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# Evaluating high volume blends of vegetable oil in micro-gas turbine engines

A. Hoxie [a, *], M. Anderson [b, c]

[a] Department of Mechanical and Industrial Engineering, University of Minnesota Duluth, 1305 Ordean Ct., Duluth, MN 55812, USA
[b] Department of Mechanical Engineering, University of Minnesota, 111 Church St. SE, Minneapolis, MN 55455, USA
[c] Department of Mechanical Engineering, Milwaukee School of Engineering, 1025 N Broadway, Milwaukee, WI 53202, USA

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ABSTRACT

Vegetable oil was examined to determine if high volume blends with No. 2 ultra-low-sulfur diesel could be successfully utilized in micro gas turbine engines. Property data, and atomization and micro-gas turbine engine studies were examined for blends of up to 75% by volume soybean oil with No. 2 ultra-low-sulfur-diesel (ULSD). Kay's and Grunberg-Nissan mixing rules were found to predict specific gravity and viscosity, respectively, based on composition to a high level of accuracy. For Kay's mixing rule the AADs were below 1%, while AADs for the Grunberg-Nissan equation stayed under 4%. Atomization tests showed an increase in cone angle of 18° for a 30-degree nozzle with a mixture of 50% soybean oil/ULSD over that of pure soybean oil. The pour point for blends of V50 and V75 were found to meet the ASTM D2880-13b Fuel Oil Specifications for gas turbine engines. For a V50 blend the spray angle was increased by 50% over that of pure SBO. The micro-gas turbine engine performed well for fuel blends up to 75% vegetable oil, with comparable engine efficiencies to that of ULSD. Engine efficiency and thrust increase with increasing RPM. The studies indicate that high volume blends of straight vegetable oil with ULSD are suitable in micro-gas turbine engines.



## 1. Introduction

As concern continues over the effects of carbon dioxide released into the atmosphere and the resulting changes to the climate, research into the efficient use of biomass-based fuels is vital. Micro gas turbine engines offer a conducive environment for researching the effective use of bio-oils in combustion applications; they provide a constant flow-through combustion environment that can handle higher viscosity, lower volatility fuels needing longer reaction times. In this study, fuel properties, atomization and combustion characteristics were conducted to evaluate whether refined, bleached and deodorized (RBD) soybean oil (SBO) could be used reliably in micro gas turbine engines. Selection of RBD SBO as the primary bio-oil to be tested was based on its low metal, ash and carbon residue content. The initial ignition tests and comparison of properties of RBD SBO to diesel fuel, and to ASTM specifications, indicated a need to modify the properties of the SBO to allow it to burn in the gas turbine engine.

Alternative fuel mixtures have focused primarily on biodiesel blends with diesel where the biodiesel is made from various feedstock. Research has focused on identifying fuel blend properties as well as performance data from compression ignition engine tests [1–11] One such study by Alptekin et al. focused on biodiesel-diesel property data of four edible feedstocks for use in compression ignition engines. They found the properties of blends up to 20% by volume of biodiesel were close to those of pure diesel [12]. Studies focused on alternative fuel blends for use in gas turbine engines are more limited in numbers and also primarily focus on biodiesel/diesel blends [13,14]. Sequera et al. examined the combustion performance of diesel, biodiesel, emulsified bio-oil and diesel/biodiesel blends on a swirl-stabilized burner similar to those in a gas turbine combustor [15]. They document low emissions and blue flames indicative of premixed combustion for all fuels tested. In a later study Panchasara et al. extended testing in the same facility to include soybean oil/diesel blends, finding slightly higher CO levels as compared to pure diesel [16]. A couple of recent studies have emerged that report gas turbine engine data and fuel properties of bio-oil mixtures with diesel or alcohols, however none of these studies are of soybean based vegetable oil or extend testing to high volumes – above 50% – of vegetable oil [17–20].

* Corresponding author.
*E-mail address:* ahoxie@d.umn.edu (A. Hoxie).

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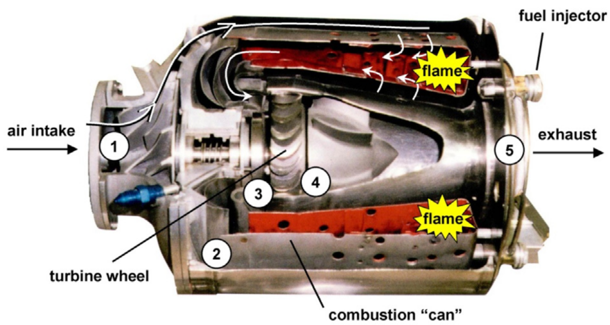


