

Performance and Emissions of Drop-In Aviation Biofuels in a Lab-Scale Gas Turbine Combustor

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There is a growing need for drop-in biofuels for gas turbines for enhanced energy security and sustainability. Several fuels are currently being developed and tested to reduce dependency on fossil fuels while maintaining performance, particularly in the aviation industry. The transition from traditional fossil fuels to sustainable biofuels is much desired for reducing the rapidly rising CO₂ levels in the environment. This requires biofuels to be drop-in ready, where there are no adverse effects on performance and emissions upon replacement. In this study, the performance and emissions of four different aviation drop-in biofuels were evaluated. They include UOP HEFA-SPK, Gevo ATJ, Amyris Farnesane, and SB-JP-8. These aviation biofuels are currently being produced and tested to be ready for full or partial drop-in fuels as the replacement of traditional jet fuels. The characteristic performance of each fuel from the prevaporized liquid fuels was performed in a high-intensity (20 MW/m³-atm) reverse flow combustor. The NO emissions showed near unity ppm levels for each of the fuels examined with a minimum at an equivalence ratio of ~0.6, while CO levels were in the range of 1000–1300 ppm depending on the fuel at an equivalence ratio between 0.75 and 0.8. For an equivalence ratio range between 0.4 and 0.6, NO and CO emissions remained very low (between 1–2 ppm NO and 2400–2900 ppm CO) depending on the fuel. The examined biofuels did not show any instability over a wide range of equivalence ratios from lean to near stoichiometric condition. These results provide promising results on the behavior of these drop-in aviation biofuels for use in high-intensity gas turbine combustors providing stability and cleaner performance without any modification to the combustor design. [DOI: 10.1115/1.4048243]

Keywords: air emissions from fossil fuel combustion, alternative energy sources, energy conversion/systems, fuel combustion, renewable energy, unconventional petroleum

1 Introduction

Due to increasingly stringent emission regulations on the combustion of fossil and alternative fuels, there is a growing demand to develop new combustion technologies to enhance combustor performance, promote fuel flexibility, and reduce emissions, and for promoting a cleaner environment. The use of these innovative techniques shall allow for alternative fuel utilization to meet the current power demand and reduce environmental impact, while maintaining high performance and efficiency [1]. Current research efforts on liquid biofuels will serve as a growth area for large-scale applications of biofuel combustion in power and propulsion applications from the expected increase in global bioenergy consumption. By 2050, biomass, with an emphasis on liquid biofuels, is estimated to have the potential to supply 20–30% of the global primary energy demand [2,3].

A sizable contribution of global fossil fuel consumption stems from the aviation industry. Approximately 12% of the total transportation energy in the United States is provided by jet fuel, equating to 3.4 quad [4]. The demand for air transport continues to rise, with expected growth of ~50% more U.S. Airline Passengers in 2038 (to 1.28×10^9) from 840.8×10^6 in 2017 [5]. Additionally, as GDP continues to rise in developing nations, the airline industry is expected to have an increased impact on both the global economy

and climate, and a shift toward alternative fuels would significantly reduce CO₂ emission as well as emission of hazardous pollutants [6].

The gas turbine is the major power generation technology within the aviation industry and has a significant global carbon footprint, yet it lacks development of renewable resource utilization. Several liquid biofuels have now emerged as the most promising source of alternative renewable fuels that can be directly integrated with current gas turbines having good combustion characteristics [7,8]. Furthermore, using biofuels as an alternative drop-in fuel in the aviation and/or gas turbine applications provides enhanced fuel flexibility and energy stability. In these applications, heat release intensity is much higher, approximately 5–20 MW/m³-atm for land-based gas turbines and 30–50 MW/m³-atm for aviation gas turbines as opposed to conventional furnace applications (0.1–1 MW/m³-atm). Thermal intensity in the aviation industry is desired to be high as weight and volume are a premium. It is noted, however, that simulating high heat release intensity for the aviation industry and land-based gas turbine applications comes with many challenges such as limited space, high velocity, and lower residence time. However, stable combustion of some biofuels under high-intensity conditions is possible due to their recent promising results.

