Journal of Applied Sciences and Arts

Volume 1 | Issue 3 Article 2

December 2017

Performance Results of Using Waste Vegetable Oil Based Biodiesel Fuel in a Turboshaft Gas Turboshaft Engine

Donald Bartlett 5218591
flyer22@siu.edu

Blaine M. Heisner
Southern Illinois University Carbondale, bheisner@siu.edu

Recommended Citation

Bartlett, Donald 5218591 and Heisner, Blaine M. (2017) "Performance Results of Using Waste Vegetable Oil Based Biodiesel Fuel in a Turboshaft Gas Turboshaft Engine," *Journal of Applied Sciences and Arts*: Vol. 1 : Iss. 3 , Article 2.
Available at: http://opensiuc.lib.siu.edu/jasa/vol1/iss3/2

1. Literature Review

1.1 Introduction

Biodiesel is a renewable liquid fuel manufactured by converting triglycerides found in vegetable oils and animal fats into alkyl esters. These esters offer similar characteristics to petroleum based diesel and jet fuels, which enable the blending, and substitution of biodiesel with petroleum fuel in the transportation industry (Demirbas, 2008). B100 is an industry term for a fuel consisting of 100% biodiesel fuel with 0% petroleum based component. B100 is commonly used as a blend stock to produce lower percentage blends, or *B-fuels*, and is rarely used as a standalone transportation fuel (AFDC, 2017). B-fuels are labeled consistently with their respective biodiesel percentage; a fuel with 11% B100 and 89% petroleum based fuel will be labeled B11.

1.2 Feedstock

Biodiesel can be made from various feedstock including straight vegetable oils (SVO), waste vegetable oils (WVO), and animal fats. In the U.S., soybean oil has been the dominant feedstock for biodiesel production, being utilized in over 50% of domestic production in most recent production years (NBB, n.d.). However, the high cost of soybean oil along with the possibility of failed crops could adversely affect biodiesel fuel production from this feedstock. Since around 70%-90% of the cost of biodiesel fuel is due to the cost of the feedstock (Szalay, Fujiwara, & Palocz-Andresen, 2015), using recycled WVO as the feedstock is a far cheaper option than using SVO. According to Predojevic (2008), using WVO for biodiesel production significantly saves cost, which is approximately 60% lower than that of SVO. The need to confirm the performance characteristics of WVO based biodiesel is significant in order to verify whether this is a valid and reliable alternative fuel.

1.3 Comparisons

Biodiesel fuels do offer many benefits over conventional petroleum based fuel, encouraging and expanding the use of the fuel. These benefits have spurred the industry to produce over 1.5 billion gallons of B100 in 2016 (USEIA, 2017). Physical characteristics of the fuel such as sulfur content, flash point, and aromatic content all show advantages over petroleum based diesel fuel (Schell, 1998). The use of biodiesel fuel offers many additional advantages over petroleum based fuels such as, reducing our dependence on imported petroleum, leveraging our limited supplies of fossil fuels, helping reduce greenhouse gas emissions, helping reduce air pollution and associated public health risks, and benefitting our domestic economy (Sheehan, Camobreco, Duffield, Graboski, & Shapouri, 2000). However, biodiesel does pose challenges to the industry due to some disadvantages over petroleum-based fuel. For example, biodiesel has approximately 9% less energy density than petroleum based diesel fuel although approximately the same energy density as kerosene based jet fuel (Demiral, 2012, p. 39). Biodiesel has been found to have multiple additional disadvantages compared to petroleum based fuels including reduced shelf life (Yuksek, Kaleli, Özener, & Özoğuz, 2009) and increased reactivity with metal and rubber components (Habib, Parthasarathy, & Gollahalli, 2009). Blending B100 with petroleum-based fuel to create B-fuels enables the blenders to take advantage of the benefits of biodiesel while mitigating the disadvantages. Using B20 in an internal combustion engine, McCormick, Williams, Ireland, & Hayes (2006) found "On average B20 caused PM and CO emissions to be reduced by 16% to 17% and HC emissions by 12% relative to petroleum diesel." (p. 34). Altaher, Andrews, & Li (2014) tested WVO based biodiesel blends in a gas turbine combustor and found "the CO emissions for kerosene fuel was about 2.5 times those for B20 and about 5 times those for B100" (p. 294).

