The Effects of Nanoparticle-Enhanced Oil on the Efficiencies of Internal Combustion Engines

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Abstract

This study was conducted to investigate the effects of nanoparticle-enhanced oil on the state variables of internal combustion engines not limited to gas turbine engines. Two samples of nano-oil were tested: one sample contained AeroShell 560 with diamond nanoparticles additives while the other constituted of zinc sulfide, boron nitride, and graphene nanoparticles. The lubricating oils were tested in a UH-60 Blackhawk Auxiliary Power Unit (APU) to examine the influence of such oils on the operating temperature and efficiency of the engine. Experimental results from the nano-oil study suggest that the use of nanoparticle-enhanced oils could provide significant improvements in engine efficiency by reducing vibration and temperature of the engine. To further characterize the effects of nano-oils, a supplementary oil study was conducted on a small 4-stroke engine. The same oil samples were tested in the experiment with the addition of a conventional Pennzoil High Mileage 5W-30 and a diamond nanoparticle-enhanced Pennzoil High Mileage 5W-30. This supplementary investigation confirmed that nano-oils improve fuel efficiency of combustion engines by reducing engine temperature and vibration. However, some oil samples yielded anomalous results, discussed in later sections of this article.

Keywords: Auxilliary Power Unit, Nano Oil ,Fuel Efficiency, Small Engine

1. Introduction

1.1. Background and Previous Research

Oil is used in turbine engines to lubricate bearings, gears, and other rotating components. Energy can be lost through heat, vibration, and wear generation, which are caused by friction between moving parts. This study examines the effects of oils containing graphene, zinc sulfide, boron nitride, and diamond nanoparticles in internal combustion engines.

Previous studies have shown that nano-oil additives have the ability to significantly reduce friction and wear in gear boxes and engines. It has also been shown that nanodiamond particles can provide large efficiency improvements in engines [1, 2, 3]. These studies show the promising benefits associated with the use of nano-oils.

1.2. Problem Definition and Methodology

This research aims to further enhance the understanding of nano-oil properties and determine any benefits associated with the use of nanoparticle oils in internal combustion engines. Based on the previous studies, nano-oils have the ability to reduce friction, which would, in turn, reduce wear while improving fuel efficiency. This may result in large cost savings if the proposed oil proves effective and is implemented across entire fleets. Maintenance costs may also be reduced if the degradation rate of wear is reduced.

Due to the limited availability of research funds, a preliminary oil study was performed on the intermediate gearbox (IGB) of an Experimental Drive Train to select at least two oil samples that showed potential for improvements in engine efficiency. Five oil samples were tested during this experimental phase: a conventional AeroShell 560 oil sample, a diamond nanoparticle oil sample, and three oil samples containing zinc sulfide, boron nitride, and graphene nanoparticles. Subsequently, the best two nano-oil samples were tested in a UH-60 APU (turbine engine) and a 5.5 HP internal combustion engine, referred to as the small engine. The collected data was analyzed against experimental data from tests using baseline oils (AeroShell 560 and Pennzoil High Mileage 5W-30) to identify the effects of nano-oils on combustion engines. The exact composition of nanoparticles in each oil is proprietary information and was not disclosed as part of this study; however, characterization of oil samples was performed using optical microscopy, transmission electron microscopy, and viscosity analysis. For easy reference, diamond nanoparticles-enhanced oil will be referred to as 'Batch A', while nano-oils containing zinc sulfide, boron nitride, and graphene nanoparticles will be referred to as 'Batch B'. The appended integers to the oil samples indicate differences in the concentration of nanoparticles within the sample. Figure 1 highlights the experimental phases of this study as well as the oil samples and state variables examined during each phase.

