was run in a micro-gas turbine engine at several throttle settings, with the results compared to those of pristine Jet A-1 fuel.

To the best of the authors' knowledge, no work on the use of DME-Jet A-1 fuel blended with Afzelia Africana biodiesel reports on its use in a MGT engine. Furthermore, it was also observed that admixing the biodiesel with the DME-Jet A-1 fuel mix was necessary for higher engine performance with marginal lower gaseous emissions in the MGT as a means to optimize the blended fuel's physicochemical features. Works on biodiesel admixed with DME-Jet-A-1 blends in MGT are lacking in the current literature; thus, this research is fixated on authenticating the exhaust emissions and performance characteristics of MGT using three fuel blends. Therefore, the aim of this research is to admix a fixed volume of Afzelia Africana biodiesel with DME-Jet-A blends in different percentages by volume in a micro-gas turbine and compare the properties with those of a neat Jet-A fuel, which served as a baseline fuel for the assessment in order to improve engine performance with lesser emissions compared to those of Jet-A fuels.

2. Materials and method

2.1. *Transesterification of Afzelia Africana crude oil*

Afzelia Africana seeds were harvested from a forest along Lagos, Nigeria, and thoroughly rinsed with distilled water to remove dirt and sand particles. The rinsed seeds were sun-dried for 48 h to allow for moisture removal before being oven-dried at 105 °C for 1 h. Furthermore, the dried seeds were crushed and transferred to a mechanical press so as to extract the crude Afzelia Africana crude oil. After extraction, the oil was transesterified with 1 wt% $KOCH_3$ (catalyst) and a 5:1 CH_3OH to oil molar ratio for 1 h at 55 °C to produce the required biodiesel (Fig. 1). The produced biodiesel was then stored in a 2000-mL reagent bottle for further use.

2.2. *Exhaust gas composition measurement*

Table 1 lists the devices that were used to measure the exhaust emissions (CO_2 CO, and NOx). To analyze the exhaust gas, a tapered quartz glass probe was adopted. Before entering the gas analyzer, the gas was treated to eliminate particles and moisture. The zero and span calibration parameters of the gas analyzer were set with standard gases. Thereafter, the emission concentrations were calculated.

The Dimethyl ether (DME) was purchased from Sigma Aldrich with 99.7% purity. The composition and properties of the Jet-A fuel and DME are presented in Tables 2 and 3 respectively.

Table 1
Instruments for Gas emission measurements.

Instruments	Error in Accuracy	% Uncertainties	Range
Digital Tachometer	± 10 *rpm*	±1	6 digits
Flow and air flow measurement	$\pm 0.2cm^2$	±1.5	–
Turbine temperature sensors (Conax)	±4	±0.2	0–2000 °C
Gas Analyzer (AVL DiComm 4000)	4%	± 1%	0–5000 ppm
CO	1 ppm	± 0.1	0–2000 ppm
NO_x	1 ppm	±0.1	0–5000 ppm
CO_2	±0.03	±0.1% *vol*	0–15%
O_2	±0.01% *vol*	±0.1	0–25%

Table 2
Jet- A aviation fuel composition.

Parameter	Jet – A fuel
Boiling point (°C)	117
Latent heat of vaporization. (kJ/kg)	330
Cycloalkanes (vol%)	20
Alkenes (vol%)	2
Alkanes (vol%)	60
Sulfur, ppm	490
Aromatics (vol%)	18

Table 3
Chemical and physical properties of DME.

Parameter	Fuel type
Chemical formula	CH_3OCH_3
Molar weight (kg/mol)	46.0
LHV, (MJ/kg)	28.4
Boiling point, 1 atm (°C)	−25.1
Explosion limits in air, (vol%)	3.5–16
Vapor pressure, 20 °C (bar)	5.00
Cetane number	57
Liquid density, 20 °C (kg/m^3)	667
Ignition temperature, (°C)	235

2.3. *Experimental procedure*

2.3.1. *Engine commissioning*

All experiments were conducted in a 30-kW micro gas turbine engine, as shown in Fig. 2; it is a test rig containing many parts with engine specifications listed in Table 4. The gas turbine engine system has the following dimensional specifications: 105 cm × 100 cm x 152 cm, length, breadth, and height, respectively, with an operational weight of 270 kg. The operating speed range and maximum thrust were 30,000–87,000 rpm and 178 N, respectively. The exhaust gas analyzer (AVL DiComm 4000) was used to analyze CO, NO_x, and CO_2 emissions. The turbine used in this test rig is a single-stage axial turbine with a single-stage radial compressor setup; the nozzle of the turbine is a fixed convergent type. The test unit is made of stainless steel. A small control unit is used to control both the engine's rotational speed and the throttle valve for fuel supply. A piston pump is used to supply the fuel effectively without the formation of air locks or fuel bubbles. The test engine runs on liquid fuel, and no lubricating oil is required to provide lubrication between bearings as the pre-setup is always done carefully. A data