Although high-intensity biofuel combustion is still a relatively new trend, several recent studies are available that provide evaluations on the performance of various liquid and gaseous fuels that are not bio-derived. Arghode and Gupta, for instance, performed studies on high-intensity combustion for gas turbine application [9]. Using methane as the fuel under high thermal intensity (in reverse flow modes consisting of three configurations at thermal intensity of 28 MW/m³-atm and five configurations at thermal

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Table 1 Examined biofuels and their properties

| Chemical properties | UOP HEFA-SPK | Gevo-ATJ | Amyris Farnesane | SB-JP-8 |
|---|-------------------------------------|-------------------------------------|---------------------------------|-------------------------------------|
| Empirical formula | C _{11.3} H _{24.4} | C _{12.5} H _{27.1} | C ₁₅ H ₂₄ | C _{11.1} H _{23.5} |
| Flash point (°C) | 46 | 38 | 107.5 | 38 |
| Freeze point (°C) | -40 | -40 | -49 | -47 |
| Boiling point (°C) | 300 | 300 | 246.85 | 150–275 |
| Energy density (MJ/kg) | 43.6 | 43.2 | 43.5 | 43.24 |
| Density at 15 °C (kg/m ³) | 778 | 750 | 770 | 779 |
| Viscosity at 40 °C (mm ² /s) | 1.3 | 1.3 | 2.325 | 1.25 |
| Chemical composition | | | | |
| Cycloparaffins (mass %) | 15 | 15 | – | – |
| Aromatics (mass %) | 0.5 | ~0 | 0.1 | 18.1 |
| Carbon and hydrogen (mass %) | 99.5 | 99.5 | 99.5 | 99 |
| Nitrogen (mg/kg) | 2 | 2 | 2 | ~0 |
| Water (mg/kg) | 75 | 36 | 75 | – |
| Sulfur (mg/kg) | 15 | ~0 | 2 | 0.3 |

intensity of 57 MW/m³-atm at an equivalence ratio of 0.7) representing gas turbine application in a combustor under distributed combustion, they showed ultra-low NO_x emission levels as well as low CO emission ranging from 64 to 96 ppm under the high-intensity combustion conditions [9]. Further investigations using several fuels (methane, propane, ethanol, and kerosene) within a self-assembled combustor operating at a heat release intensity of 36 MW/m³-atm showed less than 5 ppm NO emission levels for all the fuels examined at an equivalence ratio of 0.6 [10]. Research into alternative biofuels for the aviation industry has yielded positive results. A study on Jet-A Palm Methyl Ester blends observed up to 35% lower NO emission and greater than 30% reduction of CO at a burner-exit equivalence ratio of 7 [11].

A few studies have been conducted on evaluating the performance and emissions of bio-derived fuels for use in diesel and gas turbine engines. Cowart et al. analyzed the properties and performance of hexadecane/isocetane. Hydroprocessed renewable diesel fuel blends to be used as a fuel surrogate for military jet fuel JP-4 [12]. They found a blend of two-thirds hexadecane and one-third isocetane yielded similar combustion properties and behavior as the conventional JP-4 fuel. Cican et al. examined performance and emissions of Jet-A/biodiesel blends in a microturbojet engine [13]. They found NO, SO₂, and CH₄ emissions all reduced as biodiesel content increased up to 30% by volume and could be used as a drop-in fuel without any adverse effects on the engine. Nascimento et al. studied several alternative biodiesel fuels in a 3-kW regenerative gas microturbine in order to evaluate the performance and emissions with these alternative fuels [14]. They found using the biodiesel fuels no more than a 4.26% loss in power was found while using these biofuels and that emissions varied on fuel source as castor and palm oil biofuels were shown to have slight increases in CO level while reducing NO_x by over 25%.

In this study, the performances of four drop-in aviation biofuels were examined at high heat release intensity of 20 MW/m³-atm with the fuel injected at high velocity in cross stream relative to the air jet to simulate jet in cross-flow characteristics that simulate many gas turbine applications. The effect of equivalence ratio down to the lower flammability limit was examined to determine the role of equivalence ratio and fuel flexibility. The OH* chemiluminescence signatures provided the global flame structures evolved from the fuels used here. Fuel property effects on combustion performance and emissions of CO and NO were also examined. The biofuels used here were investigated in terms of combustion and emission performances under high heat release intensity conditions representing stationary and aviation gas turbine applications.

2 Fuels Examined

In this study, four potential aviation drop-in biofuels were examined. They included Honeywell UOP HEFA-SPK, Gevo ATJ,

Amyris Farnesane, and Swedish Biofuel JP-8. Each of these drop-in fuels are on various stages of the approval process for flight testing and some for full drop-in approval. Selected properties of the fuels examined are shown in Table 1.