1.4 Biodiesel Gas Turbine Fuel

The environmental advantages of biodiesel fuel as a component of aviation turbine fuels have caused the industry to advance the use of the fuel, albeit in a limited scope. Since the first experimental flights in 2008, over 2500 commercial flights have now been completed using renewable biofuels (Fellett, 2016). Certain characteristics of biodiesel may create additional concerns when considered specifically as a substitute for jet fuel. Not only does biodiesel have a higher viscosity than jet fuel, which affects fuel injection into combustion chambers, but also the gelling temperature is higher, leading to potential issues with engine operability and possible engine flameout (FAA, 2009). The higher cloud point of biodiesel fuel causes solids in the fuel to precipitate and plug fuel filters. This characteristic creates the need to select fuels that have a low enough cloud point to safely blend into aviation fuels (Cobb, 2008). In his *Gas Turbine Engineering Handbook* (2002), Boyce discusses gas turbine fuels:

> The gas turbine's major advantage has been its inherent fuel flexibility. Fuel candidates encompass the entire spectrum from gases to solids…Liquid fuels can vary from light volatile naphtha through kerosene to the heavy viscous residuals (p. 436)… With heavy fuels, the ambient temperature and the fuel type must be considered. Even at warm environmental temperatures, the high viscosity of the residual could require fuel preheating or blending. If the unit is planned for operation in extremely cold regions,

> the heavier distillates could become too viscous. Fuel system requirements limit viscosity to 20 centistokes at the fuel nozzles (p. 452).

As the kinematic viscosity of soybean oil based B100 approaches 10 centistokes at approximately 0ºC (Tat & Van Gerpen, 1999), it will require similar blending or preheating treatments as heavy residual fuels to meet viscosity requirements. Various entities were discovered to have experimented with biodiesel fuel in gas turbines for the purposes of measuring emissions and fuel consumption. One such experiment, carried out by do Nascimento & dos Santos (2011), a 30kW micro turbine engine was successfully operated on B10, B20, B30, B50, & B100 fuels. In these experiments, not only was the engine was operated for 20 minutes on petroleum based diesel fuel, but the B-fuels were preheated to reduce viscosity.

With the economic advantage of WVO feedstock in the manufacture of biodiesel, testing the performance characteristics of WVO based biofuels becomes more important. If these fuels are similar in performance to jet fuels, then the economic advantage of WVO based biodiesel can be exploited. However, if the performance is substandard, the use of these fuels will not be recommended. In addition to WVO based biodiesel, the performance of a commercially available, non-WVO, SVO based biodiesel fuel will be measured. This fuel can be compared to verify whether a blend of biodiesel and petroleum based diesel fuel will have similar performance characteristics to either B100 biodiesel or petroleum based Jet-A aviation fuel.

2. Methods

2.1 WVO Biodiesel

The B100 biodiesel fuel used in this study was manufactured at a remote location using a variation of the processor design known by small-scale manufacturers and hobbyists as an *Appleseed* (Alovert, 2005). This specific processor uses a Richmond brand 50-gallon electric water heater as the main processing tank. The processor includes three 55-gallon high-density polyethylene plastic drums as the settling, washing, and drying tanks. This processor is capable of handling multiple batches at one time, with each tank holding its respective product simultaneously (Figure 1).

