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MICROGAS TURBINE ENGINE CHARACTERISTICS USING BIOFUEL

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Introduction

Aviation fuels commonly used today are extracted from the kerosene fraction of the crude oil that is distilled between the gasoline and the diesel. Crude oil is not renewable and the world oil reserve is generally believed to be on the decline. In 2006, about 6.3% of the world's refinery production was used for aviation fuel. (Nygren et al., 2009) At an estimated rate of 3% increase of fuel demand per year, aviation use alone will consume the world fuel production by 2026 (Nygren et al., 2009).[1] Therefore, there is a need for the aviation industry to reduce its dependence on fossil fuels and, perhaps, replace them with alternative, renewable fuel. In addition, the use of fossil fuel negatively impacts the environment in many ways, including for example, the emission of pollutants and green house gases. (Daggett et al., 2007) Some analyses show that the airline industry is responsible for roughly two percent of the greenhouse gases emitted globally. Biofuel is a fuel obtainable from biological material and can exist in the form of solid, liquid, or gas. Unlike fossil fuel, which is derived from fossils of biological material, biofuel is renewable. Biofuel also has the advantage of biosequestration of the atmospheric CO_2 and, therefore, helps remediate greenhouse gases and, possibly, climate change. (Bajpai et al., 2009) Studies show that fuel derived from biofuel emits at least 40% less CO_2 than current conventional jet fuels. Early biofuels were made from a variety of sources such as, sugar, animal fats, or vegetable oil. Biodiesel is one of the first generation biofuels that is produced from oils or fats using transesterification. Other examples include bioalcohols, such as ethanol, propanol, and butanol. One of the more common processes used to obtain these alcohols is fermentation of sugars by the action of enzymes in microorganisms. Others processes include the fermentation of starches or cellulose, which is more difficult due to their complex structures.

There are many other valuable sources of biofuel including biogas, which is produced through anaerobic digestion of organic material by anaerobes, bioethers, syngas, and solid biofuels (eg. wood, sawdust, charcoal). Algae fuel, also known as the third generation biofuel, seems to be one of the most promising biofuels today, particularly in terms of their high yields. Algae have been reported to produce thirty times more energy per acre than land crops. (Biodiesel, 2010) Moreover, algae are biodegradable and environmentally friendly. Algae fuel is suitable for aviation use because of its low freezing point and high energy yield.

The commercial scale production, uses and regulation of biofuel is yet to be realized by the aviation industry. Biodiesels are Fatty Acid Methyl Esters (FAMEs) and are absorbable by metal surfaces. This causes concerns as biodiesels can adhere to pipe and tank walls. Measures can be taken that replace the surface material with non metallic material that would not participate in a reaction. Biodiesel has been shown to react with compounds containing several different metals including copper, zinc, tin, lead, and cast iron. In addition to its effect on metallic compounds, prolonged use of biofuels may lead to the deterioration of the rubber components in the engine. (Zehra et al., 2009) The presence of rapeseed methyl esters in the engine oil can increase corrosive wear because of the acidity of the biodiesel. (Serdari et al., 1999). Rapeseed methyl ester fuel also causes the lubricating oil to age faster. Degradation due to the oxidation of biofuel can change the viscosity, acid value, and peroxide value. (Dunn, 2005) The shelve life of biodiesel are typically six months. (Yüksek et al., 2009) Another alternative fuel that has been studied and shows potential is nitrous oxide. The raw material is abundant and is harmless to the environment as the chemical reaction produces oxygen and water. It has a reported energy rating of 1864kJ/kg and a flash point of 850°C, compared to 38°C for JetA fuel. Due to its high flash point and the limitation of test engine operating range, nitrogen is yet to be extensively examined.

