ABSTRACT

In this study, a micro gas turbine was operated with JP8 and canola biodiesel blends. The blends tested were JP8, 40% of biodiesel, 60% of biodiesel, and 80% of biodiesel by volume. The turbine was run at 3 speeds, 60,000, 80,000 and 105,000 rpm. Engine power generation and emissions performance were determined. The results reveal that as biodiesel content in the fuel mixture increased, the fuel flow rate increased to maintain the constant speed operation and equivalence ratio reduced. It was shown that TJ35 engine can operate with biodiesel blends in JP8 without sacrificing thrust. In fact, 80% biodiesel blend increased the thrust at 105,000 rpm by 2% compared to JP8. Exhaust gas temperatures slightly reduced with increasing biodiesel content. Higher biodiesel blends resulted in higher CO2, CO and CxHy emissions while O2 emissions reduced. This study demonstrates that a micro gas turbine engine could be operated successfully with JP8-canola biodiesel blends, which means the engine could be utilized in distributed and remote off-grid locations for power generation by burning renewable biodiesel fuels.

NOMENCLATURE

| BIO  | Canola Biodiesel |
| CHP  | Combined Heat and Power |
| EGT  | Exhaust Gas Temperature |
| MGT  | Micro Gas Turbine |

INTRODUCTION

Gas turbines are used in many sectors from aviation to land based industrial systems. Aviation gas turbines mostly use kerosene and have very strict fuel standards due to safety concerns. However if a gas turbine is utilized in a sector other than aviation, the users have the luxury of operating with fuel flexibility since the combustion continuously takes place at high temperatures in a pressurized chamber. Efforts to make gas...
turbines available to smaller scale applications led to the design and production of micro gas turbines (MGT). Although there is not a standard definition, micro gas turbines are defined as gas turbine engines with powers ranging between 20 kW to 500 kW [1]. Whenever power generation is required, MGT operation offers reliability, compactness, higher power-to-weight ratio, lower emissions, ease of operation and maintenance, and especially fuel flexibility. For these reasons, MGTs are very suitable for small scale remote and on-site heat and power production units and combined heat and power (CHP) systems. Availability of high temperature exhaust gases from an MGT allows overall CHP efficiencies of above 80% [2]. CHPs are especially beneficial in distributed and remote off-grid locations for power generation. MGT, basic component of a CHP unit, can operate with different types of fuels such as kerosene, diesel, ethanol, natural gas, biogas and biodiesel. Petroleum based fuels have always been favored due to their high energy content per unit volume, ease of production and handling and existing infrastructure. However, combustion of petroleum based fuels produces serious environmental consequences. Carbon dioxide (CO2) emissions result in greenhouse effect and global warming. Pollutants of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), sulphur dioxide (SO2) and soot are also emitted to the atmosphere with negative consequences [3]. Besides resulting in environmental problems, crude oil is not renewable and the world oil reserves are believed to be on decline. Environmental concerns, rapid depletion of fossil based fuels, their uneven distribution around the globe and high costs demand finding new alternative sources of energy for a sustainable and secure energy system. Therefore, there is a need for gas turbine utilizing sectors to reduce their dependence on petroleum based fuels and, perhaps, replace them with alternative, renewable fuels. Among the possibilities, the use of biofuels and especially biodiesel in land-based distributed power and CHP applications are gaining more and more attention.

Biodiesel is produced through transesterification of vegetable oils or animal fats by replacing the triglyceride molecules with an alcohol (methanol or ethanol) [4]. The transesterification reaction converts triglycerides into the fatty acid esters (biodiesel) and glycerol. These esters have chemical and physical properties that are similar to conventional diesel fuel. Biodiesel contains about 10% oxygen by weight. Various crops like canola, soy bean, palm, jatropha, babassu nuts, sunflower, corn, camelina, and olive can be used to produce biodiesel depending upon the geographical location. Algae is also investigated as a viable source of biodiesel.

Biodiesel utilization is carbon neutral in which any carbon dioxide (CO2) emitted during its combustion is absorbed during the production of the feedstock of the biodiesel. Biodiesel is also non-toxic, less polluting to environment when spilled, has high lubricity, and does not contain any aromatics or sulfur. However, biodiesel has lower energy content and higher viscosity and freezing point compared to petroleum based fuels. Moreover, biodiesel has propensity for algae formation and economically viable large scale production of its feedstock would create problems of insufficient farmland and price increases in eatable and consumable food crops [5].