Figure 1

This batch of B100 used soybean based WVO as the feedstock. The oil was previously gathered, put into containers, and settled for over a year before transesterification. Twenty-five gallons of WMO were poured into a measuring vessel, the processing pump was started and valves manipulated to transfer the oil into the processing tank. The oil was circulated, the electric heating element in the processing tank was switched on, and the circulating oil then began to increase in temperature. The oil was mixed via circulation for approximately 5 minutes, after which a sample was drawn from the pressure side for titration. Titration involves measuring the acidity of the feedstock to enable an accurate amount of base catalyst to be used to ensure a successful transesterification. The titration revealed the need to add an additional 2 ml of NaOH, ultimately leading to a total requirement of 7g per liter of oil. As our batch size was 25 gallons of oil, a conversion to liters puts the batch size at 94.64 liters of oil. At 7 grams per liter, our NaOH requirement for the batch was 662.5g. Five gallons of methanol was measured out into a HDPE container to which we mixed the NaOH. The WVO was circulated and heated by the processor until the thermostat temperature of 130°F was reached, at which time the circuit breaker for the heating element was opened. The methoxide was slowly admitted into the suction side of the circulating oil, using a ball valve to stem the flow of product to an acceptable rate. After approximately 10 minutes, the methoxide had been admitted and the transesterification process was well underway. Samples were taken after 30 and 60 minutes and tested for completion using the *3/27 Warnqvist test*. According to Tilly (2006), “This is a quick Pass/Fail conversion test for your biodiesel and works because biodiesel will dissolve into methanol while triglycerides do not dissolve in methanol. It works with washed and dried, or unwashed biodiesel that is well settled.” The test showed a complete reaction at the 60-minute mark. The product was then transferred to the settling tank and the pump and lines drained. The product was allowed to sit overnight in the settling tank at which time the glycerin byproduct was drained from the tank. The raw biodiesel was then washed using approximately 10 gallons of water for each wash cycle. For the first cycle, the water was sprayed over the top of the product, dropping through the biodiesel, collecting at the bottom of the tank. At each subsequent wash cycle, water was added to the wash tank, and then vigorously mixed with an electric drill and paint mixer attachment. After each stage of washing, the product was allowed to settle overnight before the wash water was drained off. The biodiesel was washed for five cycles at which time the wash test (Addison, n.d.) passed, indicating the biodiesel was ready to be dried.

The biodiesel was pumped to the drying tank where it was circulated while a small fan was positioned to blow across the product to evaporate the suspended moisture. As the biodiesel dried, the color darkened and the clarity improved. After approximately 75 minutes of circulation, the biodiesel was dry. The B100 fuel was pumped through a 10-micron filter and taken to the testing site. As only 5 gallons of this fuel was needed for the study, the remaining fuel was placed into the tank of a 1983 Mercedes 300D and used to deliver this fuel to the test site. The vehicle ran properly and exhibited no unusual or negative effects.

2.2 Performance Testing

Three fuels will be used in the research; two blends of biodiesel fuel referred to as B11 and B100, and the aviation kerosene Jet-A. B11 is a commercially produced fuel commonly used in diesel cars and trucks. The B11 used in the testing was obtained from a local refueling station, verifying the percentage of biodiesel from a recent purchase order. The B100 used for this research was produced by one of the principal investigators. Aviation Jet-A is the most common fuel used in gas turbine aircraft engines and was obtained from available fuel stock at the testing facility.

This research was a collaborative effort by two individuals with different expertise, one automotive technology and the other aviation technology. The testing was performed at an indoor turbine engine test cell to record the differences in engine operation and test run parameters. The research proposed materials and method involved the use of an aviation gas turbine engine test cell equipped to operate a turboshaft engine (Figure 2).

Figure 2

The engine used for this study was a Rolls Royce Allison 250-C20 turboshaft engine. This engine is commonly used in helicopter aircraft. The engine compressor has a six stage axial flow and a single stage centrifugal compressor. The combustor is a single can type with one each igniter and fuel nozzle. The turbine section has two stages of gas producing rotors and two power rotors. This engine is capable of producing 420 shaft horsepower (SHP). Ten parameters were recorded during each test run (Figure 3). The parameters selected for this comparison were starting capability, fuel pressure, rpm of the gas producing turbine as (%N1) and the power turbine as (%N2), exhaust gas temperature (EGT), and time from initial start to maximum gas producing turbine rpm (%N1).