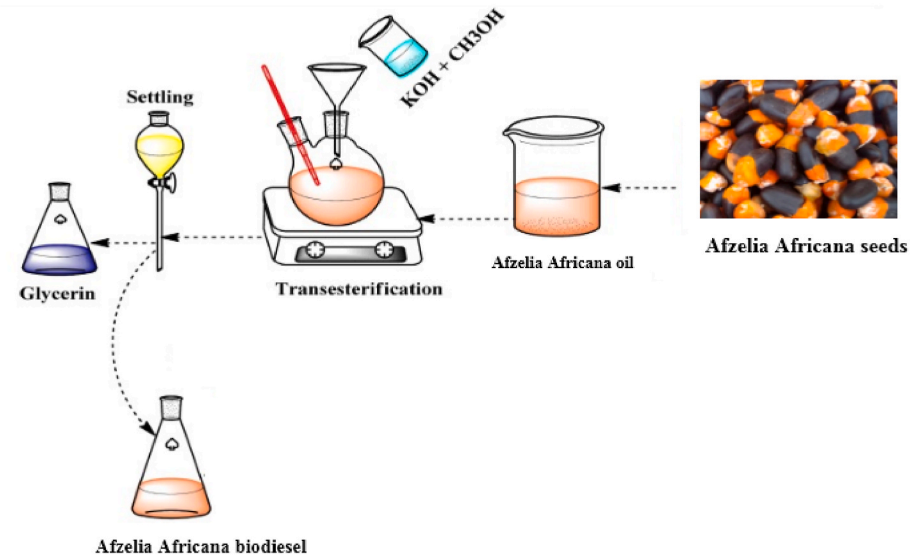

Fig. 1. Transesterification of Afzelia Africana crude oil.

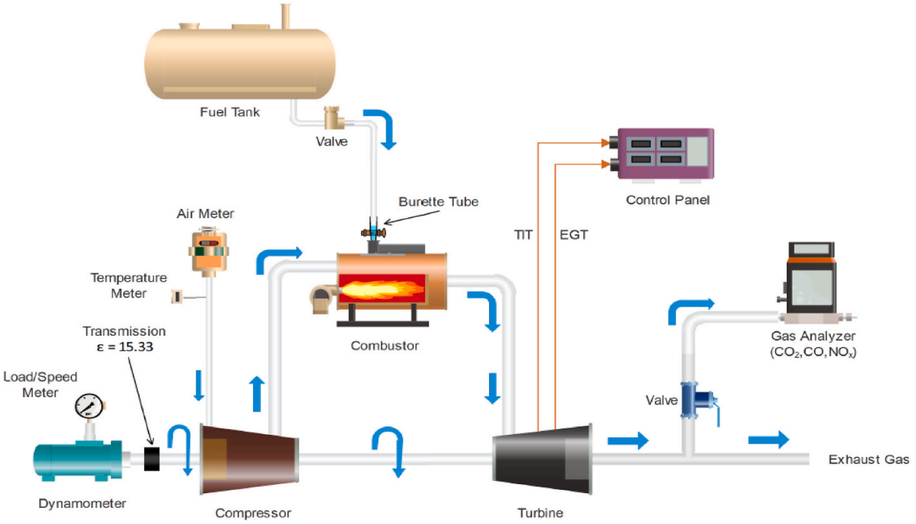

Fig. 2. Schematic diagram of the simple gas turbine engine.

Table 4
Specification of gas turbine Solar T-62T-32.

Turbine type	Single stage axial flow
Maximum speed	87,000 rpm
Maximum thrust	178 N
Maximum EGT	720 °C
Maximum TIT	870 °C
Air mass flow rate	0.5 kg/s (1.1 lb/s)
Compressor	Single stage centrifugal impeller
Compression ratio	2.5:1
Specific fuel consumption	1.2 lbm/h lbf (mild thrust)

acquisition system was installed in the engine, which measured the dynamic pressure and static temperature at the compressor inlet, the stagnation pressure/temperature at the compressor exit, the turbine outlet/inlet locations, the stagnation pressure at the thrust nozzle exit, and the static temperature. The rotational speed of the engine and the fuel supply throttle valve are controlled by a simple control unit. The piston pump supplied fuel without stimulating the formation of fuel bubbles. Throughout the runs, the temperature of the system was maintained at 750 °C using the temperature control unit. Pressure and temperature measurements were taken at various parts of the engine, including the compressor inlet, compressor exit, turbine inlet and exit, and also the nozzle exit. Pitot tubes were used to evaluate the stagnation pressure, and the stagnation temperature was measured with K-type thermocouples situated at various locations throughout the engine. The oil, fuel, and air supply pressures, as well as the thrust, fuel flow rate, and revolutions per minute, were all assessed. The capacity of the flow meter is 0–2 L/min. The flow meter can also measure the viscosity of the fuel up to 15 cSt [31]. The capacity of the pressure-measuring sensors is 0–15 psi. The inlet pressure differential is what determines the air mass flow rate. The properties of the gas emissions were determined with a specialized exhaust gas analyzer (DICOMM4000). The exhaust system is the focal point at which the probe is positioned. The engine pump and other components could be damaged if the blended fuels are used to start the turbine engine, hence, the MGT was commissioned with Jet-A fuel first for 20 min before the blends were used to run the MGT. The stagnation pressure was calculated by using the most common velocity/pressure measuring device (i.e., the pitot tube). The NOx, CO, and CO_2 emissions were evaluated by determining the emission properties of the exhaust gases. The static thrust was measured using a calibrated load cell, and the thrust-specific fuel consumption (TSFC) was determined using the measured values. Table 5 shows the experimental parameters and program adopted in evaluating and taking measurements.

