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Waste and Cost Reduction by Reprocessing Used Motor Oil into a Synthetic Diesel Fuel

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Abstract: *Utah Valley University has implemented a program to reuse waste motor oil (WMO) generated on campus into a synthetic diesel fuel for use in its diesel utility vehicles. This paper describes the research performed by a team of undergraduate students to develop and test synthetic diesel fuel mixtures from WMO. We developed a cost-effective, scalable, process to "clean" the WMO. Mixtures of "clean" WMO and regular unleaded gasoline where prepared, characterized, and then tested in a diesel engine/generator. We developed a stoichiometric fuel model to explain the engine test results. This model provides a theoretical framework for preparing synthetic diesel fuel mixtures from WMO. We successfully developed a synthetic diesel fuel for the diesel utility vehicles on-campus, reducing disposal and fuel costs.*

1. INTRODUCTION

Utah Valley University (UVU) has an abundance of waste motor oil (WMO) from the airplanes, motor vehicles, and utility vehicles operated by the University. For example, the Aviation Science Department operates and maintains 23 aircraft. FAA regulations require aircraft motor oil to be changed every 50-flight hours. This results in the generation of over 500 gallons of waste motor oil (WMO) per year. Mario Markides of the Aviation Science Department initiated this project to reduce WMO disposal costs. Fortunately, Federal regulations allow a generator of WMO to reprocess and use it within the organization[1]. UVU has a fleet of diesel utility vehicles on campus that can use fuel prepared from WMO. The objective of this project is to repurpose the WMO generated on-campus into a synthetic diesel fuel using a cost-effective, scalable process developed by our team.

Hobbyists

Diesel engine hobbyists have been using WMO to fuel their engines for many years[2]. Typically, hobbyists mix WMO with unleaded gasoline. The most common mixture is 80 volume % WMO and 20 volume % unleaded gasoline (80:20).

WMO

Although diesel fuel, motor oil, and unleaded gasoline are primarily composed of aliphatic hydrocarbons, their respective properties prevent them from being used interchangeably in different internal combustion engine (ICE) configurations. For example, low compression, spark-ignited, engines require fuel with a higher octane number to prevent pre-ignition of the fuel, which causes engine knock. For comparison, modern, high compression, diesel engines inject the fuel at top-dead-center (TDC), requiring a fuel with a low octane number, so the fuel ignites instantly. Motor oil is composed of 80-90% base oil (C_{18}-C_{34}, Polyalphaolefins (PAOs), Esters, Alkylated Naphthenes (ANs)) and additives. Additives include viscosity index improvers (large polymeric molecules), dispersants (polyamines, surfactants), detergents/neutralizing agents (calcium, magnesium, and sodium sulfonates, phenates, and salicylates), friction modifiers (very polar esters or partial esters, seal conditioners (esters), corrosion inhibitors (zinc dialkyldithiophosphates), anti-oxidants (phenols and amines), pour point depressants (polymeric molecules), antifoams (silicone products), and diluent oil (mineral oil) [3,4]. Some of these additives could produce abrasive, oxides during combustion. However, we did not test for engine damage during this stage of the project. WMO also contains metal particles from engine wear and carbon particles from incomplete combustion. The WMO is "cleaned" before using it as a fuel, in order to remove potentially harmful contaminants. We tested two "cleaning" methods for this project: distillation and centrifugation.

Diesel Engine Operation

This project requires a complete understanding of modern diesel engine operation. Diesel engines intake a fixed volume of air during the intake stroke of each 4-stroke cycle. The air is compressed and heated on the compression stroke. Fuel is injected just after the piston reaches TDC, starting the power stroke. The fuel spray should ignite instantly when mixed with the hot air, which requires a fuel with low octane number (high cetane). A high-octane fuel (greater than approximately 40) will not ignite under these conditions. For optimum performance, the fuel should burn completely forming carbon dioxide gas (CO_2) and water vapor (H_2O). All diesel engines are designed to run on a lean fuel/air stoichiometric mixture. Lean operations means slightly less fuel is injected during the power stroke than there is oxygen to combust it completely. If the normalized fuel/air stoichiometric mixture is greater than 1.0 (rich) then incomplete combustion will occurs with the formation of soot (unburned carbon particles), carbon monoxide (CO), and volatile organic compounds (VOCs), which are unburned or partially burned fuel.