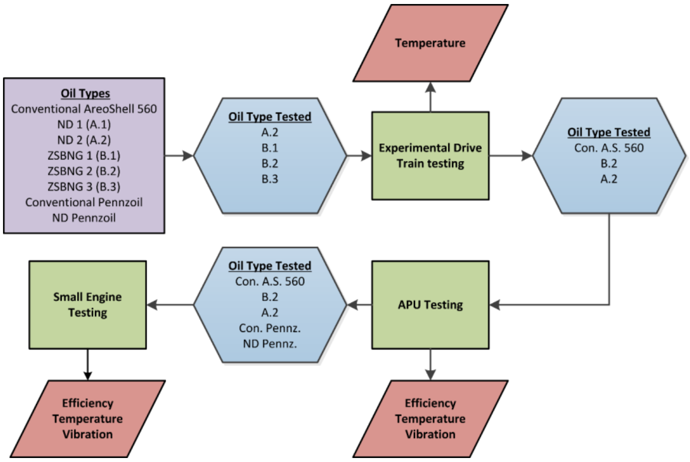

Figure 1. Experimental Flowchart

2. Test Stand Descriptions and Procedures

2.1. Description and Procedure for Experimental Drive Train

The Experimental Drive Train (EDT) is composed of several AH-64 drive train components, driven by a 5.5 HP motor. The test stand is used to develop new technologies while using less resources than the main test stand. The IGB, located at the tail end of the shaft, was equipped with four thermocouples at the Input Roller Bearing (IRB), Input Duplex Bearing (IDB), Output Roller Bearing (ORB), and the Output Duplex Bearing (ODB).

Four runs using conventional AeroShell oil were performed first, followed by four runs with each nano oil. The oils tested include: Conventional, Batch A.2, Batch B.1, Batch B.2, and Batch B.3. All oils were tested four times, and each run lasted for 50 minutes with the drive shaft operating at a speed of 4,863 rpm. The only source of data collected for this test was temperature measured at each of the bearings. The IGB was flushed multiple times with conventional oil between each run to remove any remaining nanoparticles.

2.2. Description and Procedure for the Auxiliary Power Unit

During start-up, the fuel boost pump injects fuel from the on-board fuel tank, through a filter, and then to the fuel inlet manifold on the APU. After the turbine reaches full speed, it draws fuel on its own and the boost pump can be turned off. This fuel continuously combusts and causes the turbine to rotate, which transfers torque through the reduction drive assembly to the output shaft. The water brake dynamometer is attached to this shaft and is controlled by water pressure from a hose. This is connected to a pressure regulator then to a manual valve outfitted with a pressure gauge. The pressure regulator prevents inconsistent water pressure from affecting the torque applied by the water brake. The flow rate of water is adjusted to create a consistent torque load applied to the output shaft of the APU.

The APU runs were performed uninterrupted for 45 minutes. Vibration, oil temperature, exhaust temperature, RPM, fuel consumption, and torque readings were collected throughout the duration of each run. In addition, local climate conditions, including humidity, ambient temperature, and barometric pressure, were recorded throughout each run. Seven runs were performed for Conventional AeroShell, Batch A, and Batch B oils. The APU was flushed with conventional oil between Batch A and Batch B runs to remove any leftover nanodiamond particles. The measurements taken during the last 30 minutes of each test were compared.

Data was analyzed using RStudio and Microsoft Excel. The overall efficiency, oil temperature, and vibration data were compared between oil samples. The fuel flow rate was not directly compared, because slight inconsistencies in RPM and torque were present due to small variances in water pressure and human error associated with manually adjusting the torque. To account for this, the overall efficiency of the APU was examined in this study using Equation 1, which relates the output power (W) to the input power from the fuel (E_{in}). The output power was calculated using Equation 2. The energy density of the fuel was calculated by using Equation 3.

$$APU\ Efficiency = \frac{W}{E_{in}} \quad (1)$$

$$Output\ Power\ (W) = \frac{RPM\ \times Torque}{5252} \quad (2)$$

$$E_{in} = Energy\ density_{fuel}\ \times\ m_{fuel} \quad (3)$$

Engine efficiency accounts for all system losses, highlighting its validity as a comparative indicator for the oil samples, it also provides a way to normalize fuel flow data so that fuel consumption can be compared. Since efficiency represents the ratio of output power to input power, it can be used to study fuel flow for each oil type at specific horsepower values.