Test Run	% N1 Turbine Max. RPM	% N2 Power turbine RPM	EGT C°	Throttle position	Oil Temp C°	Oil pressure	Fuel pressure	Fuel Flow (GPM)	Time to Max. N1	Test Total Time	Comments
JET A FUEL ENGINE COLD											
JET A FUEL ENGINE HOT											
B11 FUEL ENGINE COLD											
B11 FUEL ENGINE HOT											
B100 FUEL ENGINE COLD											
B100 FUEL ENGINE HOT											

Figure 3

Fuel was supplied to the engine from a ten-gallon tank that was elevated to gravity flow to an electric pump that supplied a constant pressure to the engine driven fuel pump (Figure 4). Each of the three fuels was supplied in the same manner. Each time the tank was empty and dried before introducing a different fuel. The supply lines, pump, filter, and the engine fuel control unit were drained and purged by pumping the currently tested fuel through them before the test run.

Figure 4

The engine was operated from desktop computer that displayed the parameters using National Instruments software. Starting and ignition were initiated by a mouse input to a screen icon simulating buttons. A manually hand operated throttle control with analog output to the computer was used to signal a linear servo actuator connected to the engine fuel control unit (Figure 5). The digital output from the computer to the actuator was kept the same to eliminate any variation in fuel supply by the fuel control unit. All of the test runs were recorded using *Screenpresso* screen capture software for review and analysis (Figure 6). A video of each test run was reviewed and parameters were recorded on a spreadsheet for comparison.

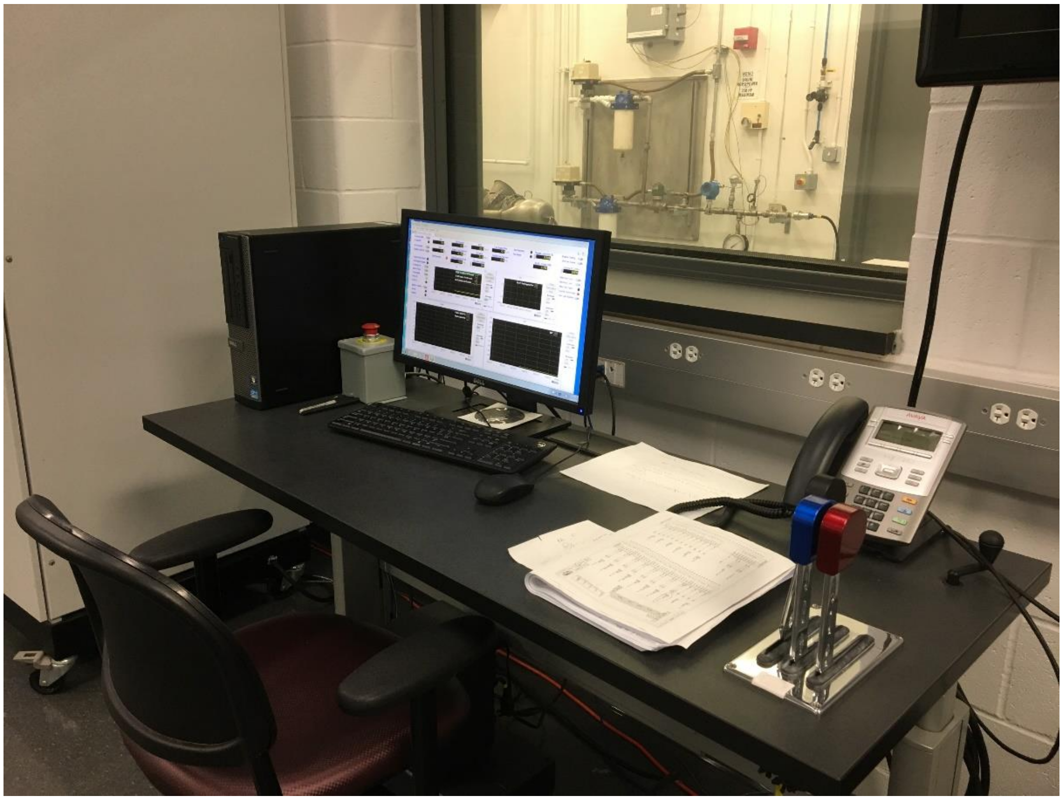
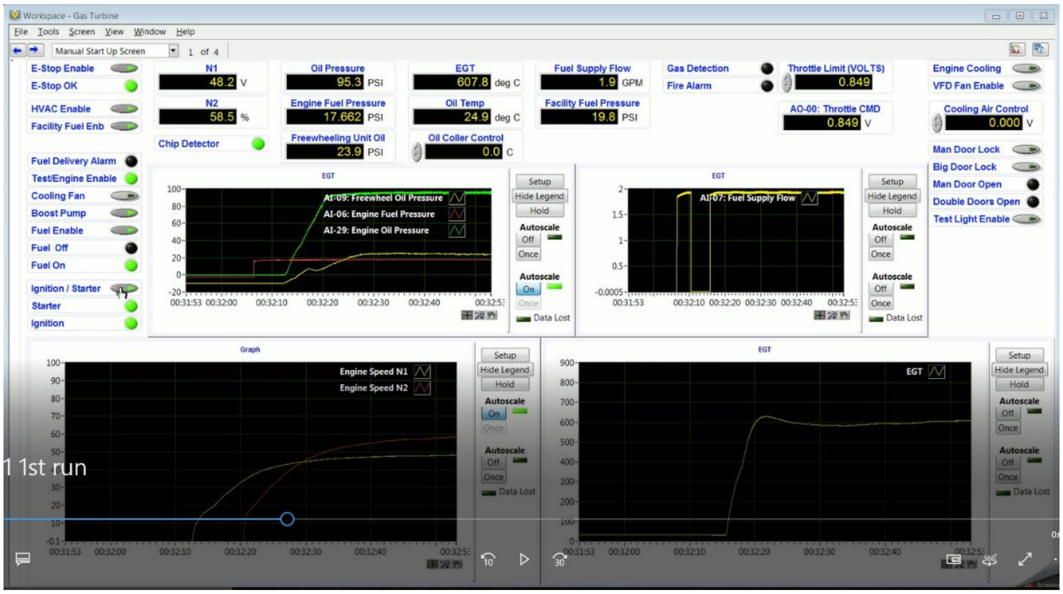