2.3.2. *Preparation of the fuel mixtures*

The Jet-A fuel was obtained from one of Nigeria's refineries (Table 2), and the DME (Table 3) was purchased from Sigma Aldrich. The neat Afzelia Africana biodiesel fuel was produced from the raw Afzelia Africana seed oil by transesterification (Section 2.1). Separate three-component mixtures (biodiesel/DME/Jet A) with a fixed amount of biodiesel and different amounts of DME and Jet A fuel were made in different volumes (Table 6a and b). For example, the sample code A10B10J80 stands for 10% v/v biodiesel, 10% vol/vol DME, and 80% vol/vol Jet A-1 fuel and so on. At room temperature, the fuels were admixed and agitated. After several months of storage at ambient temperature, there was no separation of the components which confirmed that the mixtures were homogeneous and stable. Table 6a and b list the qualities of the fuels and their blends. The amount of O_2 in the fuel improved as the percentage of biodiesel/DME in the blend increased. However, when there is an increased DME concentration in the blend, the calorific value of the fuel-blends blend drops. On a mass basis, Jet-A has a higher heating value than DME. The Jet-A fuel has a surface tension of 24.2 mN/m, which is similar to DME's (25 mN/m). DME has a higher latent heat of vaporization (467 kJ/kg) compared to Jet-A fuel (330 kJ/kg), although DME's boiling point (198 °C) is lower than Jet A's (118 °C). The engine's fuel injector or rubber components can be damaged as a result of prolonged exposure to alcohol; hence, in order to overcome this challenge, a fuel manifold was fitted to the MGT fuel supply line so as to allow the engine to first run on Jet-A fuel. The fuel was replaced with the blended fuels after 10 min of running the engine with Jet-A fuel. To analyze the engine performance with various fuel blends, the thrust (T), thrust-specific fuel consumption (TSFC), fuel consumption, and turbine gas temperature were measured. For emission characteristics, the emission levels of CO, CO_2 and NO_x were measured. The results of all fuel blends were compared with the results of neat Jet-A fuel at different engine speeds, at three intervals from 30,000–80000 rpm. All the data were acquired using a 6218 DAS from National

Table 5
Study parameters and the experimental program used.

Study Parameter	Program Used/Instrument
Throttle position and fuel flow rate	DAQ (Data acquisition system)
Static thrust	DAQ
Thrust specific fuel consumption	DAQ
Turbine inlet temperature	Thermometer
NOx, CO, CO_2	The exhaust gas analyzer (AVL DiComm 4000)

*All equipment and instruments used in taking measurements were calibrated and adopted based on the manufacturers' instructions and recommendations.

Instruments that was coded in LabView. The parameters such as pressure and temperature were captured at the inlet and outlet sections of the turbine, and the uncertainties of the measuring instruments are as given in Table 1. Table 5 shows the study parameters and the experimental program used in the course of this investigation.

2.4. Uncertainty measurements

Errors may occur during the process of obtaining measurements as a result of the incorrect calibration of any measurement device. Uncertainties are mostly determined by the measure of repeatability obtainable in three measurements with a low level of or insignificant magnitude of standard deviation. The uncertainty correlation (eqn. (1)) was adopted in calculating the percentage uncertainty of all measured/pertinent parameters displayed in Table 5.

$$\Delta R = \left[\left(\frac{\partial P}{\partial v_1}\Delta v_1\right)^2 + \left(\frac{\partial P}{\partial v_2}\Delta v_2\right)^2 + \ldots + \left(\frac{\partial P}{\partial v_n}\Delta v_n\right)^2\right]^{\frac{1}{2}} \tag{1}$$

Where ΔR represent the total uncertainty.

P – is a function of the independent variables of v_1 , v_2 …… … … v_n.

$\Delta v_1, \Delta v_2 \ldots\ldots\ldots \Delta v_n$ *are the independent variable uncertainties.*

$$\Delta R = \sqrt{(Digital\ tachometer)^2 + (flow\ and\ air\ flow\ measurement)^2 + (Turbine\ tempearture\ sensor)^2 + (Turbine\ tempearture\ sensor)^2 + (NO_x)^2 + (O_2)^2 + (CO_2)^2 + (CO)^2}$$

$$\Delta R = \sqrt{(1)^2 + (1.5)^2 + (0.2)^2 + (0.1)^2 + (0.2)^2 + (0.15)^2 + (0.1)^2}$$

Thus, the percentage overall uncertainty (ΔR) is ± 1.83 %.

3. Results and discussion

The physicochemical properties of all the tested fuels and their blends are presented in Tables 6a and 6b, respectively. The tested fuels include Jet A fuel, DME, biodiesel, A10B10J80 (10% DME + 10% biodiesel + 80% Jet A fuel), A15B10J75 (15% DME +10% biodiesel + 75% Jet A fuel), and A20B10J70 (20% DME +10% biodiesel + 70% Jet A fuel). The properties determined are as follows: sulfur content, flash point, density, kinematic viscosity, cetane number, calorific value, and pour point. All the tests were conducted in line with the ASTM (American Society for Testing and Materials) standards.

Fig. 3 illustrates the FTIR spectra of the blended fuels. The peaks of the blends at 2918 and 2849 cm^{-1}, represent aliphatic C–H stretching vibrations of the CH–CH$_2$ and –CH$_3$ groups in the Jet A fuels, respectively [16]. The peaks at 1464 cm^{-1} and 1734 cm^{-1} correspond to the methyl esters present in the biofuels, and the absorption wavelength at 962 cm^{-1} represents the bending vibrations of the C=C band. For the blended fuels, the absorption wavelengths at 2848 and 2914 cm^{-1} correspond to the methyl (-CH$_2$) C–H asymmetrical/symmetrical stretching bonds. The wavelengths 1375 and 1464 cm^{-1} correspond to the –O– ether and the –OH alcohol groups of DME respectively. The wave number 722 cm^{-1} corresponds to C and phenyl compounds aliphatic chain-rocking. The wave numbers 2914-2848 (methyl (-CH$_2$) C–H asymmetrical/symmetrical stretching bonds), 1463 and 722 cm^{-1} collectively confirm the presence of ether, methyl and aldehydes in the DME, biodiesel, and Jet A fuel blends. The wavelengths 2918 and 2849/cm confirm the bonds (methyl (-CH$_2$) C–H asymmetrical/symmetrical stretching bonds) present in the A10B10J80 and A15B10J75 and the wavelength 2914-2848/cm (A20B10J70) is an indication of the same bonds in the JET fuel. Furthermore, at 1464 cm^{-1} and 1734 cm^{-1} it indicates the methyl esters (fixed biodiesel) in the blends; finally, at the 724 cm^{-1}, 962 cm^{-1} and 722 cm^{-1} marks, the presence of DME is confirmed in the A10B10J80, (A15B10J75), and (A20B10J70) fuels.