Vibration was measured with an accelerometer and the data was collected at 20 kHz. This resulted in about 15,000,000 data points per run which were analyzed by performing a Fast Fourier Transform (FFT) and by calculating the Root Mean Square (RMS) value of each set of data. A FFT transforms the vibration data from a time domain to a frequency domain, outputting vibration magnitudes with respect to the frequency at which they occur. This approach is useful because different rotating components vibrate at different resonance frequencies. The RMS value allows for comparisons of the overall vibration energy between oil types, while the FFT enables the evaluation of vibration data occurring at individual frequencies.

Multiple studies suggest that variations in ambient temperature and pressure can affect turbine efficiency [4, 5], therefore, a correction factor was applied to the fuel flow. The variable $W_{corrected\ fuel,}$ shown in Equation 4, is the fuel flow after the correction is applied. The variable W_{fuel} represents the measured volumetric fuel flow. The variable δ is the ratio of measured barometric pressure to a standard sea level barometric pressure, and θ is the ratio of measured ambient temperature to a standard temperature of 15°C. The corrected volumetric fuel flow is multiplied by the density of the fuel to determine the mass flow rate of the fuel [6].

$$Corrected\ Fuel\ Flow\ (W_{corrected}) = \frac{W_{fuel}}{\delta\sqrt{\theta}} \quad (4)$$

Oil temperature was also corrected for effects caused by the difference in ambient temperature as shown in Equation 5 [7]. After the average oil temperature throughout each run was determined, a Tukey Honest Significant difference (HSD) test was performed to compare the runs for each oil type.

$$Correction\ for\ Oil\ Temperature\ (T_{oil-corrected}) = T_{oil} + (100°\mathrm{F} - T_{ambient}) \quad (5)$$

2.3. Description and Procedure for the Small Engine

The Small Engine Test Stand contains a 5.5 HP 4-stroke engine with a fuel flow meter. RPM, torque, and ambient conditions were measured by the dynamometer. A DAQ utilizing LabVIEW software was used for gathering oil temperature and fuel flow data.

The engine was run initially for ten hours with conventional motor oil to allow for break-in. After this, four runs were performed for each type of oil. Five types of oil were tested: Pennzoil High Mileage 5W-30, Pennzoil High Mileage 5W-30 with a nanodiamond additive, AeroShell 560, AeroShell 560 with nanodiamond particles (Batch A.2), and AeroShell 560 with graphene, zinc sulfide, and boron nitride particles (Batch B.1). The nanodiamond additive used in the Pennzoil oil is a blend formulated by NanoPro specifically for pistons engines. The Pennzoil and AeroShell base oils were used to flush the engine between runs, removing nanoparticles that were left in the engine and returning the engine to a baseline state. ANOVA and Tukey's HSD were used for analyzing data from the last 30 minutes of each run during which the engine was assumed to be at steady state. Ambient condition correction factors were applied to the small engine as well, however the coercion factor equations used are specifically for piston engines. Equation 6 shows the correction factor used to account for variances in ambient barometric pressure and temperature. The variable P is ambient barometric pressure in millibars, and the variable T is ambient temperature in degrees Celsius.

$$cf = 1.176\left[\left(\frac{990}{P}\right)\left(\frac{T+273}{298}\right)^{\frac{1}{2}}\right] - 0.176 \quad (6)$$

2.4. Procedure for Offline Analyses-Viscosity and Microscopy

Viscosity was measured using a Brookfield Engineering Co. LVDV II viscometer, a cone and plate type rotary viscometer. The dynamic viscosity of oil samples (in mPa·s) were obtained from shear stress in the fluid from pre-calculated values in the software. The viscometer is accurate to within ±1.0% and reproducible within ± 0.2% [8]. Conventional AeroShell, Batch A.2, and Batch B.1 samples were tested at each ten degree increment ranging from 20°C to 90°C. Nine measurements were taken at each temperature and averaged together.