Biodiesel utilization in compression ignition internal combustion engines has been widely studied and reported to be a possible alternative to diesel fuel. However biodiesel utilization in gas turbine engines is limited. Since diesel fuel is widely used in gas turbines, biodiesel and their blends with diesel fuel were also investigated to assess the effects of biodiesel on the performance of the gas turbine engines. Nascimento et al. [6], Chiaramonti et al. [7] and Bolszo and McDonell [8] tested the use of diesel, biodiesel and their blends on a commercial 30 kW micro gas turbine engine. Nascimento et al. reported that biodiesel and its blends yielded similar thermal performance compared to diesel fuel with slightly higher CO and lower NOx emissions. Chiaramonti et al. observed higher levels of CO emissions with biodiesel. Bolszo and McDonell also reported higher NOx emissions for biodiesel operation. Krishna [9], using the same 30 kW engine, investigated soy oil biodiesel blends ranging from 0% to 100% in a micro turbine normally running on ASTM #2 heating oil. Krishna found no adverse effects on efficiency and emissions with biodiesel.

Biodiesel utilization in kerosene burning gas turbines has also been studied. Lopp [10] tested a gas turbine using jet fuel and soy biodiesel with 0, 10 and 20% blends. Although the fuel consumption increased slightly with the addition of biodiesel in the blend, biodiesel exhibited a comparable performance to jet fuel. Tan and Liu [11] also investigated used oil feedstock biodiesel and Jet A-1 blends on a micro turbojet engine. However Tan and Liu reported that the fuel consumption decreased with the increased biodiesel content in the blend and for the same fuel volume flow rate, the engine thrust increased with the increased percentage of biodiesel. Corporan et al. [12] investigated the effects of soybean biodiesel up to 20% by volume on gaseous and particulate matter emissions of a J8 fueled helicopter turbine engine running at 3 power settings, idle, cruise and take of power. Their results indicated reductions in soot emissions and no adverse effect on gaseous emissions. It was also reported that the engine performance was unaffected.

Gires et al. [13] tested a 400N thrust turbojet engine with Jet A and palm oil biodiesel at 20% volumetric blend. It was found that the 20% blend produced comparable results to the tests with Jet A particularly with thrust and thermal efficiency. Habib et al. [14] investigated performance and emissions characteristics of a 30 kW gas turbine engine burning Jet A, soy methyl ester, canola methyl ester, recycled rapeseed methyl ester and their 50% by volume blends in Jet A over a range of throttle settings. The addition of biodiesel resulted in a reduction in static thrust and thrust-specific fuel consumption, and increased thermal efficiency. The CO and NO emissions were reduced with the biodiesel blends. Silva et al. [15] studied the performance and emissions of kerosene and biodiesel blends on a 60hp turboshift engine. Their tests revealed that as
biodiesel percentage increased, the fuel consumption increased and thermal efficiency and pollutant emissions decreased.

Motivated by these encouraging results, a micro gas turbine was operated in this study with JP8 and canola biodiesel blends to assess the suitability of its design to biodiesel utilization.

**EXPERIMENTAL STUDY**

**Micro Gas Turbine Engine and Instrumentation**

A model TJ35 micro gas turbine designed and manufactured by TUSAŞ Engine Industries, Inc (TEI) located in Eskişehir, Turkey was used in the tests. Technical details of the TJ35 MGT are given in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Technical details of the TJ35 MGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Inlet diameter</td>
</tr>
<tr>
<td>Minimum diameter</td>
</tr>
<tr>
<td>Maximum speed</td>
</tr>
<tr>
<td>Maximum thrust</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
</tbody>
</table>

TJ35 engine shown in Fig.1 incorporates a vaporizer to mix fuel with incoming air. Therefore, fuel injection related issues of spray formation and atomization are avoided, which makes TJ35 efficiently operable with a wide range of liquid fuels.

Air mass flow is measured by a calibrated bellmouth. Volumetric fuel flow rate and lubricating oil flow rates are measured by turbine flowmeters. Temperatures, static and total pressures at the compressor and turbine exit and exhaust gas temperatures are also measured.

