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Particulate Emissions and Size Distributions of Biofuel in Micro Gas Turbine Engine

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Mohamed A. Altaher[1], Karamat Mohammed[2], Hu Li[2]

[1]Chemical Engineering Department, Faculty of Engineering, Sebha University
[2]Energy Research Institute, Leeds University, Leeds, UK.
Corresponding Author: altaher_moh@hotmail.com

Abstract

Atmospheric CO2 has been reported to be on a rapid increase in recent times mainly due to the rising consumption of fossil fuel for anthropogenic activities. Currently the situation is that of the 25% fossil fuel consumption by the transportation sector, aviation sector consumes about 13% of transport fuel consumption, which is the second biggest sector after road transportation. Therefore, the applications of biofuels have been increased in aviation. The aim of this work is to investigate and compare biodiesel and its blends with syntactic kerosene. The pollutants of particulate emissions and their size distributions were analyzed. Jet A1 and blends of Jet A1 and biodiesel in volume ratios of 90:10 (B10), 80:20 (B20), 70:30 (B30), 50:50 (B50) and 30:70 (B70) mixed with 2.5% turbine lubricating oil were tested. The fuels were tested at three load conditions (throttle settings): Full power, 70% and idle condition. Scanning Mobility Particle Sizer has been used to determine the particulate size distribution and the number of concentration of diluted exhaust gases. The results showed that particulates from all throttle settings showed uni-modal distribution characteristics. Particulate number concentration of each fuel increases with the increase in throttle position. The increase in biodiesel ratio in biodiesel blend has also increased the particulate size concentration. More particulates were seen to be produced with Jet A1 and lower blends of biodiesel. The engine also produces a significantly higher number of particles at full power for all fuel types.

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Keywords: Biodiesel, Micro Gas Turbine Engine, Scanning Mobility Particle Sizer, waste cooking oil, pollutants.

قياس انبعاثات الجسيمات الصلبة وتوزيعها الناتجة من الوقود الحيوي في محرك التوربين الغازي المصغر

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محمد العالم الطاهر[1]، كرمات محمد[2]، هيو لي[2]

[1]قسم الهندسة الكيميائية، كلية الهندسة، جامعة سبها
[2]مركز بحوث الطاقة، جامعة ليدز ، بريطانيا

الملخص

ان نسبة غاز ثاني أكسيد الكربون في الغلاف زادت بنسبة سريعة في الآونة الأخيرة ويرجع ذلك أساسا إلى الارتفاع في استهلاك الوقود الأحفوري للأنشطة البشرية. يشكل قطاع النقل 25% من استهلاك الوقود الأحفوري ويستهلك قطاع الطيران حوالي 13 ٪ من هذا الاستهلاك وهو ثاني أكبر قطاع بعد النقل البري. لذلك، تم زيادة نسبة استخدام الوقود الحيوي (الديزل الحيوي) في مجال الطيران. ان الهدف من هذا العمل هو دراسة ومقارنة وقود الديزل الحيوي بنسب مختلفة مع الكيروسين. تم قياس ومقارنة ملوثات انبعاثات الجسيمات وحجمها. تم خلط الوقود الحيوي بنسب متفاوتة مع الكيروسين العادي علي النحو التالي:- 90:10 (ب 10) ، 80:20 (ب 20) ، 70:30 (ب 30) ، 50:50 (ب 50) و 30:70 (ب 70) وتم اضافة زيت تشحيم التوربينات بنسبة 2.5 ٪. تم اختبار الوقود في ثلاثة ظروف تحميل: الطاقة الكاملة (100%)، 70 ٪ وحالة الخمول وتم الاختبار في محرك التوربين الغازي الصغير. تم استخدام جهاز قياس حجم جسيمات لتحديد توزيع حجم الجسيمات وعدد تركيز غازات العادم المخففة. أظهرت النتائج أن الجسيمات من جميع إعدادات الخانق أظهرت خصائص توزيع أحادية الوسائط. يزداد تركيز عدد الجسيمات لكل وقود مع زيادة ظروف التحميل. كما أدت الزيادة في نسبة

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وقود الديزل الحيوي في مزيج وقود الديزل الحيوي إلى زيادة تركيز حجم الجسيمات. واظهرت النتائج ايضا ان وقود الكيروسين العادي ينتج مزيد من الجسيمات وكذلك المخلوط بنسب بسيطة مقارنة بالنسب العالية. لوحظ ايضا زيادة عدد الجسيمات بشكل كبير عند الحمل الكامل للمحرك لجميع أنواع الوقود.