Figure 5



N1 48.2 V
N2 58.5 %
Oil Pressure 95.3 PSI
Engine Fuel Pressure 17.662 PSI
Freewheeling Unit Oil 23.9 PSI
EGT 607.8 deg C
Oil Temp 24.9 deg C
Oil Coller Control 0.0 C
Fuel Supply Flow 1.9 GPM
Facility Fuel Pressure 19.8 PSI
Throttle Limit (VOLTS) 0.849
AO-00: Throttle CMD 0.849 V
Cooling Air Control 0.000 V

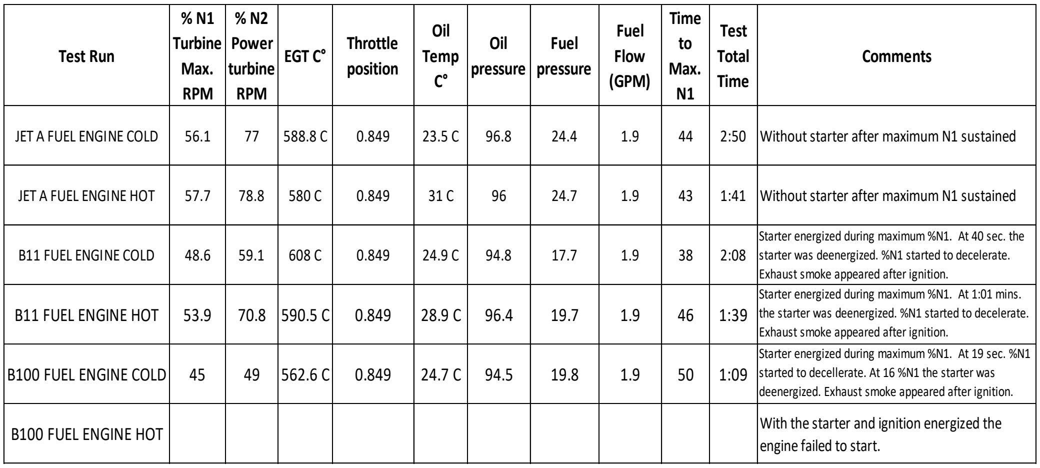
Figure 6

Six test runs were made, two for each of the three fuels with the engine started cold and with the engine hot. The cold test runs were performed after a twenty-four hour period, to allow the engine to return to room temperature. Hot test run were performed immediately after the cold test run.

3. Results

The results of the study were to qualitatively compare six of the ten parameters collected during the test runs; 1. starting capability, 2. fuel pressure, 3. rpm of the gas producing turbine %N1, 4. rpm of the power turbine %N2, 5. exhaust gas temperature (EGT), and 6. time from initial start to maximum gas producing turbine rpm (N1) (Figure 7).

The first two test runs using Jet-A fuel were used to record normal operating parameters with the engine cold and hot. The starting sequence for all six test runs was: The engine is fuel pump switch ON, followed by energizing the starter motor and the ignition. When the %N1 gas producing turbine-rotor reached 20%, the throttle was positioned to allow fuel flow to the combustion section. At maximum %N1 the starter was de-energized. The engine shut down occurred by moving the throttle position back to the zero fuel flow position. The six parameters for all test runs are displayed in Figure 7, for both cold and hot engine test runs.



Test Run	% N1 Turbine Max. RPM	% N2 Power turbine RPM	EGT C°	Throttle position	Oil Temp C°	Oil pressure	Fuel pressure	Fuel Flow (GPM)	Time to Max. N1	Test Total Time	Comments
JET A FUEL ENGINE COLD	56.1	77	588.8 C	0.849	23.5 C	96.8	24.4	1.9	44	2:50	Without starter after maximum N1 sustained
JET A FUEL ENGINE HOT	57.7	78.8	580 C	0.849	31 C	96	24.7	1.9	43	1:41	Without starter after maximum N1 sustained
B11 FUEL ENGINE COLD	48.6	59.1	608 C	0.849	24.9 C	94.8	17.7	1.9	38	2:08	Starter energized during maximum %N1. At 40 sec. the starter was deenergized. %N1 started to decelerate. Exhaust smoke appeared after ignition.
B11 FUEL ENGINE HOT	53.9	70.8	590.5 C	0.849	28.9 C	96.4	19.7	1.9	46	1:39	Starter energized during maximum %N1. At 1:01 mins. the starter was deenergized. %N1 started to decelerate. Exhaust smoke appeared after ignition.
B100 FUEL ENGINE COLD	45	49	562.6 C	0.849	24.7 C	94.5	19.8	1.9	50	1:09	Starter energized during maximum %N1. At 19 sec. %N1 started to decellerate. At 16 %N1 the starter was deenergized. Exhaust smoke appeared after ignition.
B100 FUEL ENGINE HOT											With the starter and ignition energized the engine failed to start.

Figure 7

The B11 fuel test run with the engine cold, started and accelerated. The starter remained energized during maximum 48.6% N1 and 59.1% N2. At 40 seconds into the test, the starter was de-energized. N1 started to decelerate. Exhaust smoke appeared after ignition and continued during the test. The B11 fuel test with the engine hot, started and accelerated. The starter remained energized during the maximum 53.9% N1 and 70.8% N2. The maximum %N1 and %N2 were higher for the hot engine test. At 1:01 minutes into the test, the starter was de-energized. N1 started to decelerate. Exhaust smoke appeared after ignition and continued during the test. In both cold and hot test runs the engine failed the reach the standard sustained 57-58% N1. The engine would not maintain the maximum N1 without the starter energized. The fuel pressures were lower as compared to the Jet-A. This was due to the higher viscosity and the lower rpm of the engine fuel pump driven by the turbine section. Exhaust gas temperature (EGT) was higher because of the lower airflow supply from the compressor section to the combustor. The compressor section is driven by the gas producing turbine, which did not reach the %N1 rpm as the engine test using Jet-A. During all test that started the time from initial start to maximum %N1 averaged 1.3% N1 per second.