The B100 biofuel used in this study is a mixture of methyl esters of fatty acids. It is made from a combination of used oil feedstock such as restaurant oil. Table 1 shows a comparison of some of the properties of kerosene with that of the B100 biofuel. The heat of combustion is lower for B100 than that of kerosene. The kinematic viscosity of B100 is about three times higher than kerosene. The B100 fuel also has a slightly higher density as compared to Jet A-1/kerosene. This is due to the larger chemical structure of the B100 biodiesel than that of the kerosene, which affects the freezing point of the fuel, resulting in gelling of the fuel. Although we have not observed in the operation of our engine, these conditions can lead to engine operability problem and possible engine flameout. (FAA, 2009)

Property	Jet A-1	Biofuel (B100)
Density (kg/m³)	810	880
Distillation Range (°C)	177 – 300	>200
Kinematic Viscosity 40°C (mm²/s)	1 – 2	2.97
Heat of Combustion (MJ/L)	> 35.1	32.08
Flash Point (°C)	> 38	68
Freezing Point (°C)	-47	>0

Table 1. Comparison of fuel properties.

Engine Runs Setup

Figure 1 shows the micro turbojet engine that has been used as the test platform of the current study. The MW54 engine runs on a single spool radial compressor and a turbine. The combustion chamber is of the annular type with reverse flows for enhanced vaporization and mixing of the fuel mixture. This feature makes it particularly attractive to the current study. For operations, two types of fuel are used. Propane is used during the startup and kerosene for normal runs. The engine can operate in a manual start mode or automated start via an engine control unit (ECU). During a run, engine operation parameters and gas properties at the different stages along the air path can be measured.

The turbojet engine mounting bracket is secured to a tripod-like wood mount on a test bench. The cross sectional shapes of the three mounting legs follow that of the NACA0012 airfoil. All supply lines and electronic wirings are routed through the hollowed rear mounting leg to the lower deck of the test bench. The turbojet engine is mounted on the customized bracket that holds the exhaust gas temperature (EGT) sensor and load cell as illustrated in Figure 1.

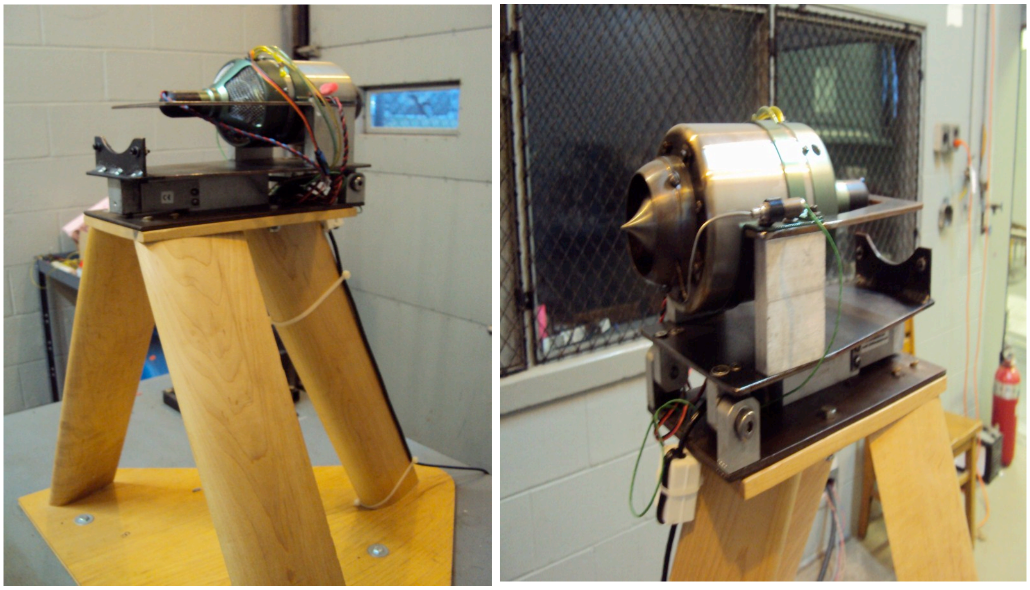

Figure 1. Turbojet engine lab setup

A voltage output strain gage type of load cell is installed on the bottom plate of the engine mount to measure thrust. Figure 2 illustrates the placement of the load cell and the measurement technique used. The thrust line, F1, above the pivot pins of the upper plate, where the engine is mounted, creates a moment that applies a force, F2, directly onto the load cell. Using simple moment summation, the engine thrust F1 can be calculated. To account for friction, calibrations are performed by transferring dead weights forces parallel to the propeller thrust line through a pulley system. We have also used the same setup to ensure the integrity of the engine mount to beyond the maximum obtainable thrust of the turbojet.