3.1. Fuel characteristics of engine performance

3.1.1. Throttle position and fuel flow rate

Fig. 4 presents the variations in the engine speed for all the tested fuels at various throttle valve openings as a means of controlling the supply of the fuel. It can be seen that when the fuel supply increased, there was also an increase in the engine speed, regardless of the fuel's composition. In comparison to all the other fuel blends and the Jet-A fuel, the fuel sample A10B10J80 attained the highest maximum engine-speed. There were slight differences in the properties of the Jet-A fuel and their blends as the throttle valve was opened from 20 to 80%. The A10B10J80 blend generated slightly higher engine speeds at all the different adjustments of the throttle valve opening owing to its lower viscosity compared to those of the other blends. This is due to the amount of DME that was injected into the biodiesel-Jet A fuel mix which was used in running the MGT. The fuel's flow rate also increased as a result of the lower viscosity of the fuel relative to those of the 15–20% DME injected biodiesel-JETA fuel mixtures which had higher viscosity. According to the results, the A15B10J75 and A20B10J70 blends had lower engine speeds relative to those of the Jet-A fuel. The engine speeds for the A20B10J70, biodiesel, and DME were less than those of Jet-A fuel at various throttle settings. At the maximum throttle position, the engine speeds for the Jet-A, A10B10J80, A15B10J75, A20B10J70, DME, and biodiesel were 66986, 68998, 67002, 66944, 65048, and 60094 rpm respectively; these results corroborate the findings in the works of ref. [23].

Fig. 5 depicts the variations in the flow volume of the fuels for the various fuel blends at different throttle openings. Jet fuel, A10B10J80, A15B10J75, A20B10J70, DME, and biodiesel had fuel volume flow rates of 0.86 L/min, 0.83 L/min, 0.76 L/min, 0.72 L/min, 0.7 L/min, and 0.68 L/min at 80% throttle opening, respectively. At various throttle positions (20%, 40%, 60%, and 80%), the fuel's flow rate was determined. The fuel blends containing the Jet fuel had higher volume flow rates relative to the other fuels. Due to higher fluid velocity, i.e., when the concentration/proportion of the JET fuel in the blends (in terms of % vol/vol) increased, the fuel's volume flow rate increased owing to the induced lower viscosity imposed on the fuel mixture by the JET-A1 fuel compared to other constituents. These results are in accordance with the results documented in Ref. [24], where flow rates ranging from 0.66 to 0.88 L/min, were documented.

3.1.2. Static thrust

All the tested fuels were run at the same throttle levels and at varying engine speeds, as illustrated in Fig. 6. The operating speed was in the range of 40000–70000 rpm at the maximum throttle setting due to the reduced heating value of the fuel as imposed by the blended additive in the Jet A fuel relative to that of the pristine Jet A fuel, while the differences in the heat of vaporization and viscosity of the fuel may also

Table 6a

Physicochemical characteristics of the tested fuels.

Fuel type (% v/v)	Density (kg/m^3)	Kinematic Viscosity @ 40 °C (mm^2/s)	Cetane number	Flash point (°C)	Calorific Value (MJ/kg)	Pour point (°C)	Sulfur content (% wt.)
Jet fuel	809.5	3.4	44.1	39	42.2	−31	0.01
DME	667.1	0.2	57	–	19.3	–	–
Biodiesel	844.0	4.6	46	192	42	3	–

Table 6b
Physicochemical characteristics of the fuel blends.

Fuel type (% v/v)	Density (kg/m^3)	Kinematic Viscosity @ 40 °C (mm^2/s)	Cetane number	Flash point (°C)	Calorific Value (MJ/kg)	Pour point (°C)	Sulfur content (% wt.)
A10B10J80	809.1	3.2	45.9	80	41.7	−1	–
A15B10J75	817.3	3.5	45.5	83	41.4	1	0.001
A20B10J70	821.4	3.7	45.2	82	41.0	−1	–

Note: Several mixed trials of the fuel blends in different proportions/ratios were considered in this experiment in order to obtain the optimum fuel mix for the best performance of the MGT. However, after several trials, the blends: A10B10J80, A15B10J75, and A20B10J70 displayed the best characteristics and were thus adopted for use in the MGT.

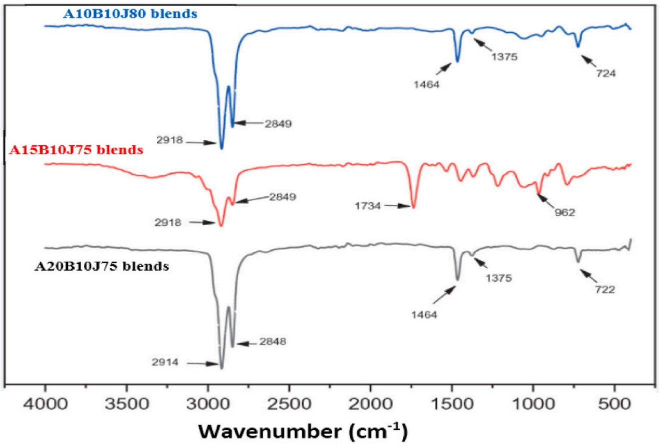

Fig. 3. FTIR Spectrum of the blended fuels A10B10J80, A15B10J75 and A20B10J70.