الكلمات المفتاحية: وقود الديزل الحيوي، محرك توربيني غازي صغير، مسح حجم الجسيمات الحركية، نفايات زيت الطهي، الملوثات.

Introduction

Biofuels are attractive alternative to petroleum fuels. Presently in road transportation, biofuels are the most important form of renewable energy demonstrating a relatively low cost alternative [1]. The use of alternative biofuel is aimed at achieving energy, environmental and agricultural policy goals which are assessed using economic cost benefit analysis [2]. The use of biofuels has many benefits which includes; reduction of environmentally detrimental emissions from petroleum based fossil fuels, sustainability, rural development and security of supply [3]. Biofuels are used to power engines, heat homes, and for cooking. Recently, sustainable biofuels have been introduced in air transportation to help in reducing our dependence on fossil fuels and in reducing greenhouse gas (GHG) emissions from air industry [4]. Biodiesel has been widely studied and used in gas turbine and diesel engines [5,6,7].The performance and emissions characteristics of a 30 kW gas turbine engine burning a variety of fuels (Jet A, soy methyl ester, canola methyl ester, recycled rapeseed methyl ester, hog-fat biofuel) and their 50% (volume) blends in Jet were studied over a range of throttle settings [8]. They found that the addition of biofuel resulted in a reduction in static thrust and thrust-specific fuel consumption, and increased thermal efficiency. In the same vein, Xue et al[9] reported that the use of biodiesel led to the substantial reduction in particulate matter emissions (PM), hydrocarbon (HC) and carbon monoxide (CO) emissions accompanying with the imperceptible power loss.

In this work, the particulate size distribution and number concentration were analyzed for Jet A1 and various biodiesel blends using a micro gas turbine engine. The research was conducted in light of increasing interest in biofuels as an alternative to fossil fuels with the objective of contributing to the development of biofuel technology in the aviation industry.
Particulates from all throttle settings showed unimodal distribution characteristics. Particulate number concentration of each fuel increases with increase in throttle position. Increase in biodiesel ratio in biodiesel blend also increased the particulate size concentration. This research provides a step forward in integrating into the development of biofuel technology in the aviation industry and also giving insight into the appropriate blend of biodiesel that could be safe for the efficiency of the engine and environmentally friendly. Findings obtained from this analysis would play a great role in a low cost means of testing biofuel.

Materials and Methods

This paper utilized quantitative data collection tools to analyze different blends of biodiesel that could be used as an aviation fuel, which is focused on collection and analysis of numerical data and statistics. The numerical data was collected with Scanning Mobility Particle Sizer (SMPS) with a Differential Mobility Analyses (DMA). Careful analysis was done to prepare a statistical data to analyze the possible blend of biodiesel that could be both environmental friendly and engine efficient. Analysis of this was performed in the laboratory using a micro gas turbine engine for determining its chemical/thermodynamic properties and its physical properties. Some of which includes the particulate size distribution, number concentration, quantify and detect emission rate. The research was carried out on an affordable scaled down version of a turbo jet (MW54 Mk3), it comprises of centrifugal compressor, combustion chamber, and a converged exhaust cone. Fuel was injected into the vaporizer tube which directs the fuel vapor to the combustion chamber where it is mixed with air.
The fuel that was used to power the micro gas turbine engine (Figure 1) in this research was a biodiesel derived from waste cooking oil from food industry which has been converted into high quality

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biodiesel. Jet A1 and blends of Jet A1 and biodiesel in volume ratio 90:10 (B10), 80:20 (B20), 70:30 (B30), 50:50 (B50) and 30:70 (B70) mixed with 2.5% turbine lubricating oil were tested. Jet A-1 is a kerosene type of fuel suitable for most turbine engine aircraft produced to international standard. The flash point Jet A-1 is above 38 °C and the freezing point is -47 °C. The fuels were tested at three load conditions (throttle settings): Full power, 70% and idle condition. At maximum thrust, the engine consumed 210 mL of fuel in a minute and 50 mL of fuel at idle position.