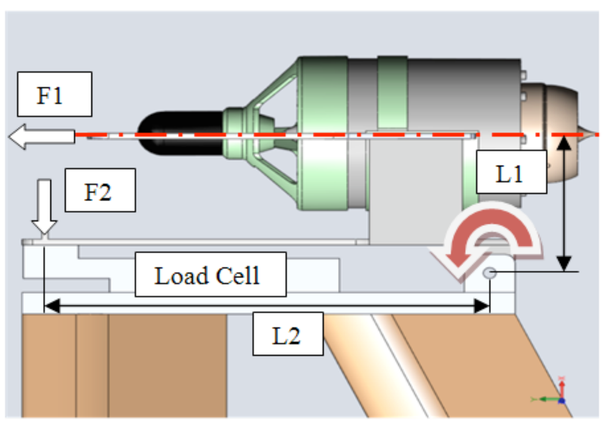

Figure 2. Thrust Management

Engine exhaust gas temperature (EGT) is measured using a thermocouple. A case pressure port is installed with a digital pressure gage to provide a digital readout from the computer. A single fuel flow meter and a single fuel pump are installed on the engine fuel supply line. A

FADEC ECU pre-programmed by WREN Turbines, incorporating a fuzzy logic-based control algorithm that adapts to the different engine parameters when it operates, monitors the engine run parameters and controls the fuel supply to the engine. It ensures that the engine operates within the programmed specification through engine speed (RPM), EGT, and throttle level. In case of an apparent inconsistency among the engine operating parameters that may indicate an abnormal engine run, for instance, between the RPM and the exhaust gas temperature, the ECU will automatically shut down the engine. A 0.5 inch steel plate is mounted perpendicular to the turbine plane of rotation, and away from the line of sight in front of the control room window.

Multiple LabVIEW programs have been developed in house to perform different tasks. (Liou and Leong, 2007) One of the LabVIEW programs developed is the Engine Control Interface (ECI) that will measure, manage, and control pneumatic valves, relays, and sensors. Data acquisition (DA) can be executed on demand through the ECI. Parameters displayed in the front-end LabVIEW program are provided by the ECU with a RJ45 connector through a serial port (RS-232) connection. This provides real time data to the DA, which is in sync with the ECU. This real time data can be stored in text file format. The throttle level on the ECU is controlled through the LabVIEW front end to provide a stable signal source. In case of a computer failure, the ECU will be able to detect and shut down the engine immediately to prevent a loss of engine control and other undesirable scenarios. A change of the throttle level in the LabVIEW front end triggers a signal sent to the ECU, which varies the power input to the fuel pump and the fuel flow to the engine, resulting in changes of engine RPM, pressure, EGT, and thrust. The fuel pump power is controlled by the ECU "fuzzy logic" system correlating a 1024 step division to the fuel pump power supplied to the ECU. With a calibrated throttle level, the ECU will regulate the fuel pump power according to the throttle level desired, while monitoring the RPM and EGT as feed backs.

The fuel used in the present engine runs includes kerosene and its mixture with the B100 biofuel. The mixing ratio varies from 0%, which contains only kerosene, to 100%, which contains only the B100 biofuel. We have run fuels with mixture ratio of 0%, 5%, 10% and subsequent increments of 10% up to 100%. The fuel is mixed with Mobile Jet Oil II for lubrication purposes at a ratio of 20:1. The engine characteristics such as the thrust, RPM, fuel consumption, and EGT are reported in the following.