2.1 Honeywell UOP HEFA-SPK. Honeywell UOP is a fuel refinery and processing company based in Illinois [15]. They are currently producing both diesel and jet fuel from a renewable refinery process, which utilizes vegetable oils, animal fats and greases. Currently, the inedible oils from camelina are used in this refinery process, with other fuels of interest including jathropha, halophytes with plans to incorporate biomass waste, as well as oils produced from algae. Various biofuels are produced through a deoxygenation reaction, followed by isomerization/hydrocracking, followed by a distillation process to separate various fuel components including hydrogen, light fuels, jet fuel and diesel fuel. Due to the processing techniques, the aviation fuel used in this study is called Bio-Derived Synthetic Paraffin Kerosene (Bio-SPK), hydroprocessed esters and fatty acids SPK (HEFA-SPK), or Green Jet. Currently, this fuel is approved in a 50/50 blend with Jet-A with goal of developing a version which can be used as a 100% jet fuel replacement [15–17]. HEFA-SPK has the highest energy density out of the biofuels tested in this study which provides a significant advantage in sustaining longer flights with less fuel.

In one study, a 50% HEFA-SPK derived from Camelina and 50% Jet A-1 blend was tested in a turbofan engine with a 20-kN power rating. Results showed a small but significant drop in CO₂ and NO_x emissions at 95% engine load when using the 50% blend in comparisons to pure Jet A-1 fuel [18]. A similar study tested a 48% HEFA-SPK and Jet A-1 blend in a GTM 140 miniature turbojet engine with varying operational points (motor rotational speed). Results indicated that the blended HEFA-Jet fuel mixture yielded significantly lower CO, CO₂, and NO_x emissions when compared to pure Jet A-1 [19].

2.2 Gevo ATJ. Gevo is a renewable chemicals and biofuels company based in Colorado [20]. Their goal is to produce low carbon fuels including renewable gasoline and jet fuel. Gevo produces isobutyl and ethyl alcohols from various feedstocks including corn starch, sugar cane, sugar beets, and sorghum. Through a biorefinery process, these alcohols are then converted into various products including jet fuel, octane, and plastics. Currently, Gevo alcohol to jet is approved as a 50/50 blend aviation fuel. General electric aviation is currently developing a jet engine combustor which can work on 100% Gevo ATJ as a part of the Federal Aviation Authority's (FAA) Continuous Lower Energy, Emissions and Noise (CLEEN) program [21,22]. In a combustion test study conducted by NASA using 100% Gevo-ATJ fuel heated to a maximum temperature of 830 K and a maximum pressure of 24.13 bar, NO