For this project, we measured the properties of various mixtures of WMO, gasoline, and diesel and compared them to standard diesel fuel. We also ran these mixtures in a test diesel engine under variable load conditions to determine their energy density compared to diesel fuel. Finally, we performed calculations to explain our results.

2. METHODS

Distillation

We initially tried to "clean" the WMO by distilling it. Distillation has the ability to remove all non-volatile contaminants and produce primarily pure aliphatic hydrocarbons. However, we found distillation of the WMO to be a difficult, time consuming, process with the simple pot still and condenser we assembled. The distillate, though clear, had a very strong odor. During distillation, we likely overheated the WMO resulting in pyrolysis of some of the additives. The cost of appropriate distillation equipment was prohibitive. In addition, distillation is potentially dangerous for untrained personnel. For these reasons, we decided to stop using distillation for this project.

Two Cycle Centrifugation

Most hobbyists simply filter their WMO before using it in their fuel mixtures. However, we found that available paper and plastic filters are slow and quickly become plugged with contaminants. Consequently, we chose to use centrifugation as a high throughput form of filtration that removes the most dense contaminants from the WMO, including metal particles, sludge, and water. We used a PA Biodiesel Ultimate Force Centrifuge with a 1500 W, in-line, oil pre-heater, shown in Exhibit 1. This 3450 RPM centrifuge is effective, because it keeps the WMO in the spinning bowl for approximately 3 minutes at a flow rate of 10 GPH. We filtered the WMO with two separate cycles through the centrifuge. We cleaned the centrifuge bowl between cycles to remove the accumulated sludge. Although centrifugation did not remove the carbon particles (the "cleaned" WMO is still black), we found centrifugation to be a low cost, fast, efficient process for filtering WMO.

Exhibit 1: *Centrifuge used to filter WMO. Diesel engine/ generator used to test fuels*

Fuel Characterization

We prepared volumetric mixtures of "cleaned" WMO with regular unleaded gasoline (85 octane) and/or diesel fuel. We measured the specific gravity, and viscosity of low-sulfur, highway diesel fuel, "cleaned" WMO, and WMO/gasoline, and WMO/diesel mixtures. The specific gravity measurements were performed using a Fischer Hydrometer (Art #11510D, Lot# 10/29/2015). The viscosity measurements were performed using a Fischer Viscometer Tube (13-616G, 350). The viscometer was placed in a room temperature water bath for these measurements. Slow motion videos of the viscosity experiments were made to determine the precise time it took for each fuel to flow out of the upper reservoir and through the calibrated capillary.

Diesel Engine Tests

The key experiment for this project was running the fuel mixtures in a diesel engine powered generator shown in Exhibit 1. We controlled the load on the diesel engine by connecting the generator to an electric heater with variable power settings. In this way, the generator/heater worked like a dynamometer for the diesel engine. We started the engine with diesel fuel and ran it for 15-20 minutes to reach a stable operating temperature. After switching to the fuel being tested, we measured the amount of time 1.0 liter of each fuel ran the diesel engine at ½ load (2,500 W) and 4/5^{ths} load (4,185 W). During each run, we collected exhaust particles on pre-weighed VWR 413 filter papers (5-13 micron particle retention) placed 10. inches from the engine exhaust. We used a laboratory vacuum pump to pull exhaust through the filter paper (shown in Exhibit 1). After each test, we switched back to diesel fuel to clean-out the fuel lines before shutting down the engine.