Results

The following presents the results of the turbojet engine runs using the various blends of the B100 fuel with kerosene at ten different mixing ratios, from kerosene only (0%) to B100 fuel only (100%). The data are collected continuously onto a spreadsheet using the LabVIEW program and then analyzed. Figure 3 shows the variation of the engine RPM with the throttle level in terms of its percentage of the full throttle. The engine speed increases linearly with the throttle level for all mixing ratios considered and the engine speeds are the same at the same throttle level. With the increase of the mixing ratio, or blending more biofuel with kerosene, the RPM value shows a flat region. This flat RPM values first appears at the highest throttle level tested and then becomes wider as the mixing ratio increases. The ECU fuel flow control was manufactured to operate the engine using kerosene as fuel. The high viscosity of the B100 biofuel demands higher fuel pump power at the same throttle position than that regulated by the kerosene-based ECU.

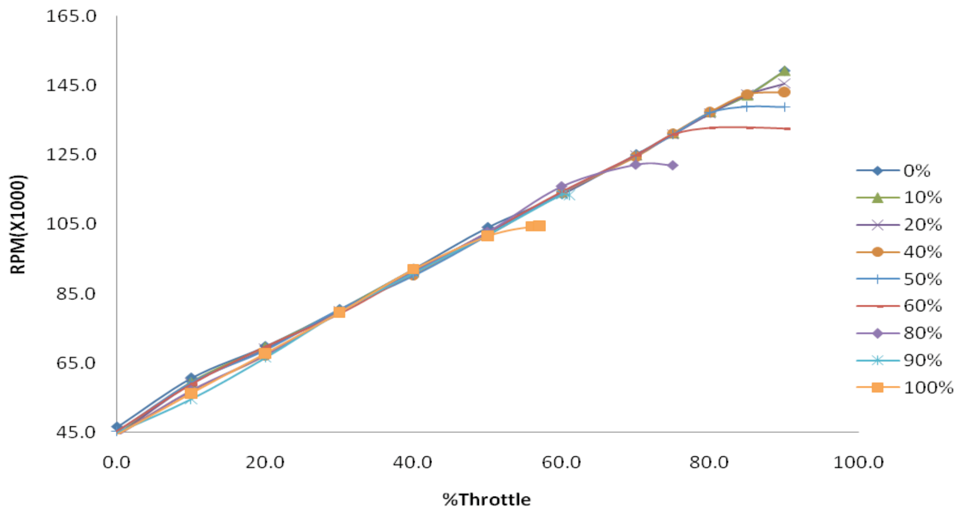

Figure 3. Engine speed variation with the throttle level.

Figure 4 shows the variation of the engine thrust with the throttle level. The engine thrust increases with the throttle level. The thrust values show a very consistent change with the throttle level for all blends of fuel. In Figure 5, the engine thrust is shown against the engine RPM. For runs with all of the various blending of the biofuels, the measured engine thrust varies in a consistent manor with the engine RPM, showing that the operational performance of the engine has not changed during the runs. Figure 6 shows the changes of the EGT with engine speed. The overall trends of the EGT variation are fairly consistent across all blends and all RPM. The temperature of the exhaust gas stream varies significantly with radial distance to the jet centerline. Since the thermal couple is only loosely fitted through a hole on the wall of the nozzle, the location of the temperature probe, being exposed to the high speed exhaust stream, can shift from one engine run to the next and causes the observed variations.