The B100 fuel test run with the engine cold and the starter energized during maximum 45.0% N1 and 49.0% N2. At 19 seconds N1 started to decelerate. At 16% N1 the starter was de-energized and continued to decelerate. Exhaust smoke appeared shortly after ignition and continued during the test. The B100 failed to maintain N1 with the starter energized. After a purge of the fuel system, a hot engine with the starter energized and the ignition on, the engine failed to start and accelerate. It was determined after the results of the failed hot start attempt, the cold start results occurred because of an incomplete purging of Jet-A fuel from the entire fuel system which allowed the engine to start initially on Jet-A and operated inefficiently after the flow of B100 reached the combustor.

4. Discussion and Conclusions

After completing the experiments of this study, we are now able to conclude that the performance results of biodiesel fuels in gas turbine engine were substandard to the performance results of using standard Jet-A aviation fuel. The failure of both B100 and B11 to maintain satisfactory engine operation is sufficient qualitative data to not recommend either of these fuels in an unmodified gas turbine aviation engine such as our Rolls Royce Allison 250-C20 turboshaft. The inability of the biodiesel fuels to perform in this engine would necessitate further investigation to determine if these factors could be overcome and then successfully utilized in gas turbine engines. As Demiral (2012) had eluded to the fact both B100 and kerosene based jet fuel have approximately the same energy density, we could conclude this was not a factor in the substandard performance. Using B11, a lesser percentage B-Fuel, in the engine did improve performance, however not to an acceptable level. Due to the progressive reduction in viscosity with greater percentages of petroleum-based fuel, the possibility of improved engine performance with B11 could be due to the reduced viscosity. As eluded to in the FAA report (2009), higher viscosity can negatively affect engine performance. From this, the inference is made that using an even lesser percentage of B-fuel through further blending would increase engine performance, possibly to an acceptable level. Boyce (2002) suggests preheating the fuel as another method of reducing heavier fuels’ viscosity. In addition, the success of Nascimento and dos Santos (2011) experiment with running preheated biodiesel blended fuels in a gas turbine is both encouraging and inspirational. For future research, we would propose to perform the study again with two additional variables; testing lower percentage B-fuels such as B5, and the preheating of the B-fuels to reduce the fuel viscosity. Until biodiesel based fuels are tested to have similar performance characteristics as Jet-A fuel, we cannot recommend their usage in gas turbine engines used in aircraft.

However, there may be opportunities to use B-fuels in applications that do not require the performance specifications expected when using turbine engines in aircraft. Turbine powered electrical generators, water pumps for irrigation, and other land-based applications could likely use B-fuels since issues caused by altitude change and temperatures are not a factor.

5. References

Addison, K. (n.d.). *Biodiesel and your vehicle-Quality testing-Wash test.* Retrieved from http://journeytoforever.org/biodiesel_vehicle.html

Alovert, M. (2005). Biodiesel Homebrew Guide. *Self-published textbook. alovert@ b100. org*.

Altaher, M. A., Andrews, G. E., & Li, H. (2014). Study of Biodiesel Emissions and Carbon Mitigation in Gas Turbine Combustor. *American Journal of Engineering Research, 03*(11), 290-298. Retrieved from http://ajer.org/papers/v3(11)/ZF031102900298.pdf

Alternative Fuels Data Center. (2017). *Biodiesel blends.* U.S. Department of Energy. Retrieved from https://www.afdc.energy.gov/fuels/biodiesel_blends.html

Boyce, M. P. (2002). *Gas turbine engineering handbook.* Gulf Professional Publishing/Elsevier.