Two different microscopes were used to observe the oils and their subsequent particle clumping. During the mixing process of the oils, clumps of particles were visibly noticeable in the original Batch B oil. To determine the size of these clumps, a KEYENCE VHX-5000 optical microscope with a lens capable of 5000x magnification was used to examine and measure the particle clumps in Batch A.2 and Batch B.1. A Hitachi H8000 Transmission Electron Microscope (TEM) was used to measure the size of individual particles in the Batch B.1 oil. This device has a resolution of 1.5 nm and a magnification of 2,000-800,000x.

3. Results and Discussion

3.1. EDT Results

Temperature data from the last 20 minutes of each run was analyzed in RStudio. The last 20 minutes of data were chosen to give the gear box adequate time to warm up. ANOVA and Tukey's HSD tests were used to analyze the data. Table 1 shows the results from EDT testing. The difference in average temperature between the conventional oil and each nano-oil, at each location, is shown in this table. A positive value indicates that the temperature rose by that amount, while a negative value indicates that the temperature decreased by that amount.

Table 1: EDT Temperature Differences Between Conventional AeroShell and Nano Oils (°F)

Oil Type	IDB	IRB	ORB	ODB
Batch A.2	-2.45	-0.95	-1.08	-1.19
Batch B.1	-8.06	-10.20	-9.39	-13.46
Batch B.2	-2.78	-8.65	-10.93	-11.83
Batch B.3	5.45	-7.84	-15.53	-13.07

From this table, it is evident that all of the nano-oils reduced the temperature in the gearbox for at least three of the four thermocouples. The disparity in the temperature reduction values associated with Batch A.2 and Batch B.2 oil samples can be attributed to the higher concentration of nanoparticles in Batch B. While graphene has an extremely high thermal conductivity, diamond nanoparticles have a higher thermal conductivity than any of the particles found in Batch B. To provide greater temperature reduction benefits, Batch B must have a higher concentration of particles, or provided much better friction reduction. The exact concentrations are proprietary and are only known by the manufacturer. The presence of nanoparticles in nano-oils explains the improvements in heat transfer performance because the nanoparticles, especially diamond and graphene, enhanced the thermal conductivity of the base oil. Batch B.1 had the lowest nanoparticle concentration out of the Batch B oils, and the findings suggests that it caused the most uniform heat transfer, likely due to its lower viscosity which allowed for easy flow throughout the gearbox. As a result of this testing, Batch B.1 was selected for testing in the APU, along with Batch A.2. For the rest of this document Batch B.1 will be referred to simply as Batch B and Batch A.2 will be referred to as Batch A.

3.2. APU Results

Each run was tested for consistency before being analyzed with an ANOVA test and a Tukey (HSD) test in RStudio. A t-test was performed to determine the percent error in the data for a 95% confidence interval. Equation 1 was used to find efficiency from horsepower and flow rate. The data analyzed from the final 30 minutes of each run consisted of approximately 1,800 data points for fuel flow and efficiency. Torque and RPM were sampled more frequently and consisted of about 18,000 data points. The large number of data points caused the percent error to be extremely small.

Efficiency was calculated for Conventional oil and then Batch A and Batch B oils. Batch A and Batch B oils were compared to Conventional AeroShell oil. The results suggested that both nano-oils improved overall APU efficiency. The p-value was calculated as part of the Tukey HSD test to determine if the values were significantly different with final values ranging from zero to one. The p-value was less than $2x10^{-16}$ for all of these calculations, providing very strong evidence that the means were not statistically different. This test was performed for a 95% confidence interval. The average values for fuel flow, torque, RPM, and efficiency are shown in Table 2.