Figure1. Experimental engine and instrumentation

The engine was mounted on a stand fixed to the test bench, which has a slider platform. The engine thrust was measured using a potentiometer; this was as a result of a pressure transducer that was mounted on the stand to measure the resistance change. The resistance changes detected by the pressure transducer were measured by a strain gauge in terms of voltage, which was then converted into thrust using the relationship between engine thrust and resistance changes. A pressure gauge was also installed to measure pressure; the pressure gauge was mounted in a way that it would be visible to the operator. A thermocouple placed through an opening in the exhaust cone protruding at about 2mm into the exhaust steam was used to measure the exhaust gas temperature. The FADEC which is a control system for the engine was used to

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regulate and control fuel pump, measure rpm, throttle positions and exhaust gas temperatures and also for operating the devices used for starting the engine.

TSI model 3963 SMPS equipped with model 3080 Electrostatic Classifier and model 3081 Differential Mobility Analyser (DMA) is an automated system that have been used to determine the particulate size distribution and the number of concentration of diluted exhaust gases within the size range of 14.3 nm to 685 nm. Exhaust gases from the exhaust cone was channeled into a 20 cm diameter duct, where the exhaust gases was diluted by the ambient air. Samples from the exhaust were taken with the use of a stainless steel probe; dipped 2 m down the entrance of the duct was for SMPS. The CO and CO_2 concentrations were measured at the outlet plane of the engine exhaust and the particulate sampling location where the particles samples were taken. The dilution ratio of the gases from the exhaust was determined by the difference in CO and CO_2 concentrations at two positions. The regulated pollutants were discussed and published in a previous work [10].

Results and Discussion

1. Determination of Particulates at Ambient Air

Ambient air in the laboratory was recorded for sensitivity check of the instrument and as a control of the particulates formed during turbine operation. Ambient air was measured for size distribution and particulate concentration. Based on the Environmental Protection Agency review of air quality criteria and the National Ambient Air Quality Standards (NAAQS) that permits ambient air concentration not exceeding 50 µg/m^3 for an annual average and 150 µg/m^3 for a 24 hr average more than three times in three years [8], the ambient air had no limitation on the measurement of the exhaust particulate because the particulate concentration in the ambient air were in the range of hundreds to thousands.

2. Exhaust Gas Temperature and Pump Power as a Function of Blending Ratio

Exhaust gas temperature (EGT) provides quantitative information of the progress of combustion in engine [8,12]. The relationship between exhaust gas temperature and throttle position for Jet A1 and different blends of biodiesel is shown in Figure.2 below. It can be observed that with increase in throttle position, exhaust gas temperature increased in Jet A1 and all biodiesel blends. However, the EGT showed a decreasing trend from B30 to B70 at idle position. The minimum exhaust gas temperature at idle throttle setting was to be 576°C in B30 followed by 552°C in B50 and the lowest EGT is 512°C for B70. At 70% throttle position, there was an increase in EGT from biodiesel blend B10 until B50 at 628°C before the temperature decreased at B70 to 612°C. Ii is also reported decrease in temperature as the proportion of biofuel increases in the blend of biodiesel [13].

Figure 2 shows increase in EGT with increase in throttle position could be attributed to the increase pressure which may be due to improved combustion of fuel as a result of improved atomization which is in good agreement with similar work [8,13].