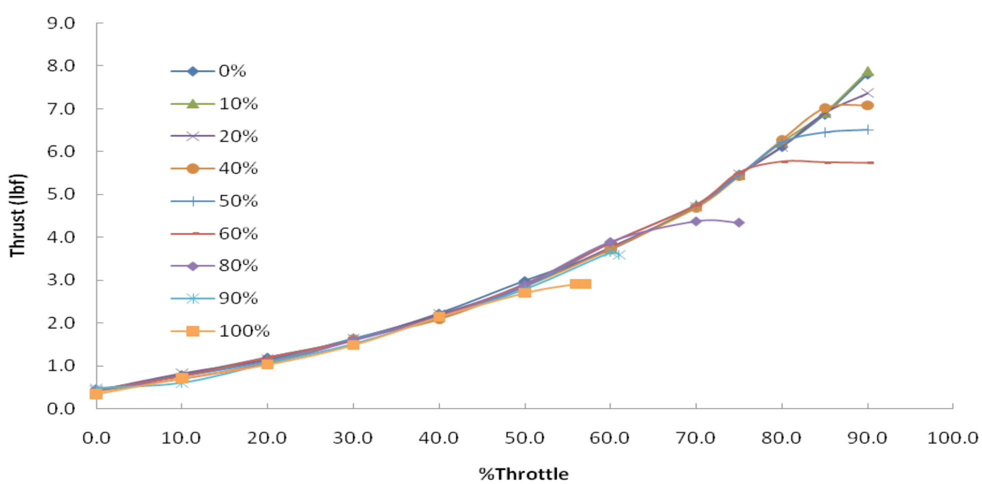

Figure 4. Engine thrust variation with fuel mixing ratio

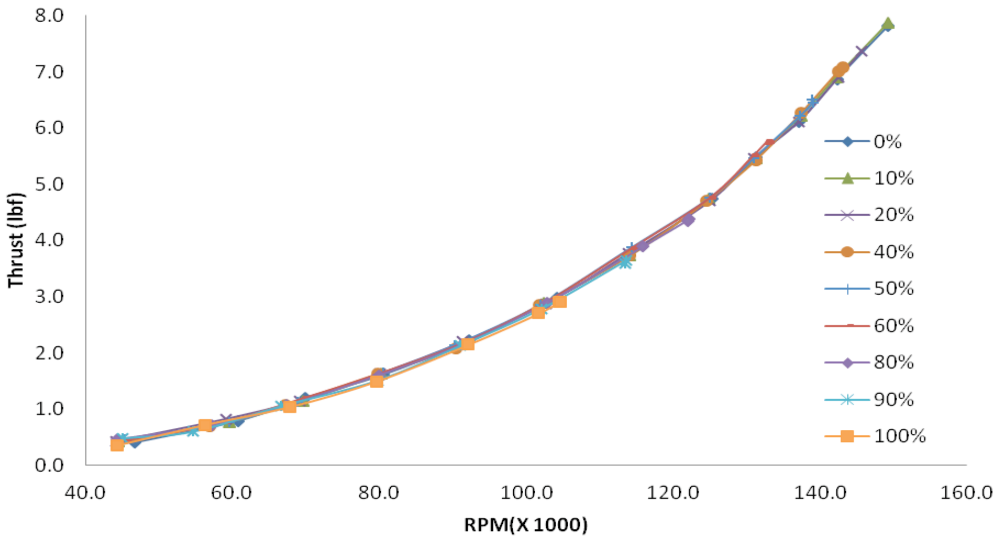

Figure 5. Consistency of engine performance thrust variation with engine speed.

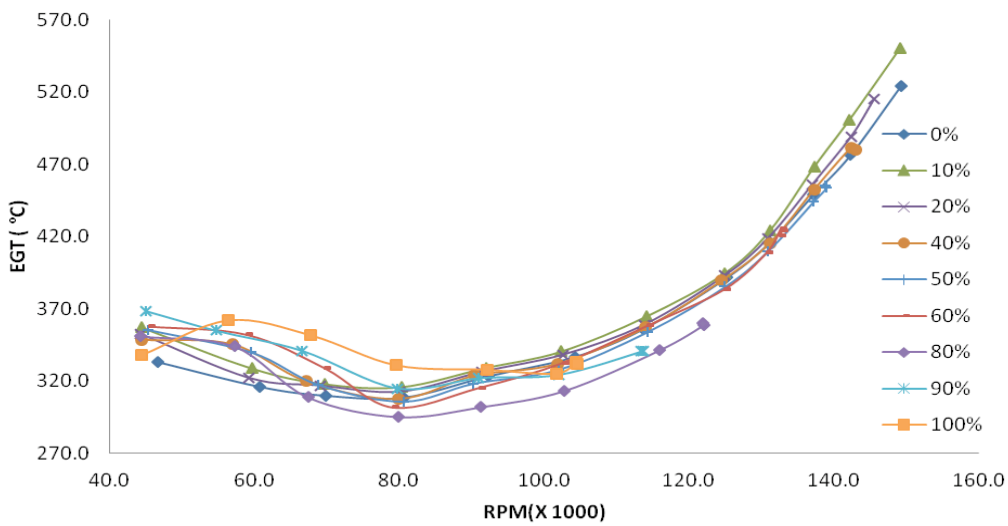

Figure 6. Engine exhaust gas temperature.