Table 2: Efficiency and Fuel Flow Results

Oil Type	Average Corrected Fuel Flow (mL/s)	Average Output Torque (ft-lb)	Average RPM	Average Efficiency (%)
Conventional	12.93	14.80	12009.62	5.54
Batch A	12.75	14.77	12000.03	5.59
Batch B	12.50	14.76	11990.02	5.70

Oil temperature was analyzed from the 15 to 45 minute portion of each run. An ANOVA test and a Tukey (HSD) test were performed using RStudio. The correction factor was applied by using Equation 6 which corrects the oil temperature to represent the results that would be expected for an ambient temperature of 100°F (37.78°C). As was the case for conventional oil, the correction for ambient temperature effects significantly reduced the percent error in the data. The average Batch B oil temperature was noticeably higher than that of Conventional and Batch A oils.

Batch A oil appeared to lower the oil temperature by 1.4 degrees Celsius. However the p-value for this comparison was 0.1755, indicating that the means are not statistically different, therefore, there was no statistically significant difference in temperature. Batch B increased the temperature by 6.93 °C. The p-value for this comparison was $1x10^{-7}$ indicating that there was a definite statistical difference between the mean oil temperature of the conventional oil and Batch B oil. It is evident that the Batch B oil operated at a much higher temperature than the other two oils. An increase in temperature could have been a result of increased friction or from increased heat transfer from a heat source, such as the combustor.

Table 3: Oil Temperature Results

Oil Type	Oil Temperature (°C)	Corrected Oil Temperature (°C)
Conventional	81.90 ± 4.44	99.78 ± 0.73
Batch A.2	82.77 ± 2.68	98.38 ± 1.46
Batch B.1	98.32 ± 3.78	106.71 ± 1.80

Vibration data from all seven runs were averaged so that it could be compared to the other oil types. An ANOVA test and a Tukey (HSD) test were performed using RStudio. The average peak magnitude for Conventional oil was 2.53 ± 0.66 g, and the average RMS was 25.90 ± 5.46 g and occurred at a frequency of 6,418.41 Hz. The average peak magnitude for Batch A was 1.65 ± 0.67 g, and the average RMS was 20.22 ± 4.07 g, and occurred at a frequency of 6,413.69 Hz. The average peak magnitude for Batch B was 1.40 ± 0.48 g, the average RMS was 19.07 ± 3.06 g, and occurred at a frequency of 6,406.71 Hz. The values in Table 4 represent the reduction in vibration when using each nano-oil instead of Conventional oil.

Table 4: Batch A and Batch B versus Conventional Results

Vibration Data for Nano-Oils Compared to Conventional Oil				
Oil Comparison	**Peak Magnitude (g)**	**p-value for Magnitude**	**RMS (g)**	**p-value for RMS**
Batch A vs Conventional	-0.88	0.04	-5.68	0.06
Batch B vs Conventional	-1.12	0.01	-6.82	0.02

3.2.1. Discussion of APU Results

The experimental findings show that there was an increase in efficiency for Batch A and Batch B oils. Batch A reduced the peak vibration by 35% and the RMS by 22% while Batch B resulted in a 44% reduction in peak vibration and a 26% reduction in the RMS, suggesting that friction was reduced by a substantial amount. Vibration can result from contact of surface asperities during mixed-boundary lubrication and can greatly be reduced when an elastohydrodynamic regime occurs. This type of lubrication involves a compressible layer of oil that provides complete separation of the two surfaces. Oil with a higher viscosity usually results in a thicker boundary layer between surfaces. While this reduces friction between components, drag forces in the oil increase. The results suggest that both nano-oils improve the fluid film, resulting in decreased vibration and increased efficiency.