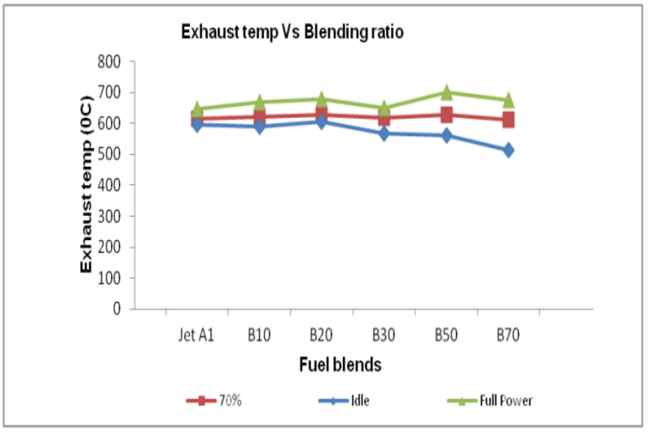

Figure 2.Relationship between exhaust temperature and fuel blends

On the other hand, increase in EGT with increase in the biodiesel blend may be due to delayed combustion or slower combustion characteristics of biodiesel blends and lower cylinder gas temperature. Pump power is the power is the power demand by the engine to maintain certain fuel supply to ensure the required output power. It can be seen from Figure.3 below that pump power is almost uniform at idle throttle position which is about 9%, but there was a sudden drop in the pump power at B30. Decrease in pump power could be linked to loss of heating value, higher viscosity, higher oxygen content and combustion rate [9, 14]. The same observation at idle position was the same for the 70% throttle position where the pump power of all the fuels was 34%, which is a similar result with testing waste cooking biodiesel blends (B10, B20, B30, B40 and B50) at full load of a 2 cylinder 4 stroke diesel engine [15].

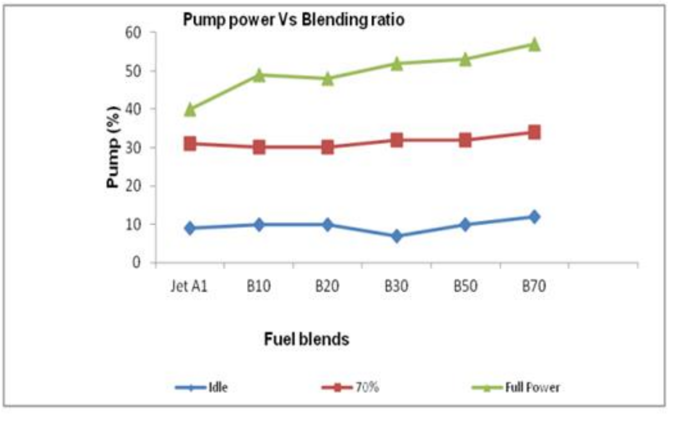

Figure3. Relationship between pump power and fuel blends.

Pat et al. also reported similar results were obtained with Thumba oil biodiesel blends (B10, B20 and B30) [16]. There was a surprising increase at full power from 40% with Jet A1 to 59% with B70, similar observation was reported by Gumus and Kasifoglu where power increases with increase in biodiesel blends [17]. Increase in pump power with increase in biodiesel percentage in the blends could contribute to higher oxygen content, higher biodiesel consumption, - shorter ignition delay and - advance of injection timing. Further, it is reported that of the 27 literatures reviewed on the effect of pure diesel on engine, 70.4% agreed that engine power will drop with biodiesel [9]. He further explained that this result showed some fluctuations. The increased pump power with higher biodiesel blends reflected the higher demand from engines for more fuels due to low calorific values of biodiesel and higher viscosities of biodiesel. Figure 4 below show the relationship between rpm and the blending ratios.

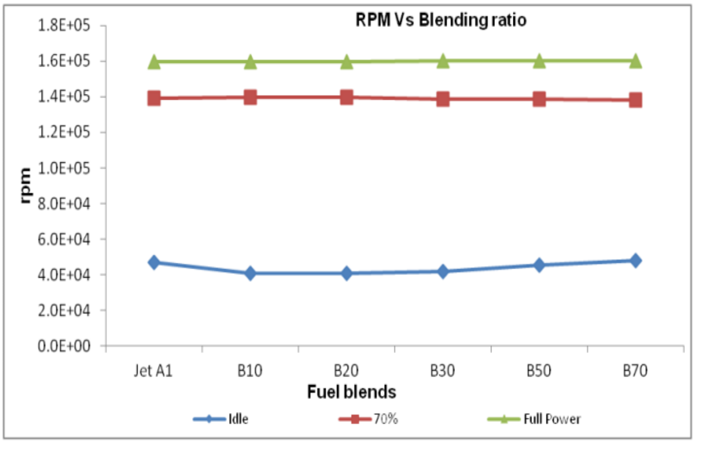

Figure4. Relationship between rpm and fuel blends.