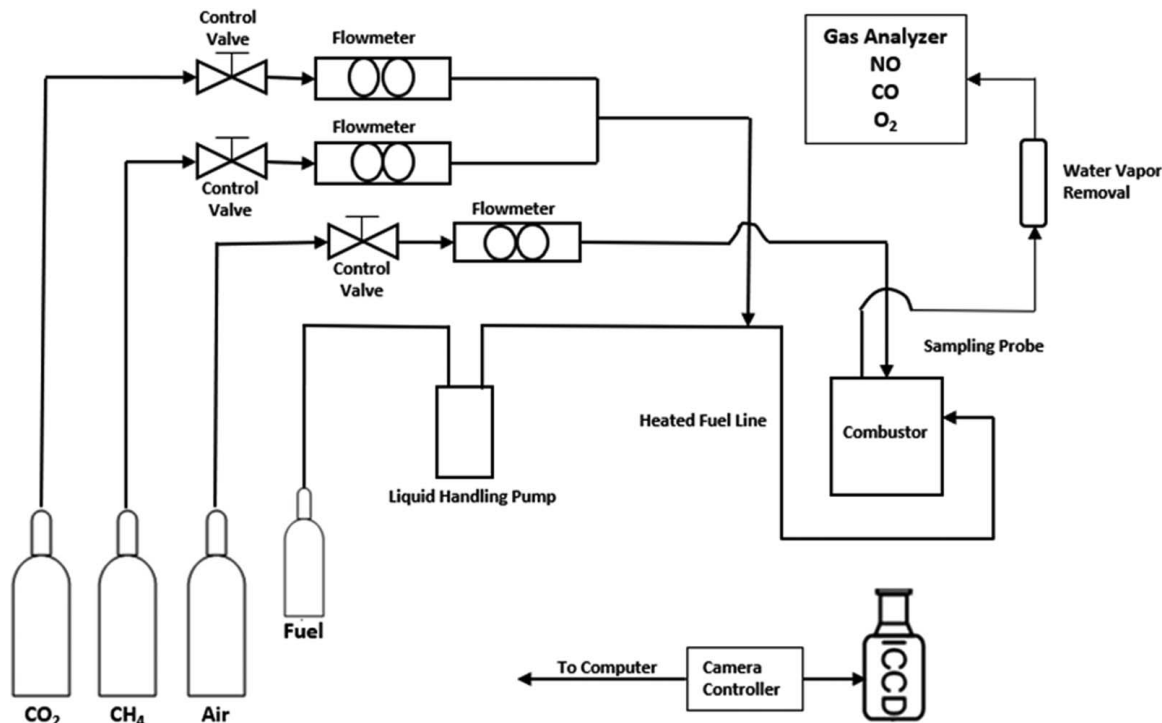


Fig. 1 Schematic diagram of the experimental facility

emissions were reduced by 5–18% in comparisons with Jet-A. However, the ATJ fuel showed more propensity to blowout at higher flame temperatures [23].

2.3 Amyris Farnesane. A joint project between Total, an integrated energy, oil and gas company, and Amyris, a bioscience and renewable products company has been implemented to develop a drop-in jet fuel blend [24]. Amyris produces farnesene from cellulosic feedstocks in Brazil. Specifically, sugarcane syrup is processed through the use of microbes in order to produce the farnesene, with additional plans to expand to production from woody feedstocks [25]. Currently, only 10% farnesene in jet fuel blends have been approved. The Brazilian airline GOL has been using blends of up to 10% Amyris Farnesene since 2014 on selected flights [26]. A study was performed using 10% and 20% farnesene–kerosene blends in a CFM56-5C4 gas turbine engine at various power settings of the turbine during takeoff and landing. Emissions from the 10% and 20% blends to pure kerosene showed almost identical CO emission trends. However, the NO_x emission showed slight decrease using the blended fuel than pure kerosene. The results showed no significant differences between the 10% and 20% blends [27].

2.4 Swedish Biofuels JP-8. Swedish Biofuels is a company based in Stockholm, Sweden that focuses on research and development of alternative fuels. Their current project for a 100% drop-in alternative substitute for JP-8 is funded by the U.S. Government Defense Advanced Research Projects Agency (DARPA) and is charged with producing a completely renewable synthetic jet fuel or BIOJET100 [27]. Swedish Biofuels currently uses an alcohol to jet process with additional chemical synthesis for producing required aromatic content necessary for 100% replacement of current aviation fuels, followed by a ratification process to produce diesel and gasoline in addition to jet fuel. Current work on this project involved various development and testing phases to ensure all standards and safety criteria are met [27,28]. The fuel SB-JP-8 is now in the certification process stage for both military and civilian applications; however, although all required properties have met or exceeded jet

fuel testing criteria, they are still expected to take a significant amount of time for approval as it is first fuel that seek 100% replacement of petroleum-based jet fuels.

3 Methods

The schematics of the experimental setup and diagnostics is given in Fig. 1. The CDC combustor was operated in a reverse non-premixed flow orientation, with the fuel injection from the side. The combustor dimensions were 3" by 1.75" by 1.5", having an air injection diameter of 3/8" and a fuel injection diameter of 1/8". Air was injected at 300 K, while the fuel was preheated to 600 K in order to pre-vaporize the liquid fuel. This temperature was determined to avoid thermal decomposition while ensuring complete vaporization of the fuels prior to injection.

To start the combustor, a propane torch was used as a pilot flame at an injection port located near to the bottom of the combustor. Methane and air were introduced until stable combustion took place without the assistance of the propane torch. The torch was then removed, and an alumina plug inserted to seal the pilot burner port. The intensity was then ramped up to 20 MW/m³-atm while the fuel line was heated up to 600 K, at which point the methane was slowly switched over to liquid fuel vapors until the combustor was running completely on prevaporized liquid fuel.

Pre-vaporization of the liquid fuels was achieved using a heating tape that preheated the fuel to a temperature of 600 K ± 10 K. The liquid fuel flowrate was controlled using a liquid fuel positive displacement pump (VICI M50), with a precision of ±0.5%. The air flow rate was controlled through a differential pressure laminar flow controller with an uncertainty of 0.2% of full scale and 0.8% of the reading.

Detailed investigations on the overall emissions were performed with each fuel at the various defined experimental conditions. The NO emission was measured using a NO chemiluminescent gas analyzer, CO by the non-dispersive infrared method, and O₂ by the zirconia cell method. The uncertainty of emissions sampling was ±0.5% full scale for CO and ±1% full scale for NO, CO₂, and O₂. For OH* chemiluminescence intensity distribution, an ICCD camera coupled with a 307-nm narrow bandpass filter was used.