As mentioned earlier, engine characteristic data are continuously sampled by using the LabVIEW program front end that is used to run the engine. Table 2 shows a summary of the satistics of some of the quantaties sampled over a period of time at a single throttle level. The distributions of EGT, thrust, and RPM have standard deviations (STD) of less then 1% of the mean values. Figure 7 shows the distribution of the occuring count of the sampled RPM data in the same time period.

Table 2. Statistics of measurement.

	RPM (x1000)	EGT (°C)	Thrust (lbf)
STD	0.219	1.307	0.0243
MIN	91.2	292	2.21
MAX	92.1	298	2.319
MEDIAN	91.8	294	2.251
MOD	91.8	294	2.251

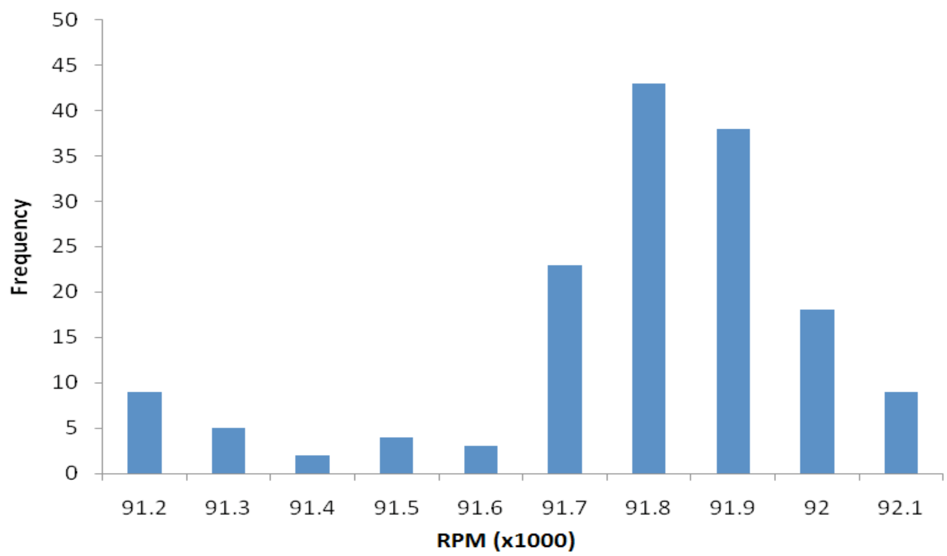

Figure 7. Engine RPM distribution.

The measured fuel volume flow rates are shown in Figure 8. The fuel pumped to the engine increases with RPM. This is observed for all mixing ratios, from 0% to 100%. There is an apparent downward shift of the total fuel consumption by volume, signifying a reduction of fuel consumed, with the increse of the mixing ratio. Recall that the 0% blend contains only kerosene and the 100% fuel blend only B100 biofuel. The fuel consumption decreases with the increased percent of the biofuel. The biofuel combustion at the relatively fuel-lean conditions is more complete and this can further reduce CO_2 emmission. Figure 9 shows the correlation between the fuel consmption and the thrust produced. Engine thrust is seen to increase wth the increased amount of fuel pumped to the engine for all the mixing ratios used. With the same fuel volume flow rate, the engine thrust increases with the increased percentage of biofuel used in the blending. For instance, at the fuel flow rate of 30 mL/min, the run using the B100 biofuel produced 200% more thrust compared to that by using kerosene. The heating value of the biofuel used is somewhat lower than that of kerosene. Therefore, the trend apparently indicate a more efficient combustion of the biofuel in the present engine.