It can be observed that there was a uniform engine speed of an average of 159,800 for Jet A1 and the biodiesel blends at full power. At 70% throttle position the engine speed 139,000 was seen to be similar for Jet A1 and biodiesel blends B10, B20, B30 and B50 but slight decrease to 138,800 occurred for biodiesel blend B70.

When the engine was at idle position, the engine speed for Jet A1 was 46,700 but decreased slightly to 42,200 at B10 and B20 then later increased for B30, B50 and B70 to 42,900, 44,600 and 46,700 respectively, with Jet A1 and B70 being on the same speed at idle position.

3. Particulate Number Size Distribution

An average dilution ratio of 7 was used for calculating the particulate concentrations; this was as a result of the CO and CO_2 concentrations at the engine exhaust cone plane and the particulate sampling point that showed the dilution ratio of the exhaust flow was 6-8, which depends on power conditions. Particulate number

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size distribution and diameter of particulates of different fuels at different throttle positions were measured and compared as seen in Table 1 below. It was seen that for the test on Jet A1 and the different biodiesel blends, the particle number size distribution clearly show a unimodal or lognormal distribution.

Table 1. Particulate size distribution and peak size of each fuel at different throttle position

	Idle		70%		full Power	
	N/cm^3	nm	N/cm^3	nm	N/cm^3	nm
JetA1	6.49×10^7	44.5	9.46×10^7	61.5	9.46×10^7	68.5
B10	7.29×10^7	46.1	1.03×10^8	66.1	1.15×10^8	79.1
B20	7.91×10^7	57.3	1.23×10^8	85.1	1.29×10^8	88.2
B30	1.49×10^7	202	2.40×10^7	269	2.57×10^7	269
B50	1.95×10^7	259	3.10×10^7	269	3.10×10^7	279
B70	1.20×10^7	120	1.88×10^7	113	1.93×10^7	119

Figure 5, Figure 6 and Figure 7 reports the size distribution of functions obtained by testing Jet A1 and biodiesel blends at idle position, 70% power and full power, respectively.