Cobb, A. J. (2008). *U.S. Patent Application No. 12/009,887*.

Demirbas, A. (2008). *Biodiesel: A realistic fuel alternative for diesel engines*. London: Springer.

Demirel, Yaşar. *Energy: production, conversion, storage, conservation, and coupling*. Springer Science & Business Media, 2012.

do Nascimento, M. A. R., & dos Santos, E. C. (2011). Biofuel and gas turbine engines. In *Advances in Gas Turbine Technology*. InTech.

Federal Aviation Administration Aircraft Certification Service. (2016). *SUBJ: Fuel: Jet fuel containing FAME (Fatty Acid Methyl Ester)*. (Special Airworthiness Information Bulletin, SIAB: NE0925).

Fellett, M. (2016). Now boarding: Commercial planes take flight with biobased jet fuel. *Chemical & Engineering News, 94*(37). Retrieved from http://cen.acs.org/articles/94/i37/boarding-Commercial-planes-take-flight.html

Habib, Z. B., Parthasarathy, R. N., & Gollahalli, S. R. (2009). Effects of biofuel on the performance and emissions characteristics of a small scale gas turbine. In *Proceedings of the 47th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*.

McCormick, R. L., Williams, A., Ireland, J., & Hayes, R. R. (2006). *Effects of biodiesel blends on vehicle emissions: fiscal year 2006 annual operating plan milestone 10.4* (No. NREL/MP-540-40554). National Renewable Energy Laboratory (NREL), Golden, CO.

Mehta, P. S., & Anand, K. (2009). Estimation of a lower heating value of vegetable oil and biodiesel fuel. *Energy & Fuels*, *23*(8), 3893-3898.

Nabi, M. N., Akhter, M. S., & Shahadat, M. M. Z. (2006). Improvement of engine emissions with conventional diesel fuel and diesel–biodiesel blends. *Bioresource Technology*, *97*(3), 372-378.

National Biodiesel Board. (n.d.). *Project showcase: feedstock*. Retrieved from http://nbb.org/results/project-showcase/feedstock

Predojević, Z. J. (2008). The production of biodiesel from waste frying oils: A comparison of different purification steps. *Fuel*, *87*(17), 3522-3528.

Schell, J. S. (1998). *Plant Oils as Fuels: Present State of Science and Future Developments: Proceedings of the Symposium Held in Potsdam, Germany, February 16-18, 1997*. Springer.

Sheehan, J., Camobreco V., Duffield, J., Graboski, M., Shapouri, H. *An overview of biodiesel and petroleum diesel life cycles*. No. NREL/TP-580-24772. National Renewable Energy Lab., Golden, CO (US), 2000.

Szalay, D., Fujiwara, H., & Palocz-Andresen, M. (2015). Using biodiesel fuel for gas turbine combustors. *Fuel*, *84*(82), 80.

Tat, M. E., & Van Gerpen, J. H. (1999). The kinematic viscosity of biodiesel and its blends with diesel fuel. *Journal of the American Oil Chemists' Society*, *76*(12), 1511-1513.

Tilly. (2006, July 7). Jan Warnqvist's Conversion Test- Outstanding! (3/27) [Msg 1]. Message posted to http://biodiesel.infopop.cc/eve/forums/a/tpc/f/9411061471/m/8281092351

U.S. Energy Information Administration. (June 2017). *Monthly biodiesel production report*. Washington, DC: U.S. Department of Energy. Retrieved from https://www.eia.gov/biofuels/biodiesel/production/biodiesel.pdf

Van Gerpen, J. (2015). *Used and waste oil and grease for biodiesel*. Retrieved from http://articles.extension.org/pages/28000/used-and-waste-oil-and-grease-for-biodiesel

Yüksek, L., Kaleli, H., Özener, O., & Özoğuz, B. (2009). The effect and comparison of biodiesel-diesel fuel on crankcase oil, diesel engine performance and emissions. *FME Transactions*, *37*(2), 91-97.