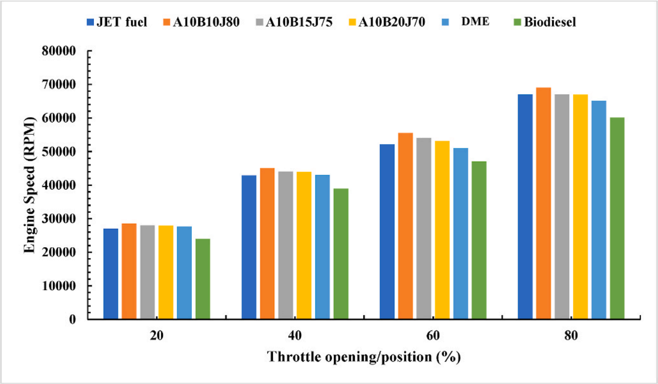

Fig. 4. Variation of throttle valve opening/position versus engine speed.

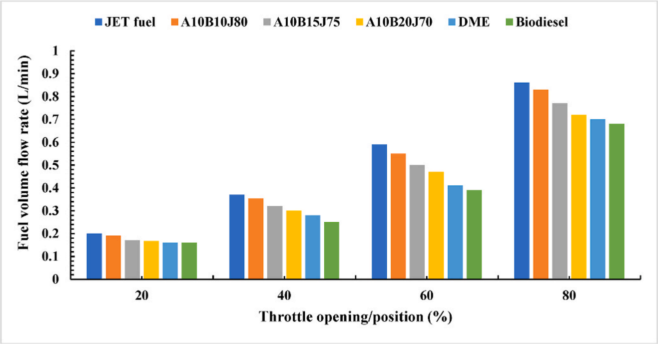

Fig. 5. Variation of throttle open position versus fuel volume flow.

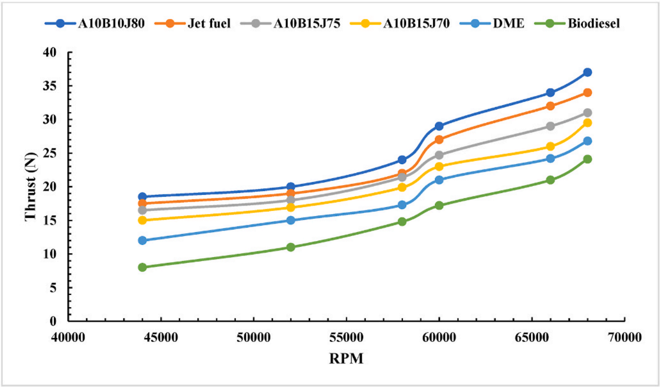

Fig. 6. Engine speed on static thrust of various fuels.

have influenced the heat release rate and combustion of the fuel blends. The A10B10J80 blend displayed a higher thrust of 3% over that of the Jet-A fuel, whereas the other fuel blends gave lower thrusts compared to that of the Jet-A1 fuel. Additionally, due to the alcohol level and high O_2 content of the exhaust gas, the A10B10J80 gave greater thrusts compared to that of the Jet A1 fuel [24]. The A10B15J75 and A10B20J70 blends did not really perform as expected considering that they contained lower proportions of Jet A fuel and higher proportions of DME which are below and above the minimum composition required for maximum thrust respectively. In comparison to the Jet A1 fuel, at the highest speed (68,000 rpm), the A10B15J75 and A10B20J70 gave 3 and 4.5% lower thrusts and had less visible effects on the performance characteristics of the engine, respectively. Prior tests conducted with biodiesel, propanol, ethanol, and pure DME, as determined by other research scholars, gave comparable observations, as presented in Ref. [25]. Owing to the further induced lower heating values of the 15–20% DME containing fuels, the thrusts obtained for the A10B15J75 (31 N) and A10B20J70 (29.5 N) fuels were lower; similar findings were documented in Ref. [26], which reported 29.5 N and 30.5 N as thrusts, respectively. As the DME concentration in the blends increased, the maximum thrust produced by the MGT engine dropped [7]. As a result of having a comparative calorific value (i.e., 41.7 MJ/kg) relative to that of the neat jet A fuel (42.2 MJ/kg) as well as the synergistic interactions of the DME and Afzelia biodiesel and JET A1, which would have led to the production of light/volatile components and modification of the properties of the fuel mixture, the A10B10J80 fuel gave the highest thrust (37 N) compared to those of the other fuels and fuel blends; thus this can be attributed to its lower kinematic viscosity (ratio of viscosity to density) (i.e. 3.2 mm^2/s -A10B10J80) vs 3.4 mm^2/s which was recorded for the JET A1 fuel; however, it was observed that the higher density of the increased proportions of DME imposed lower thrusts in the fuel blends with higher (15–20%) DME proportions. In addition, the higher latent heat of vaporization is also a determinant factor that influenced the thrust of the A10B10J80 blend. Although, the Africana Afzelia biodiesel had a higher calorific value compared to those of the blended fuels, its higher viscosity posed increased resistance to the fuel's thrust characteristics.

3.1.3. *Thrust specific fuel consumption (TSFC)*

Fig. 7 shows the variation of TSFC with engine speed. The thermal efficiency of a system is measured by the fuel's weight flow rate (N/h) consumed per unit thrust (N). The overall hourly amount of fuel (N/h) burned by the engine to generate a large amount of thrust is known as the engine-TSFC. As expected, the Jet A fuel had the highest TSFC compared to the other tested fuels due to its slow diffusion rate imposed by its density amid its moderate viscosity when compared with those of the other fuels. When compared to Jet A fuel, the fuel A10B10J80 exhibited a 14% reduction in fuel consumption at the lowest speed, while the fuel A10B20J70 was only about 36% less; the plot shows that in decreasing order magnitude of the TSFC is: JET A1, A10B10J80, A10B15J75, A10B20J70. At high speed (68,000 rpm), the TSFC of the A10B10J80 is close to that of the pristine Jet A fuel, which may be due to the lower viscosity and latent heat of vaporization of both fuels. Higher calorific values and low fuel atomization at higher engine loads are the causes of lower TSFCs. All the biofuel blends showed lower TSFCs compared to those recorded for the Jet A1 fuel. The presence of DME in the blends reduced the blended fuel's TSFCs without compromising the resulting engine thrusts; similar trends were also observed in Ref. [27].