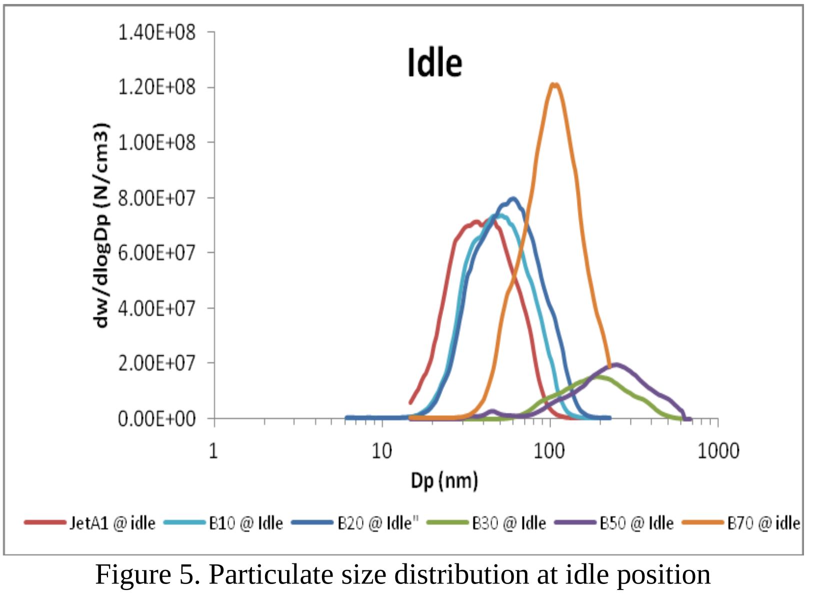

Figure 5. Particulate size distribution at idle position

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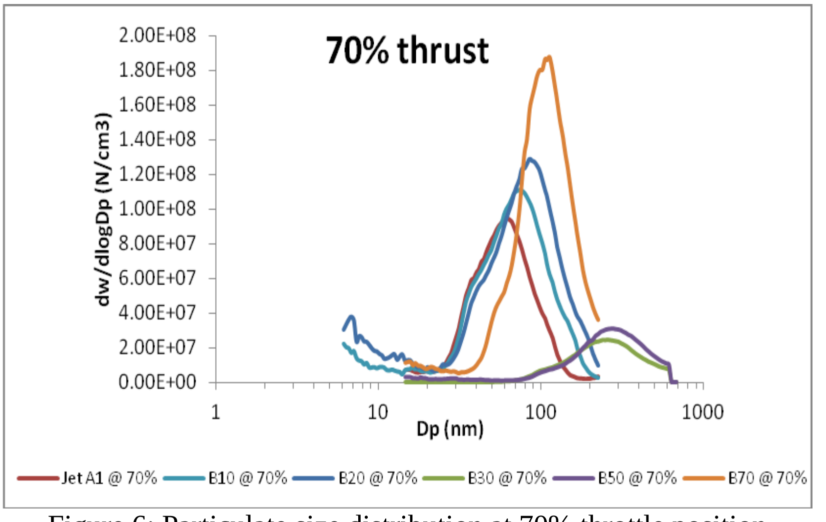

Figure 6: Particulate size distribution at 70% throttle position

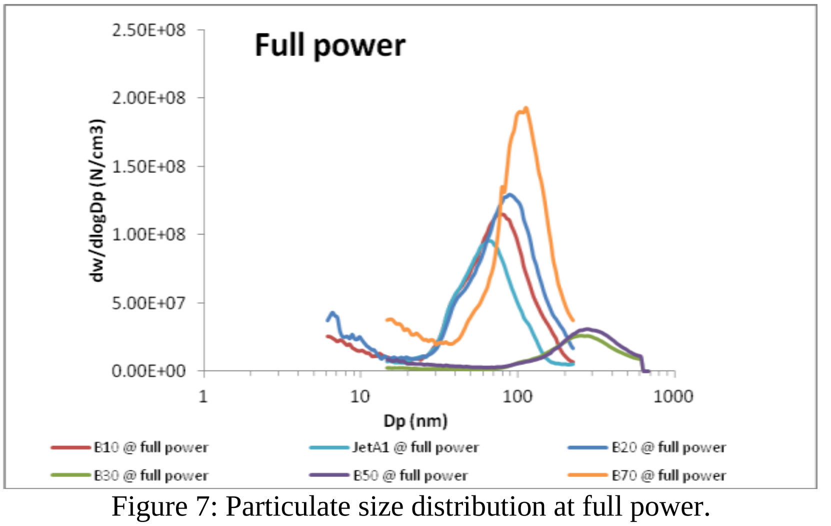

Figure 7: Particulate size distribution at full power.

The highest peak particle size is observed at 279 nm at full power, followed by 269 nm at 70% and lastly 259 nm at idle position, all with B50. Jet A1 was noticed to have the least particle size with its peak at 44.5 nm diameters at idle position, 61.5 nm diameters at 70% and 68.5 nm diameter at full power. The same observation was reported in other studies [18, 19, 20, 21]. Although there was a slight decrease in the size distribution with B70, which is 119 nm at full power, 113 nm at 70% power and 120 nm at idle position. These results could be due to higher biodiesel ratio which results to poor atomization. Thus, full power produced the highest concentration of particles at 1.29x108 N/ cm^3 with B20, the least was produced at idle position at 1.20x107 N/ cm^3 with B70.

At idle throttle position, particulate concentration is higher than those detected at ambient air [18]. With increase in load, the particulate number concentration of each fuel increases. Increase in biodiesel ratio in biodiesel blend also increases the particulate size concentration in B10 and B20. Although, there was a slight decrease from B30 to B70, this changes could be due coagulation that occurred as a result of collision of smaller particulates in the lower volume of biodiesel. This developed a wider tail for B30 and B50 as seen in Figures 5,6,7 below. The increase in particulate number was more significant from idle to 70% power; increment of particulate number concentration from 70% to full power was noticed to be minimal.