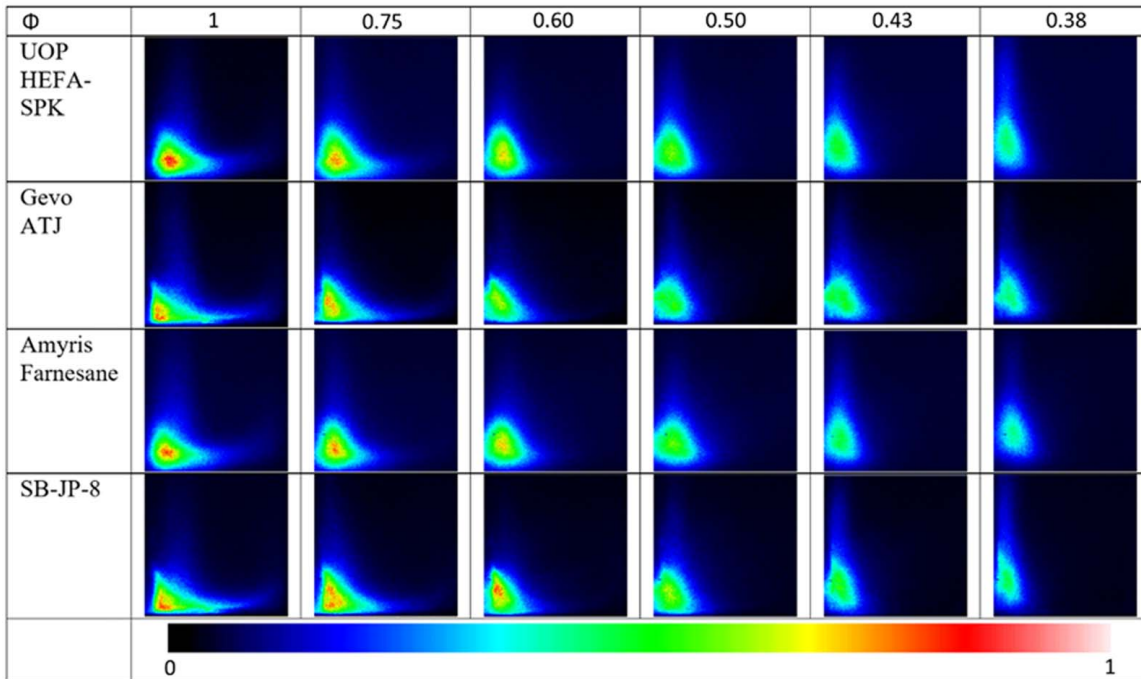


Fig. 2 OH* chemiluminescence at various equivalence ratios (Φ) for different drop-in biofuels

The experimental investigations reported here focused on reaction zone behavior determined by OH* intensity profiles along with resultant pollutants emission. For each fuel, the fuel flowrate was kept constant, to result in a constant thermal load in the combustor. The air flowrate was varied in order to change the equivalence ratio. The combustor was operated at a constant heat load of 2.58 kW, corresponding to a thermal intensity of 20 MW/m³-atm.

shows the characteristic OH* chemiluminescence distribution for each of the fuels. From the figure, one can see that a decrease in the equivalence ratio decreased the peaks in OH* intensity distribution due to a reduction in peak temperatures. The OH* chemiluminescence intensity is highest at the stagnation point where the flame was stabilized at the bottom of the combustor. Each of the fuels produce similar profiles and intensities, indicating similar energy release from each of the fuels.

4 Results and Discussion

4.1 OH* Chemiluminescence. The initial investigations focused on quantifying the reaction zone distribution with various biofuels at different equivalence ratios. This was carried out by measuring the OH* radical distribution, normalized to the peak intensity in the stoichiometric case, in the combustor. Figure 2

4.2 Pollutants Emission. NO emission levels corrected to 15% O₂ in the exhaust gases for each of the four fuels are shown in Fig. 3. NO production from hydrocarbon flames comes primarily from two reaction mechanisms, thermal (Zeldovich), and prompt (Fenimore) [29,30]. The thermal mechanism results in high production of NO in high-temperature zones and is the major contributor of NO in