The increase in temperature for Batch B oil is an unexpected outcome and requires additional testing to completely determine the cause. Increased friction usually causes increased vibration and heat. Batch B most likely reduced overall friction because of the heat reduction in the IGB, the efficiency improvement in the APU, and the vibration reduction in the APU, suggesting that the higher APU oil temperature resulted from other factors. The average temperatures during the 15 to 45 minute portion of the runs are shown in Figure 2. A higher combustor temperature, as seen with Batch B, signifies increased efficiency. Less heat may be generated by friction, but more could be transferred from the rest of the engine. This suggests that Batch B conducted heat much more efficiently than the other oils.

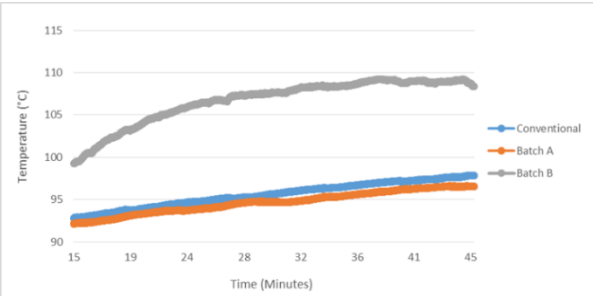

Figure 2: Transient APU Oil Temperature

The runs were not performed long enough for steady state temperatures to be reached because the APU on an UH-60 usually runs for less than 30 minutes before take-off, in which it does not reach steady state, therefore, analyzing steady-state data would not provide useful information for realistic scenarios. Figure 2 suggests that Batch B may have decreased friction, but may have also had a lower specific heat which caused its temperature to rise at a faster rate. The combustor may have also been operating at a higher temperature because of reduced friction. Hence, the oil temperature increase was most likely caused by an increase in the combustor temperature. Oil filter clogging could have also been a likely cause of increased temperature for

Batch B oil. The clogging of the filter reduced oil flow, resulting in higher oil temperatures due to slower heat exchange. Both nano-oils provided overall efficiency improvements. While the reduction in fuel consumption is fairly small, cost-savings could be significant in the long-term.

3.3. Small Engine Results

The efficiency results for each run for all five types of oil along with the average efficiency for each type were calculated. The average efficiency values for Pennzoil, Pennzoil with diamond nanoparticles, Conventional (AeroShell 560), Batch A.2, and Batch B.1 were 21.29%, 20.88%, 21.83%, 21.58%, and 22.43% respectively. The efficiency was higher for conventional turbine oil than for Pennzoil oil. The use of nanodiamond (ND) particles reduced the efficiency in both Pennzoil and AeroShell 560 while the use of Batch B.1 resulted in increased efficiency. The results, when calculated with a Tukey HSD test, are shown in Table 5.

Table 5: Comparison of Small Engine Efficiency Results

Oil Type	p-value	Difference (95% confidence)
Pennzoil		[redacted]
Pennzoil w/ND Additive	$< 2 \times 10^{-16}$	-0.44%
Conventional (AeroShell 560)		[redacted]
Batch A.2	$< 2 \times 10^{-16}$	-0.26%
Batch B.1	$< 2 \times 10^{-16}$	0.06%

The average corrected temperature values for Pennzoil, Pennzoil w/ND additive, Conventional (AeroShell 560), Batch A.2, and Batch B. 1 were calculated to be 106.81°C, 104.73°C, 105.28°C, 103.52°C, 103.64°C respectively. The results, when calculated with a Tukey HSD test, are shown in Table 6.

Table 6: Comparison of Small Engine Temperature Results

Oil Type	p-value	Difference(°C) (95% confidence)
Pennzoil		[redacted]
Pennzoil w/ND Additive	$< 2 \times 10^{-16}$	-1.67
Conventional (AeroShell 560)		[redacted]
Batch A.2	$< 2 \times 10^{-16}$	-1.88
Batch B.1	$< 2 \times 10^{-16}$	-1.63

The average RMS values for Pennzoil, Pennzoil w/ND additive, Conventional (AeroShell 560), Batch A.2, and Batch B.1 were 1.879 g, 1.886 g, 1.957 g, 1.971 g, 1.656 g respectively. The Batch B.1 runs had the lowest RMS values and using this oil instead of conventional oil resulted in a 15.4% reduction in RMS. The results, when calculated with a Tukey HSD test, are shown in Table 7.