3.1.4. *Turbine inlet temperature (TIT)*

Fig. 8 illustrates the variation of TIT as a function of engine speed. At different throttle settings, the TIT, which was monitored immediately after the combustion chamber, improved as a result of an increase in the fuel's flow rate. The TIT varied non-monotonically with engine speed for all the fuels with biodiesel having the least TIT, while the A10B10J80 and Jet-A1 fuels gave the highest TITs. The recorded TITs of all the fuels were between 700 and 1000 K. Fig. 8 shows the turbine temperatures for the blended fuels, DME, biodiesel, and Jet-A1 fuels at various speeds. As the engine speed increased, the turbine inlet temperature increased as well. At 80% throttle valve opening, the TIT dropped to 984 K, which is ideal for the Jet-A1 fuel. Compared to Jet-A1 fuel, there was not much difference between the TIT obtained for the A10B10J80, A15B10J75 and A20B10J70 fuel blends [3]. All of the turbine temperatures recorded for the fuel blends were lower than those of Jet-A fuel. Due to the lower calorific value of the blended fuels, the maximum temperatures generated by the A10B10J80, A10B15J75, A10B20J70, biodiesel, and DME fuels at 68000 rpm were 950 K, 892 K, 844 K, 795 K, and 887 K, respectively. These results justify the findings in the work of Ref. [29], where the recorded TITs ranged from 850 to 950 K and the difference in the range of the recorded TITs in both works can be attributed to the use of DME as additive in the present study as well as the nature of the biodiesel adopted in both studies.

3.2. *Analysis of gaseous emissions*

3.2.1. *Effects of NO_x emissions on turbine engine*

Among the various emissions obtained from fuels used in the MGT, NO_x is thought to be the most hazardous. The NO_x emission indices of the fuels were calculated using the NO_x concentrations measured as a function of engine speed at the exhaust as presented in Fig. 9. Several researchers found that biofuel emits more NO_x emissions than fossil fuels. This is primarily due to the fuel's oxygen concentration and molecular weight of the methyl esters that make up the biofuel. DME addition to the blends, reduced the NO_x emissions. Pure DME had the lowest NO_x emission index (i.e., about 28% lower than that of the Jet-A1 fuel). 20% lesser NO_x emissions were observed in the blended fuels as compared to that of Jet A1 fuel. DME addition to the Jet A1-biodiesel blends reduced the NO_x emissions going out of the exhaust of the MGT, thus reducing the combustion temperature because of the high latent heat of vaporization [9]. As a result of the lower temperatures, pure DME displayed lower NO_x emission indices. It was observed that the temperature in the combustion chamber, vaporization and ignition delay all influenced the resulting NO_x emissions. Nonetheless, DME, having the highest cetane number assisted in achieving low emissions in the fuel mixtures. The air-fuel ratio and cetane number of all the blended fuels demonstrated a convincing reduction in the emitted NO_x emissions compared to that of the Jet A1 fuel. In other words, the higher NO_x emissions resulting from the exhaust pipe for the Jet-A fuel are due to the rapid fuel burning-rate and higher flame temperature with respect to those of the other fuels. In lieu of this, the high combustion temperature results in the production of increased nitrogen oxides from the burnt un-blended/pristine Jet A1 fuel [28]. Hence, the DME content of the fuel-blends reduced the resulting NO_x emissions in the fuels since DME gave the lowest NO emissions as presented in Fig. 8. The average results of all the tested fuels are as follows: Jet-A fuel (0.84 g/kg), A10B1070 (0.62 g/kg), A10B15J75 (0.63 g/kg), A10B10J80 (0.55 g/kg) DME

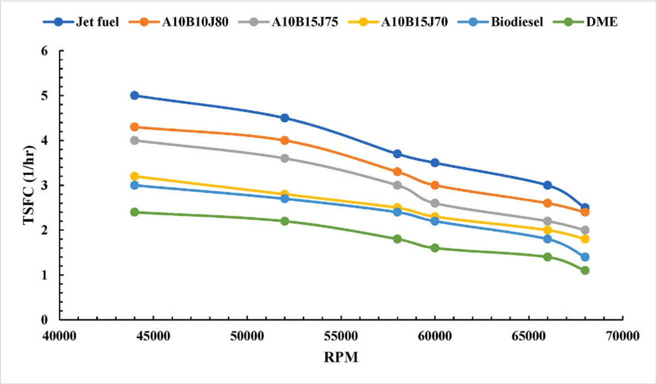

Fig. 7. Trust specific fuel consumption versus RPM of tested fuels.

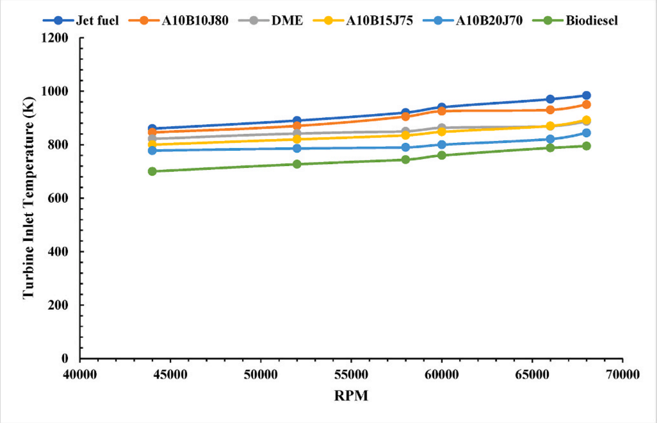

Fig. 8. Variations of Turbine inlet temperature (TIT) with engine speed.