MGT was tested at 3 speeds, 60,000, 80,000, 105,000 rpm by adjusting the throttle which controlled the volume flow rate of the fuel. Data are taken at each engine speed at a rate of 2Hz when a steady state condition is attained. A calibrated load cell is used to measure the thrust.

CO2, CO, CxHy and O2 emissions are measured with a Testo 350XL model equipment. The concentration of CxHy is on the basis of methane. NOx emissions could not be measured due to a malfunction in the NOx measuring equipment. A water cooled emission probe is used and inserted into the exhaust gases at the turbine exit cone 15 millimeters downstream from the location of the exhaust gas temperature measurement. Emissions are measured at 5 locations on the measurement plane and their average represents the emission value.

A photograph of the engine and the instrumentation is given in Fig. 2. Control room and data acquisition system are shown in Fig.3.

**Fuels Tested**

Blends of JP8 and canola oil biodiesel (BIO) were tested. The tested blends were 100%JP8 (JP8), 60%JP8+40%BIO (B40), 40%JP8+60%BIO (B60) and 20%JP8+80%BIO (B80). Biodiesel from canola oil was obtained from a commercial producer. Table 2 shows the physical and chemical properties of JP8, biodiesel and their blends. The biodiesel has oxygen in its chemical structure, has lower energy content per unit mass and
higher viscosity than JP8. However, the energy contents per unit volume of the fuel mixtures are closer to one another. In this study, the chemical compositions of JP8 and canola biodiesel are taken as C12H26 and C19H36O2, respectively.

Table 2. Physical and chemical properties of JP8 and canola biodiesel blends

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>JP8</th>
<th>B40</th>
<th>B60</th>
<th>B80</th>
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<tbody>
<tr>
<td>Density (15°C)</td>
<td>kg.m⁻³</td>
<td>799</td>
<td>830.4</td>
<td>845.6</td>
<td>862.2</td>
</tr>
<tr>
<td>Viscosity (40°C)</td>
<td>mm².s⁻¹</td>
<td>1.30</td>
<td>2</td>
<td>2.508</td>
<td>3.25</td>
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<tr>
<td>Flash Point</td>
<td>°C</td>
<td>41</td>
<td>47</td>
<td>53</td>
<td>81.2</td>
</tr>
<tr>
<td>Water</td>
<td>ppm</td>
<td>79</td>
<td>106.8</td>
<td>126.4</td>
<td>141.2</td>
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<tr>
<td>Total Contamination</td>
<td>mg.kg⁻¹</td>
<td>0.5</td>
<td>6.7</td>
<td>9.22</td>
<td>11.28</td>
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<tr>
<td>Copper Strip Corrosion</td>
<td></td>
<td>No1</td>
<td>No1</td>
<td>No1</td>
<td>No1</td>
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<tr>
<td>Iodine Number</td>
<td>g/l2/100 g</td>
<td>6.6</td>
<td>52.7</td>
<td>69.4</td>
<td>88.1</td>
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<tr>
<td>Cold Filter Plugging Point</td>
<td>°C</td>
<td>≤-45</td>
<td>-27.8</td>
<td>-21.4</td>
<td>-14.6</td>
</tr>
<tr>
<td>Cetane Index</td>
<td></td>
<td>55.6</td>
<td>47.1</td>
<td>49.04</td>
<td>49</td>
</tr>
<tr>
<td>Higher Heating Value</td>
<td>MJ.kg⁻¹</td>
<td>45.9</td>
<td>43.8</td>
<td>42.64</td>
<td>41.4</td>
</tr>
<tr>
<td>Higher Heating Value</td>
<td>GJ.m⁻³</td>
<td>36.7</td>
<td>36.4</td>
<td>36.1</td>
<td>35.7</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Power Generation Performance

Variation of the air mass flow rate with biodiesel content is given in Fig. 4. At a constant speed, air mass flow rate does not change with biodiesel content in the blend.

Figure 4. Air mass flow rate variation with biodiesel content

Fuel flow rate variations with biodiesel content and speed are given in Fig. 5 and Fig. 6 respectively. As biodiesel content increases, the fuel flow rate has to be increased to maintain the constant speed operation because the heating value of the biodiesel is lower than that of JP8.