3. RESULTS AND DISCUSSION

Specific Gravity and Viscosity

Exhibit 2 shows the results of the fuel characterization tests. The specific gravity of the WMO mixtures is slightly higher than diesel fuel. This means the mass of WMO mixtures injected will be slightly higher than for diesel fuel at any given RPM. This would give a higher fuel/air ratio for this mixture compared to diesel fuel. The viscosity of the 80:20 WMO/gasoline mixture is significantly higher than diesel fuel. We think this will result in an increase in the average droplet size from the injector nozzle, resulting in less efficient combustion. We do not think the higher viscosity affects the fuel flow rate, because diesel engines use high-pressure fuel pumps to enable fuel injection at TDC. The pressure drop due to a higher viscosity fuel is likely small compared to the overall pressure drop at the injection nozzle. On very cold days, the fuel flow of the high viscosity WMO mixtures may decrease significantly. Diesel engine hobbyists often add heaters to their fuel tank and line to eliminate this problem. We designed the 57:43 WMO/gasoline mixture specifically to give a viscosity similar to diesel fuel.

Fuel	**Specific Gravity**	**Viscosity @ 20 °C (seconds)**
Highway Diesel	0.8444±0.0005	14.16±0.05
Regular Unleaded Gasoline	0.7369±0.0001	not measured
WMO	0.8510±0.0001	not measured
80:20 WMO/Gasoline	0.850±0.001	310.96±59.97
57:43 WMO/Gasoline	0.850±0.001	14.46±0.36
50:40:10 Diesel/WMO/Gasoline	0.837±0.003	21.51±0.22

Exhibit 2: *Results of fuel characterization tests.*

Engine Fuel Tests

Exhibit 3 shows the results of the diesel engine experiments. We initially thought the run time for the 80:20 WMO/gasoline mixture would be longer, due to its higher molecular weight and thus higher energy density. However, we later realized that for our test engine the volume of fuel injected at any RPM is the same for every fuel. The higher density 80:20 WMO mixture means a greater mass is injected during each cycle. The higher exhaust particulate count for the 80:20 WMO mixtures suggests incomplete combustion of this fuel. In our 4/5^{ths} load tests with the 80:20 WMO/gasoline mixture, the engine only ran during cold weather. We think this is due to higher density air at the colder temperatures introducing more oxygen into the engine. During warm weather testing (lower air density), less oxygen entered the engine, resulting in less oxygen to completely combust the injected fuel. Under these conditions, the RPM slowly decreased until the engine stopped. We had limited particulate data for the 4/5^{ths} power runs using the 80:20 WMO mixtures. However, thick dark exhaust was observed for the short time the engine ran during warm weather tests. We could not get the 57:43 WMO mixture with high gasoline content to run in our diesel engine.

Fuel	**Engine Run Time (min/L) 1/2 Load**	**Particulate Count (mg) 1/2 Load**	**Engine Run Time (min/L) 4/5th Load**	**Particulate Count (mg) 4/5th load**
Highway Diesel	47.77±3.04	1.79±0.17	38.43±7.02	2.05±0.36
80:20 WMO/Gasoline	39.67±6.69	5.72±0.64	38.40±3.56	3.58±
57:43 WMO/Gasoline	would not run		would not run	
50:40:10 Diesel/WMO/Gasoline	39.56±2.80	0.61±0.42	30.16±1.95	1.33±1.32

Exhibit 3; *Results of diesel engine tests.*

Average Molecular Weight Calculations

Exhibit 4 shows the average molecular weight and average research octane number (RON) we calculated for the fuels we tested. For the average molecular weight calculations, we assumed the diesel fuel was pure n-pentadecane ($C_{15}H_{32}$), unleaded gasoline was pure n-octane (C_8H_{18}), and WMO was pure n-icosane ($C_{20}H_{42}$). For the average RON calculations, we used a weighted average of the literature RON values for diesel fuel (20)[5,6] and the RON number for regular unleaded gasoline (90). The RON value for WMO (a mixture of straight, cyclic, and branched hydrocarbons) was estimated using the RON value for n-octadecane from a best fit curve of the literature values for aliphatic hydrocarbons, plus the difference between the RON value for n-dodecane and the measured value for diesel fuel (also a mixture of straight, cyclic and branched hydrocarbons).