4 Geometric standard deviation, mode, geometric mean diameter and total number concentrations.

All fuel types tested in the micro gas turbine engine had a geometric mean diameter between 38.8 nm and 240 nm at all power settings as shown in Figure 8. The geometric mean increased with power settings using Jet A1, it also increased in B10 and B20 with power change from idle to 70% but remained stable for 70% power and full power.

All fuels had a geometric standard deviation ranging from 1.5 to 2.6 as shown in Figure 9. The geometric standard deviation increased with increase in throttle setting with possible exception of B30. The overall increase in geometric standard deviation and geometric mean when the micro gas turbine engine was operated under full power suggests that more accumulation of particles were formed in

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the emissions thereby increasing the total particle size and increasing the particle size diameter

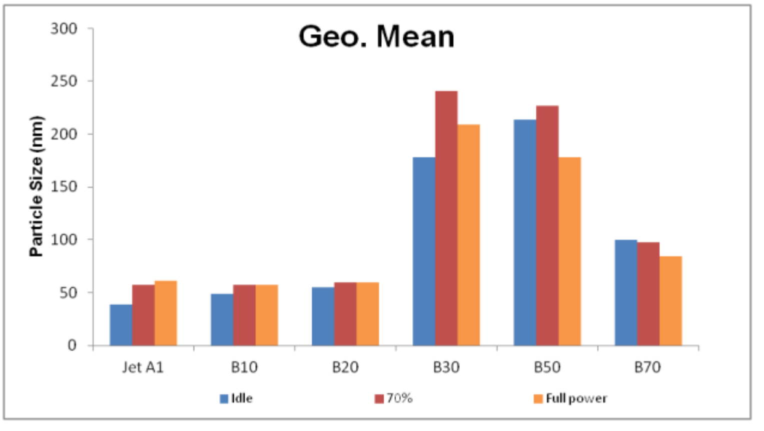

Figure8. Geometric mean particulate size at different throttle positions.

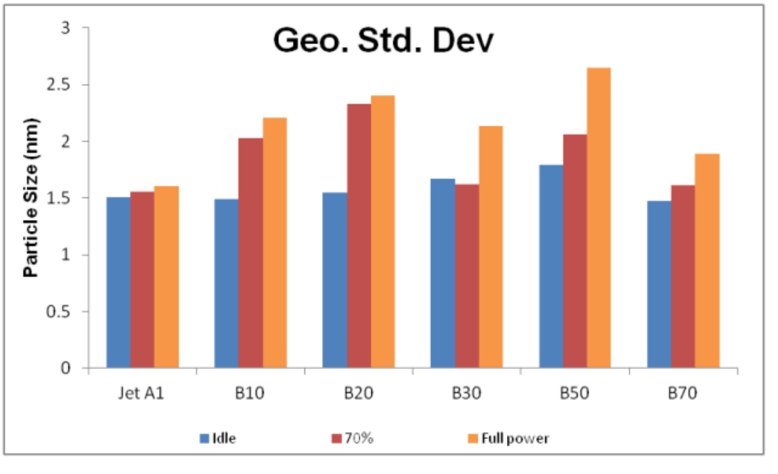

Figure9. Geometric standard deviation of particulate size at different throttle positions

There was an increase in mode size as the throttle position increased. Although, there was decrease in mode size for B30 from 70% power to full power. It was observed that the number of particles increases with throttle setting for all other fuels. A significant decrease of about 63% was noticed from B50 to B70. This signifies that more particles were produced with Jet A1 and lower blends of biodiesel and engine also produces - significantly higher number of particles at full power for all fuel types except B30 as shown in Figure 10.