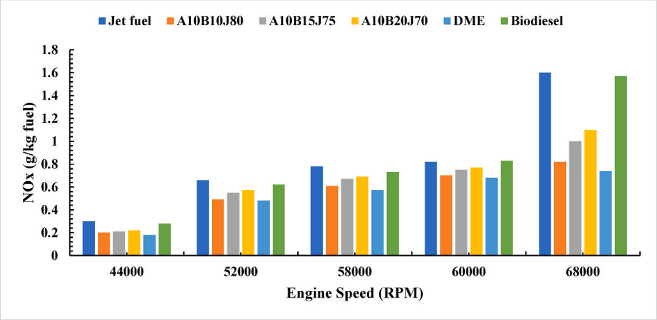

Fig. 9. Variation in NOx emission on engine speed.

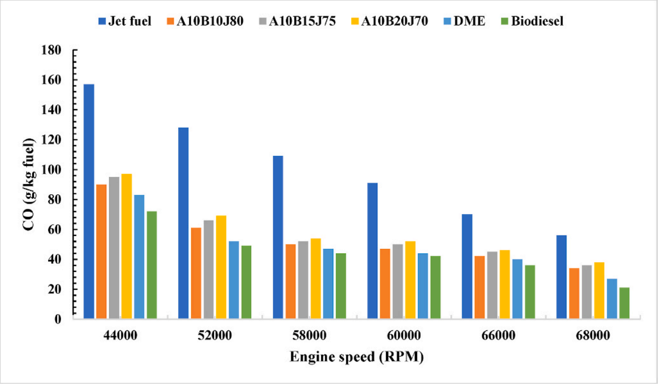

Fig. 10. Variation CO emission on engine speed.

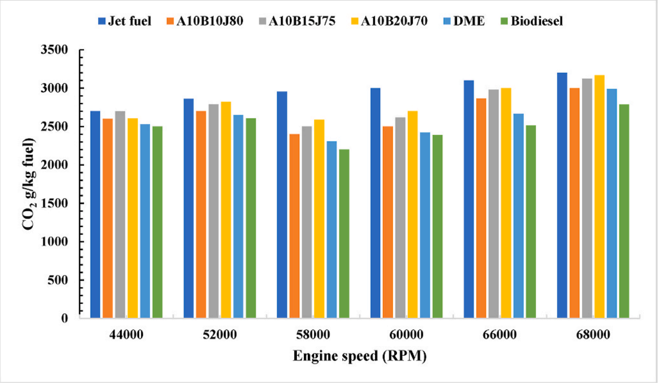

Fig. 11. Variation in CO_2 emission on engine speed.

(0.53 g/kg) and Africana Afzelia biodiesel (0.81 g/kg). The obtained results corroborate those documented in Ref. [32].

3.2.2. *Effects of CO emissions on turbine engine*

The CO emission index (EI) of all the fuels decreased with an increase in engine speed, thus implying the occurrence of complete combustion of the fuel blends. This trend has also been noticed in most biofuel applications due to the high presence of O_2 in the DME-biodiesel blends imposed by both components. In addition, the production of soot was suppressed by the presence/increased amount of O_2 in the fuel. Fig. 10 depicts the CO emissions for all the tested fuels (A10B10J80, A10B15J75, A10B20J80, biodiesel, DME, and the pristine Jet-A fuel) at various speeds. An increase in engine speed resulted in a reduction in CO emissions, as informed by the estimated emission indices (EI). For all the tested fuel blends, the resulting CO emissions were significantly reduced compared to those of the Jet-A fuel. In all the blended fuels, the quantity of carbon loss increased as documented in Ref. [20]. Due to the carbon neutral nature of the biofuel blends, alongside an increase in the carbon constituent of the fuel mixtures (i.e., bearing high carbon content by virtue of the organic nature of the constituents which may have imposed a distortion or an alteration in the carbon chain length of the JET A1 fuel in the blended fuels), a large amount of CO emissions was obtained for the fuel blends but somewhat lower than that of the JET A1 fuel with non-distorted chain length. In order of reduced CO emissions from the exhaust of the MGT, the trend trend observed for the fuels is Jet-A fuel, A10B1070, A10B1075, A10B1080, DME, and Africana Afzelia biodiesel.

3.2.3. *Emission of carbon dioxide (CO_2)*

CO_2 is among the most significant/prominent causes of greenhouse gas pollution. High carbon dioxide emissions are caused by the high O_2 and carbon contents of the fuel. A study has shown that when fossil fuels are substituted with biofuels, CO_2 emissions are reduced [22]. The EIs of CO_2 emissions increased with an increase in engine speed. Due to the lower viscosity, number of carbon atoms, and chemical structure of the fuels, the A10B10J80, A15B10J75, and A20B10J70 emitted 22, 16, and 10% lesser amounts of CO_2 relative to that received for the Jet fuel (Fig. 11).

In a bid to establish a level of comparison with the results of past literature on the subject, the findings of several studies were documented alongside those of the current study as contained in Table 7.