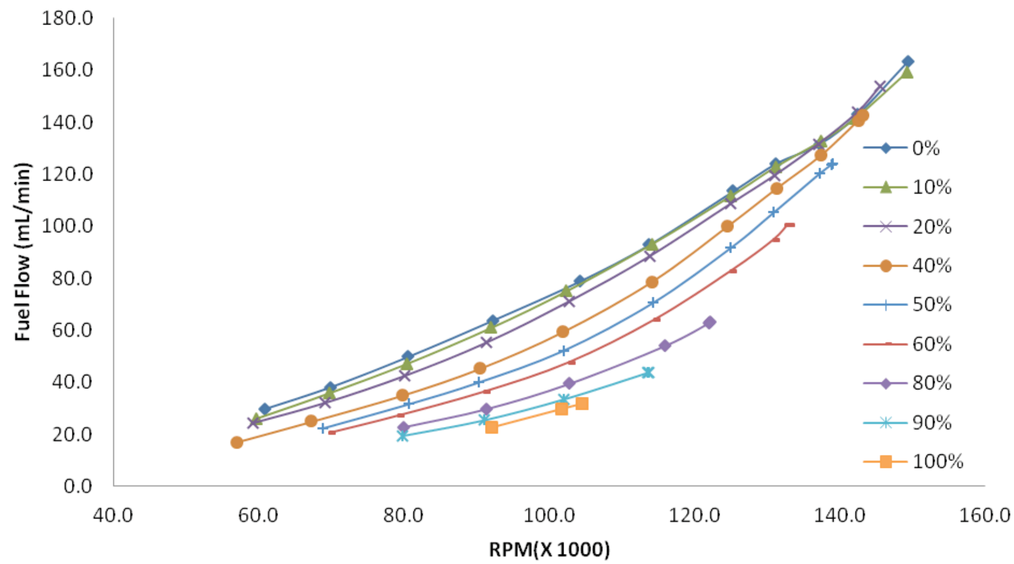

Figure 8. Volume fuel flow rate variation with engine speed.

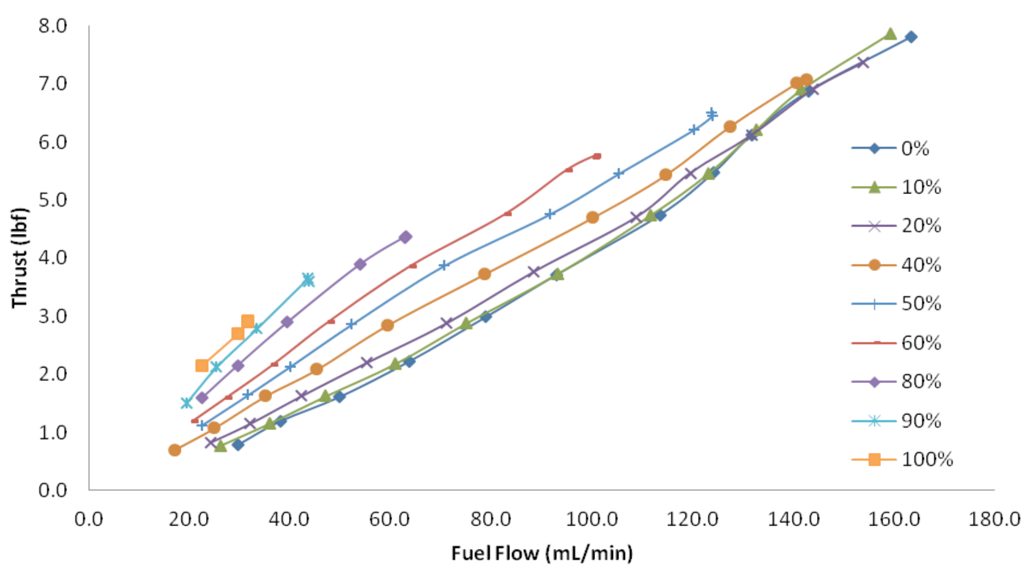

Figure 9. Engine thrust variation with different fuel mixing ratio.