Table 7: Comparison of Small Engine Vibration Results

Oil Type	p-value	Difference(g) (95% confidence)
Pennzoil		[redacted]
Pennzoil w/ND Additive	0.793	0.007
Conventional (AeroShell 560)		[redacted]
Batch A.2	0.846	0.015
Batch B.1	1×10^{-7}	-0.300

3.4. Offline Analysis Results-Viscosity and Microscopy

The samples were measured at various shear stresses and were determined to be Newtonian fluids, meaning the shear stress varied linearly with shear rate. Batch A was found to have a higher viscosity than Conventional oil, and Batch B has the highest viscosity at every temperature. The oil temperature in the APU was between 85°C and 105°C for most of the runs. At 90°C, the viscosity of Batch B was 17.97% higher than the viscosity of the Conventional oil, potentially reducing surface to surface contact, but also increasing drag forces associated with spinning oil bearings.

The optical microscope showed that there were large particles present in the initial Batch B oil, some of these particles were over 200µm. Due to the large size of the nanoparticles, NanoPro MT developed a second Batch B oil by filtering the initial Batch B oil. While the particle size was reduced, they were still measured to be in the 20 to 40µm range. The APU has a 10µm oil filter, so these particles could still clog the filter. The nanodiamond particle clumps in Batch A are much smaller than the ones present in Batch B, when viewed through an optical microscope, the majority of the clumped particles were measured to be in the 6 to 12µm range. The Batch B particles were then dried and observed with a transmission electron microscope (TEM). The individual nanoparticles were found to have an average radius of 4nm, suggesting that the large particles observed with the optical microscope are clumps of these nanoparticles.

4. Conclusion and Future Work

This research compared two different types of nano-oils and analyzed results from multiple tests to determine the effects of these oils on internal combustion engines. The effects of nanoparticle-enhanced oils on engines were examined by assessing the fuel efficiency, temperature, and vibration data an Auxiliary Power Unit and a 5.5 HP petrol engine. The oils were also characterized using viscosity and microscopy.

Batch A consists of diamond nanoparticles suspended in AeroShell 560 oil. The use of this oil resulted in a lower oil temperature during testing on the intermediate gearbox of the Experimental Drive Train but did not significantly affect oil temperature in the APU. It provided some improvement in fuel efficiency of the APU while greatly reducing vibration. These results suggest that Batch A does provide some benefits over the base oil.

Batch B contains zinc sulfide, boron nitride, and graphene nano particles. It provided greater temperature reduction compared to Batch A or conventional oils, but it resulted in a much higher oil temperature in the APU. While temperature greatly increased in the APU, vibration was substantially reduced in the APU and Small Engine. The use of Batch B also resulted in the highest fuel efficiency, indicating that the increased APU oil temperature is most likely not caused by an increase in friction. The increase in APU oil temperature may be due to the increased rate of heat transfer from the combustor to the oil and oil filter clogging.

Both nano-oils provided thermal and lubricating benefits to the internal combustion engines. Although present formulations of the oils did not provide an exceptionally large increase in fuel efficiency, the results are promising and even a slight increase can provide substantial cumulative fuel cost savings. The reduction in vibration can reduce component failures, which could reduce maintenance requirements and result in additional cost savings.

Batch B oil clogged the APU oil filter due to the aggregation of nanoparticles within the oil sample. To ensure the durability of combustion engines using nano-oils, such clogging problems need to be resolved. Future work should focus on improving the composition of nanoparticle-enhanced oils to eliminate filter clogging problems and optimize vibration and temperature reduction benefits in combustion engines.

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