Fuel	Average Molecular Weight (g/mol)	Average RON
Highway Diesel	212.42	20
Regular Unleaded Gasoline	114.23	90
WMO	282.55	-16
80:20 WMO/Gasoline	223.85	21
57:43 WMO/Gasoline	178.57	49
50:40:10 Diesel/WMO/Gasoline	217.93	20

Exhibit 4: *Average molecular weight and average research octane number (RON) calculations.*

Diesel Engine Stoichiometry Calculations

Exhibit 5 shows a model we developed of the normalized fuel/oxygen stoichiometric ratio as a function of RPM for our engine. A ratio above 1.0 means the fuel/air mixture is rich (excess fuel) and below 1.0 means the fuel/air mixture is lean. Under high load conditions, the engines slows, resulting in more fuel being injected. However, when the fuel/air mixture becomes rich, the extra fuel does not burn, resulting greater particulate production. Sensitivity analysis on our model indicates the density of the fuel has a much greater effect on the fuel/air ratio than the average molecular weight of the fuel. For example, the more dense 80:20 WMO/gasoline mixture results in more fuel injection during the power stroke. This increases the fuel/air ratio. Consequently, this fuel mixture is more likely to become rich during high load conditions. This also explains why during warm weather, this mixture would eventually cause the engine to stop; the excess, unburned, fuel cools the fuel/air mixture, preventing ignition. The model also explains why the less dense 50:40:10 diesel/WMO/gasoline mixture does not run the engine as long on one liter of fuel under high load conditions. As can be seen, this fuel mixture runs leaner than diesel fuel, so more of the mixture must be injected to keep the engine running. This mixture also produces less particulates, because it does not become rich, even under high load conditions.

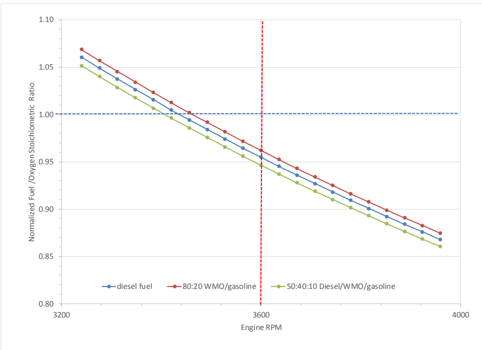

Exhibit 5: *Normalized fuel/oxygen stoichiometric ratio as a function of engine RPM for our test engine running diesel fuel, 80:20 WMO/gasoline fuel, and 50:40:10 Diesel/WMO/gasoline fuel.*

4. CONCLUSIONS

The higher density 80:20 WMO/gasoline mixture ran rich in our engine, resulting in increased particulate emissions from incomplete combustion. The lower density 50:40:10 diesel/WMO/gasoline mixture ran well under all conditions with fewer particulates, although it does require more fuel. The 57:43 WMO/gasoline mixture did not run at all, because the RON was too high for instantaneous fuel ignition. Balance is required between reducing viscosity, density, and average molecular weight by adding gasoline to WMO and increasing the RON.

We think hobbyists successfully use an 80:20 mixture of WMO/gasoline in their diesel engines, because the density, average molecular weight, and average RON of this mixture is similar enough to diesel fuel to enable operation under most operating conditions. As long as the fuel/air mixture remains lean, this fuel mixture will work. However, if the fuel/air mixture becomes rich, for example under high load conditions, there will be an increase in particulate emissions and the diesel engine will run poorly.

Finally, we conclude that a 50:40:10 diesel/WMO/ gasoline mixture will effectively fuel the diesel powered utility vehicles on campus, reducing diesel fuel costs. However, we think more research is required to insure the synthetic diesel fuel mixture will effectively run the test engine under all conditions, without damage, during prolonged use.

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