**Fig. 1.** Engine cut-away of the SR-30.

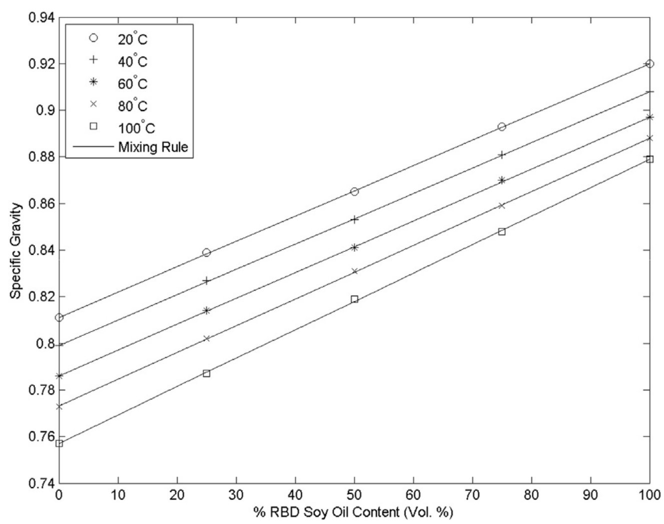


**Fig. 2.** Specific gravity dependence on SBO for multiple temperatures.

**Table 1**
% AAD values for Kay's Mixing Rule.

| Temperature (°C) | AAD (%) |
|---|---|
| 20 | 0.011 |
| 40 | 0.011 |
| 60 | 0.001 |
| 80 | 0.012 |
| 100 | 0.156 |

In this study, two methods were explored to augment RBD SBO fuel properties for successful use in a 30 kW micro gas turbine engine. The methods chosen were preheating and mixing with a secondary fuel. Heating reduces fuel viscosity leading to increased atomization and thus more complete combustion. Blending with a second fuel was also chosen as a strategy to aid ignition and flame sustainability. Number 2, ultra-low-sulfur-diesel (ULSD) was chosen as the primary fuel due to its familiarity with gas turbine engine operators and therefore its ease of use. ULSD exhibits properties suitable for gas turbine engines such as adequate flash point, viscosity and energy content.

This paper presents pertinent property data for the fuel mixtures, atomization characteristics and data from a micro gas turbine engine. Property tests include specific gravity, viscosity, and higher heating value along with cloud, cold filter plugging and pour point data. The pure components were tested as well as blends of 25, 50 and 75% composition by volume of SBO. The mixtures are referred to as V100, V75, V50, V25, V0 where the number represents the composition of SBO in the mixture.

**Table 2**
Regression coefficients, $R^2$, and AAD values for Kay's Mixing Rule.

| Fuel blend | A | B | $R^2$ | % AAD |
|---|---|---|---|---|
| V100 | −0.0005 | 0.929 | 0.994 | 0.044 |
| V75 | −0.0005 | 0.911 | 0.996 | 0.108 |
| V50 | −0.0005 | 0.891 | 0.995 | 0.099 |
| V25 | −0.0005 | 0.871 | 0.996 | 0.03 |
| V0 | −0.0005 | 0.853 | 0.996 | 0.227 |

## 2. Material and methods

### 2.1. Property measurements

All property tests were performed in triplicate for accuracy. Values are reported as averages with calculated error bars. Tests were conducted at a barometric pressure of 0.974 atm and at the following temperatures when applicable: 20, 25, 30, 40, 50, 60, 80 and 100° Celsius. A Cannon CT-1000 constant temperature water bath maintained temperatures to within 0.01 °C. Specific gravity and viscosity measurements were carried out in accordance with ASTM D1298 and ASTM D445, respectively [21,22]. Higher heating values were determined using an IKA C 200 automated bomb calorimeter, following ASTM D240 [23]. A certified Cannon AFP-102 in conjunction with a coolant circulator was used to measure the cold filter plugging point following ASTM D6371 [24]. Pour point and cloud point were measured according to ASTM D6749 and D2500 respectively using a Cannon MPC-1021 certified mini-pour/cloud point tester [25,26]. Flash point of the pure fuels and fuel blends were determined by the Agriculture Utilization Research Institute (AURI) using a Stanhope-Seta Mulitflash with a Pensky-Martens closed cup module model 34100-2.

### 2.2. Atomization studies

Atomization studies explored spray breakup characteristics of ULSD, and SBO. A 30-degree Hago nozzle was used to examine the affects of fuel blend on atomization. Non-reacting flow conditions – namely characteristics of the fuel sprays – were studied using a pulsed laser formed into a sheet and passing through the center plane of the fuel spray. The nanosecond-scale pulse duration of the laser allowed for both instantaneous and time-averaged characteristics of the sprays to be evaluated.

### 2.3. Engine studies

The SR-30 is shown in Fig. 1. The engine is outfitted with stagnation thermocouples and static and stagnation pressure sensors at each stage of the engine: upon entering the engine (1), downstream of the compressor (2), downstream of the combustion can (3), downstream of the axial turbine (4), and at the engine exhaust (5), as shown in Fig. 1. The sensors allow for a complete thermal and performance analysis of the engine. Air enters the engine through a nozzle, designed to create uniform airflow into the single stage radial compressor. The air is compressed to two times atmosphere before entering the reverse flow annular combustion can. A single stage axial turbine follows the combustion can, and leads to a thrust-producing nozzle. The fuel delivery system on the SR-30 was modified to transition between fuels while the engine is running. A switching station was developed to start the engine on ULSD and then switch to the fuel blend once the engine had stabilized. The gas turbine was switched back to ULSD prior to shutdown to flush the system of SBO thus preventing gumming in the fuel lines. After