The variations of thrust specific fuel consumption (TSFC) with the throttle level are shown in Figure 10. For the 0% fuel blend (or kerosene), the value of TSFC decreases by about 40% with the throttle level increasing from 10% to 90%. TSFC is also observed to decrease with the increased amount of biofuel in the fuel blend. The trend continues and the pure biofuel has the lowest TSFC at the three throttle levels tested. For example, at 50% throttle level, the TSFC value for the B100 biofuel run is 56% lower than that using kerosene.

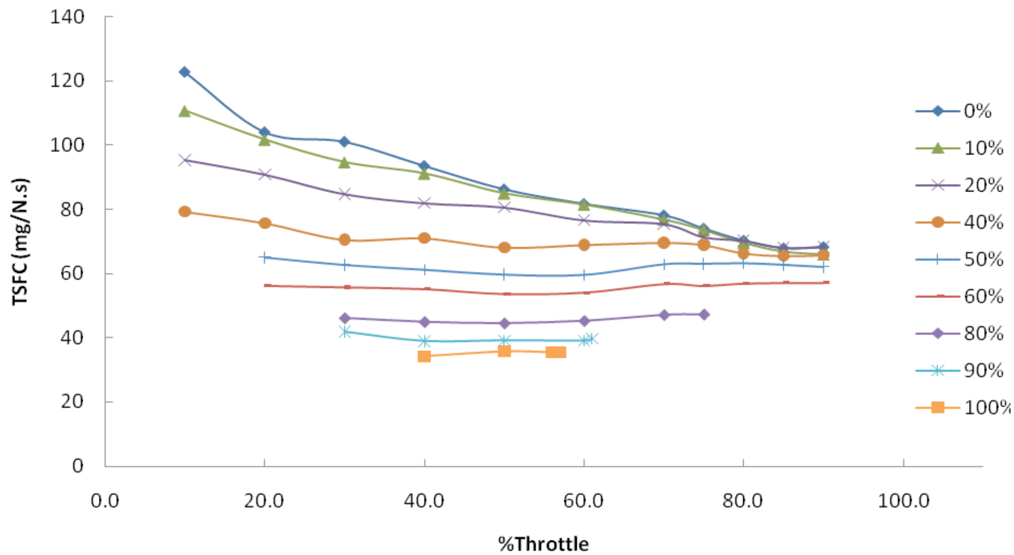

Figure 10. Engine thrust specific fuel consumption variation with fuel mixing ratio.

The low TSFC of the engine when the B100 biofuel is used can be contributed to factors such as the higher cetane index found in the biofuel than in kerosene. (Schulze and Pinder, 2008) The higher biofuel viscosity has been found to improve the fuel-air mixing and result in a more complete combustion. (Ali et al., 1995), (Ali et al., 1995) Studies have also shown a higher thermal efficiency for biofuel, which leads to a more efficient conversion of chemical energy to kinetic energy. (Habib et al., 2010), (Xuea et al., 2011)

Table 3 show estimates of the fuel costs for running the present turbine engine on three different blends of fuel, from kerosene to B100 biofuel, for one thousand hours. The estimated cost increases by a factor of about six between the cases of using the kerosene and the B100 biofuel. It should be noted that the estimates are based on our costs of purchasing the kerosene from a retail store and the B100 biofuel from a government-subsidized biofuel provider. Although the comparison may not reflect the true cost of the biofuel, the significant improvement of the engine performance in terms of TSFC using biofuel is reliable evidence for potential saving in cost.

Table 3. One thousand hours operation cost comparison based on a kerosene retail price of $2.11 per liter and B100 at $1.06.

Fuel Blend	Cost
Kerosene	$11744
50% B100-Kerosene	$4954
100% B100	$1883

Concluding Remarks

The results presented showed that the turbine engine can operate and perform in a consistent manner when the various blends of fuel were used, producing the same amount of thrust at the same engine speed. The engine thrust specific fuel consumption was found to be significantly lower for the B100 biofuel than kerosene. The more efficient combustion of the biofuel represents a significant saving in the cost of running the turbojet engine. It also indicates a possible reduction of green house gas emission from the engine. For future work, the contents of the exhaust gas can be sampled and measured. Such studies will provide a quantitative analysis of the emission content of the gas turbine engine runs on biofuels.

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