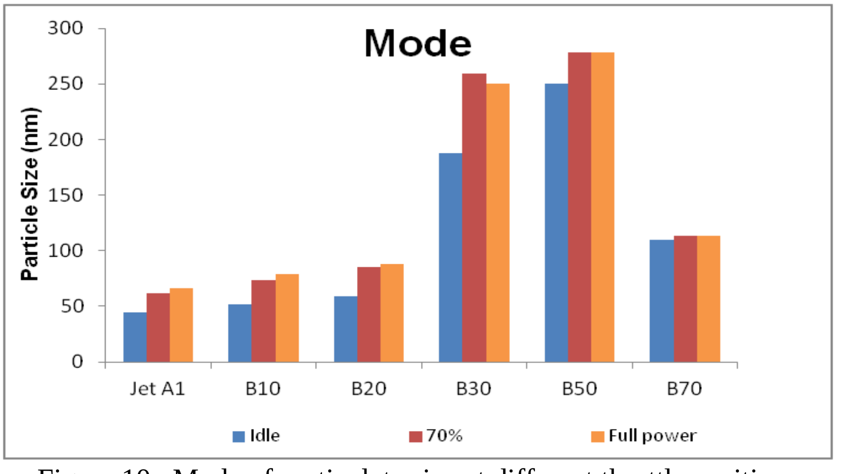

Figure 10. Mode of particulate size at different throttle positions

Total particle number concentration for all the fuel at different throttle positions is illustrated in Figure 11 below.

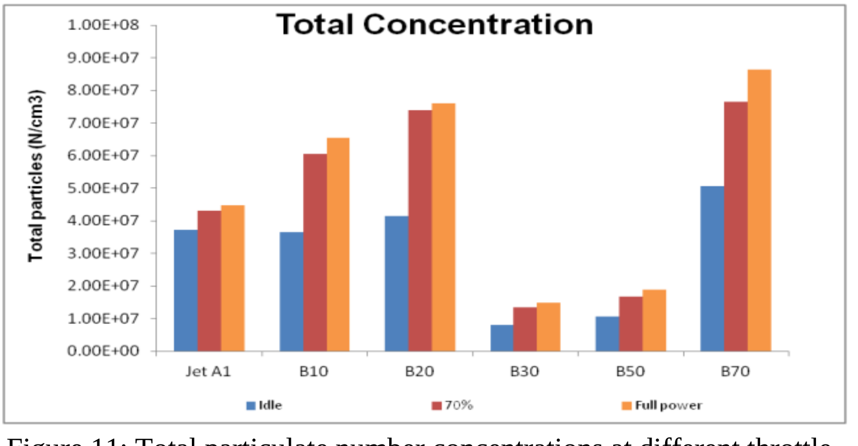

Figure.11: Total particulate number concentrations at different throttle positions.

It was observed that the number of particles increases with throttle setting for all fuels; full power had the highest number of particles while idle position presented the least.

These observations were similar to those reported by Li and Tan [20, 21] which could be as a result of substantial formation of nucleation mode particles. There was a slight increase in total particle concentration in Jet A1, B10 and B20 and a significant decrease in total particle concentration in B30 and B50. A significant increase of about 63% was noticed from B50 to B70. This signifies that more particles were produced with Jet A1 and lower blends of biodiesel and engine also produces a significantly higher number of particles at full power for all fuel types. The highest total number of particulates at full power was observed with B70 at 8.60x107 nm, the least at full power was observed in B30 to be 1.4 x107 nm. The least total concentration in the test was at idle power testing B30 which was observed to be 8.05 x10^7. This result is not similar to the report by Tan et al. [21], where the total particulate number concentration was increasing with the biodiesel blend ratio. This difference could be attributed the engine used and also the biodiesel type.

Conclusions

In this work, the particulate size distribution, number concentrations were analyzed for Jet A1 and various biodiesel blend using a micro gas turbine engine. Particulates from all throttle settings showed uni-modal distribution characteristics. Particulate number concentration of each fuel increases with increase in throttle position. Increase in biodiesel ratio in biodiesel blend also increased the particulate size concentration in B10 and B20. More particulates were seen to be produced with Jet A1 and lower blends of biodiesel; the engine also produces a significantly higher number of particles at full power for all fuel types. Larger particles resulted from the combustion of higher blends. The present research provide a step forward in the analysis of particulates from combustion of aviation fuels which could further prove the viability of biodiesel for use in the aviation industry. Thus, this could be promising and encouraging

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for production of biodiesel blends, which result in minimal emissions.

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