Figure 5. Fuel flow rate variation with biodiesel content

Equivalence ratio variation of the fuel-air mixture with biodiesel content and engine speed are shown in Fig. 7 and Fig. 8 respectively. The oxygen in biodiesel molecules results in leaner combustion and lower equivalence ratios. Therefore, as biodiesel ratio in the blend is increased as given in Fig. 7, the mixture equivalence ratio is reduced, which implies higher thermal efficiencies and more efficient combustion.

Figure 6. Fuel flow rate variation with engine speed
The effects of biodiesel content on the thrust are shown in Fig. 9 and Fig. 10. The thrust increases with rpm and biodiesel content does not reduce the thrust. These results demonstrate that TJ35 can operate with biodiesel blends in JP8 without sacrificing thrust. In fact, 80% biodiesel increases the thrust at 105,000 rpm by 2% compared to JP8, which is attributed to both higher thermal efficiencies attained as a result of leaner combustion (lower equivalence ratios, Fig. 7) at higher biodiesel content and increased fuel mass flow rate. In other words, the operation of the turbine with the products of a leaner mixture approaches to the air standard cycle resulting in higher thrust values.

Figure 7. Equivalence ratio variation with biodiesel content

Figure 9. Variation of thrust with engine speed

Figure 8. Equivalence ratio variation with engine speed

Figure 10. Variation of thrust with biodiesel content

Specific thrust, defined as thrust per unit air mass flow rate, variation with biodiesel content is shown in Fig. 11. Specific thrust exhibits similar behavior as thrust.

Figure 11. Specific thrust variation with biodiesel content
Exhaust gas temperature variation with biodiesel content is shown in Fig. 12. Exhaust gas temperatures display slight reduction with increasing biodiesel content, which may be attributed to lower adiabatic flame temperatures associated with increasing biodiesel content (lower energy release per unit mass of fuel). Although there is a reduction in EGT from engine speed of 60,000 rpm to 80,000 rpm, EGT is considerably higher (around 60 °C) at 105,000 rpm. EGTs increase with increasing engine speed due to higher ratio of heat released to heat lost in the combustion chamber, relatively higher ratio of equivalence ratios (Fig. 7 and Fig. 8) and higher initial temperatures as a result of higher compression ratios.

**Emissions**

Figs. 13-16 show CO2, CO, CxHy and O2 emissions variation with engine speed and biodiesel content. It is evident that increased biodiesel content results in higher CO2, CO and CxHy emissions and lower O2 emissions. This variation is the consequence of increased fuel flow rates with increasing biodiesel content (Fig. 5). Increased fuel flow rates result in higher presence of C containing molecules in the combustion environment, which produces higher concentrations of CO2, CO and CxHy emissions. Similarly, as engine speed increases, so do CO2, CO and CxHy emissions, which again is attributed to higher fuel flow rates associated with higher engine speeds (Fig. 6). Also, it is noted from Fig. 15 that CxHy emissions are considerably high, around 300 ppm for JP8 and 900 ppm for biodiesel blends. This is considered as the consequence of utilizing a vaporizer to mix the fuel with incoming air instead of an injector, which leads to lower atomization and evaporation rates. Moreover, the fact that the biodiesel yields a near triple value of CxHy emissions is attributed to the fact that the biodiesel has longer evaporation times [16].
O2 emissions reduce with higher biodiesel contents as shown in Fig. 16. Increased CO2, CO and CxHy concentrations in the gaseous mixture of combustion products reduce O2 concentrations. Therefore, O2 emissions pattern also follows that of CO2, CO and CxHy emissions.

CONCLUSIONS

The canola biodiesel blends with JP8 used in TJ35 MGT revealed that the turbine could be operated without any significant performance penalty compared to pure JP8 operation. In fact, 80% biodiesel blend increased the thrust by 2%. Exhaust gas temperatures slightly reduced with increasing biodiesel content. The emissions of CO2, CO and CxHy increased with increasing biodiesel content while O2 emissions reduced.

The fact that TJ35 engine incorporates a vaporizer to mix the fuel with incoming air eliminates fuel type dependency and calibration of the injection system, which makes possible the trouble free operation on biodiesel obtained from any feedstock.

Overall, this study demonstrates that a MGT engine could be operated successfully with JP8-canola biodiesel blends, which means the engine could be utilized in distributed and remote off-grid locations for power generation burning renewable biodiesel fuels.

Life cycle tests should also be performed in addition to performance and emissions tests in order to assess the occurrence of any deposits and damage on the engine components.

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