4. Conclusions

This study investigated the effect of adding varying compositions of DME and Jet-A1 to a fixed amount of Africana Afzelia fuel used in a MGT. The emission and performance characteristics of the MGT for varying proportions of DME and Jet A fuel in the blends as well as their pristine forms were examined. The Jet-A1 fuel was used to establish a baseline for comparing the performance of all the prepared fuels. The performance and emission properties of the A10B10J80, A10B15J75, and A10B20J70 biodiesel and DME, as well as those of the neat jet-A fuel, were determined at several engine speeds ranging from 44,000–68,000 rpm. Keeping the throttle positions at 20, 40, 60, and 80% varying fuel flow rates were established for all the tested fuels. The engine speed increased along with the static thrust. The maximum static thrusts achieved at 80,000 rpm for all the fuels are as follows: A10B10J80 (37 N), A15B10J75 (31 N), A20B10J70 (29.5 N), and Jet A fuel (34 N), respectively, however, the A10B10J80 displayed the highest static thrust (37 N). In terms of performance, the Jet A1 fuel was only outperformed by the A10B10J80 fuel in terms of the recorded thrusts, while in terms of TSFCs both fuels gave higher values compared to other fuels at steady increases in engine speed; however, the JET A1 fuel had the highest TFSC followed by the A10B10J80 fuel. The A10B10J80 blend delivered more thrust than that of the Jet-A fuel at the specified

Table 7
Results from other works as compared to those of the present study.

Engine specification	Biofuel type/ fuel type	Highest biofuel blends compared to JET A fuel	Biofuel Performance compared to JET fuel	Emission properties compared to JET fuel	Engine speed (rpm)	Ref.
Micro gas turbine (178 N)	*Spirulina* biofuel	B20% (20% biofuel with 80% jet- A fuel),	T ↓ TSFC ↓	CO ↓ CO_2 ↓ NO_x ↑	30000 to 80000	[28]
Micro gas turbine (178 N)	Rapeseed biofuel	R20E (Jet-A 70% fuel, 20% Rapeseed, and 10% ethanol)	T ↑ TSFC ↓ TE ↑	CO ↓ CO_2 ↓ NO_x ↓	30000 to 70000	[29]
Micro gas turbine (178 N)	Microalgae	A20 (20% microalgae 80% Jet-A)	T ↓ TSFC ↓	CO ↓ CO_2 ↓ NO_x ↓	30000 to 80000	[30]
Micro gas turbine (178 N)	glycerol	G20T (glycerol 10% with 50 ppm TiO2 and Jet-A 90%)	T ↑ TSFC ↓ TE ↑	CO ↓ CO_2 ↓ NO_x ↓	30000 to 80000	[31]
Micro gas turbine (178 N)	*Dunaliella salina*	DB50 (Jet A fuel 50% + *Dunaliella salina* 50%)	T ↓ TSFC ↓ TE ↑	CO ↓ CO_2 ↓ NO_x ↑	40000 to 60000	[32]
This study: Micro gas turbine (178 N)	Afzelia Africana	A10B10J80 (10% biodiesel-10% dimethyl ether −80% Jet fuel)	T ↑ TSFC ↓	CO ↓ CO_2 ↓ NO_x ↓	30000 to 80000	This study

*T - Thrust, TFSC- Thrust specific fuel consumption; TE – Thermal Efficiency.

engine speeds. Since more fuel was delivered into the chamber as the engine speed increased, the turbine inlet temperature was seen to increase as well. The turbine inlet temperature and engine exhaust gas temperature for all the fuels did not show significant changes despite the difference in the percentage composition of the constituents of the fuels and different fuel types. Due to the conflicting effects of the decreased calorific value as well as the presence of O_2 in the fuels, the turbine inlet temperature fluctuated non-monotonically with the adjusted compositions of JETA1-DME concentrations in the fuels. All of the fuels had comparable exhaust gas temperatures. The CO, NO_x, and CO_2 emission indices for the fuel blends were all much lower than those of the Jet-A fuel. Thus, of the three blends, the A10B10J80 fuel mix, is a potential alternative fuel for use in a MGT since the A10B10J80 mixture gave better properties and improved performance relative to those of the pristine Jet A1 fuel. Hence, of all the tested fuels, the fuel with the richest fuel properties or engine characteristics and NOx emissions is the A10B1080 fuel owing to the induced influence of DME in the fuel-mix.

5. Future investigation and recommendations/research gaps

Although, the use of Biodiesel-Jet A-DME fuel blends in a microgas turbine have been presented in the current study, more investigations into the effects of nanoparticles added to the fuel for improved stability and surface area are recommended. Also, due to the variability in qualities among the non-edible oil seeds used to produce biodiesel, it is important to test the effects (emissions and performance) of various biodiesel and biodiesel/jet fuel blends in a MGT. Since MGT emissions, performance, and combustion characteristics have been evaluated by blending biodiesel/Jet A fuels with DME, other new additives with potentials for improving the spray characteristics and engine thrust can be explored and compared with those imposed by DME. In addition, it is expected that future researches will consider the life cycle analysis/evaluation of the environmental impacts of different biodiesels and additives in JET A1 fuel over the course of their entire life cycles, their cost-effectiveness in terms of production, alongside the economic implications of different JET A1-additive-biodiesel fuel blends used in MGTs, while also considering trade off relationships in terms of minimal emissions, engine performance and Thrust Specific Fuel Consumption. The authors are also of the opinion that since apt control measures for ensuring apt injection pressure and timing were seen to affect the performance of biodiesel Jet A-DME blends, the totality of these effects in terms of their variation were not factored into the current research and hence, may be considered in future investigations.

CRediT authorship contribution statement

Babalola Aisosa Oni: Formal analysis, Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Samuel Eshorame Sanni:** Formal analysis, Investigation, Supervision, Writing – review & editing. **Olusegun Stanley Tomomewo:** Data curation, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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