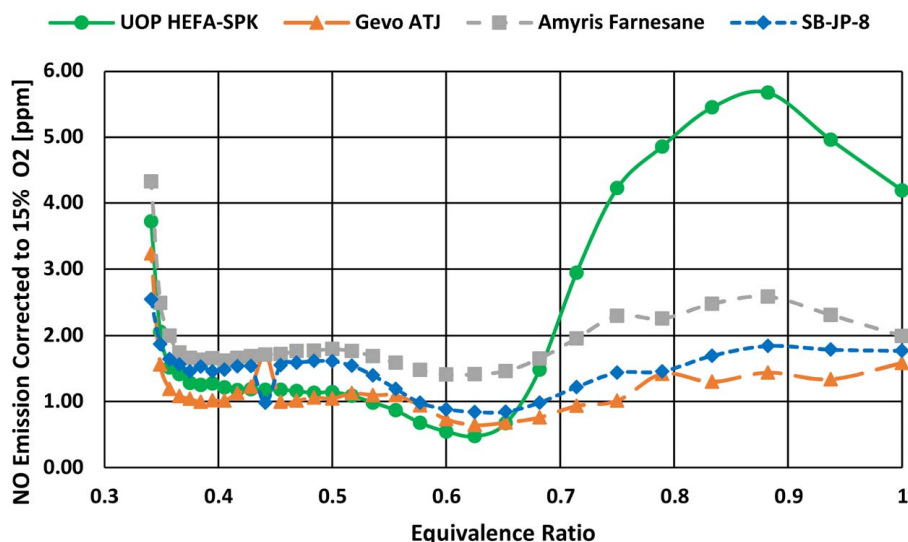


Fig. 3 NO emission at various equivalence ratios (Φ) for the different biofuels examined

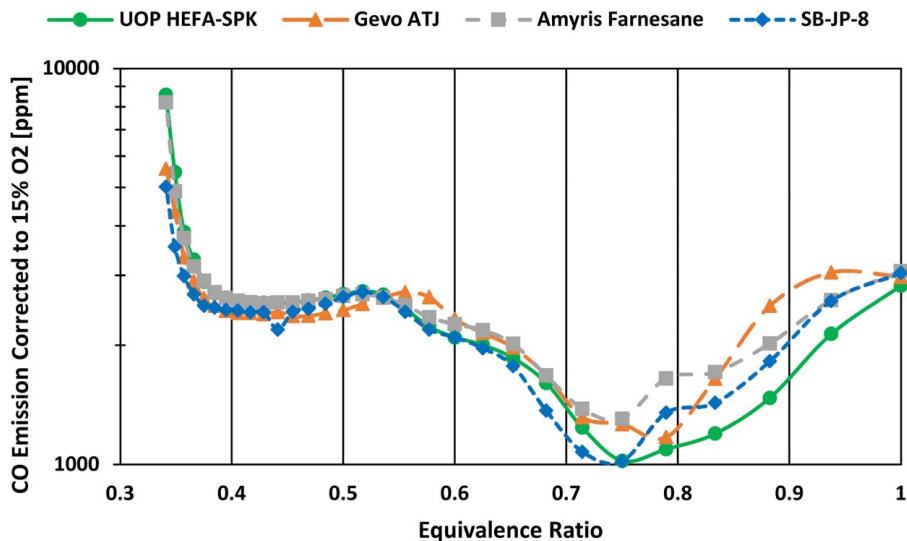


Fig. 4 CO emission at various equivalence ratios (Φ) for the different biofuels examined

diffusion flames. Prompt NO on the other hand is formed from the resulting reactions of the CH radicals formed with the molecular nitrogen to form NO. At temperatures greater than 1800K, the thermal NO mechanism is the dominant NO production mechanism. By reducing peak temperatures in the CDC combustor, thermal NO can be reduced by increasing thermal field uniformity while reducing and mitigating the hot spots. In Fig. 3, it can be seen that near stoichiometric equivalence ratios provided the highest NO yield. At stoichiometric ratio for each fuel, the resulting flame temperatures were higher. Each of the fuels provided minimum NO level at an equivalence ratio of near 0.6, with a slight increase after this point. The minimum for NO is due to a decrease in peak temperatures at reduced equivalence ratios, while the slight increase below $\Phi = 0.6$ is attributed to prompt NO that has greater effect at low equivalence ratios. At equivalence ratios between 0.4 and 0.5, NO emission remained very low until the combustion destabilized at approximately an equivalence ratio of 0.35.

Just before flame blowout at the lower flammability limit, the increase in oxygen content in the exhaust due to incomplete combustion led to a higher corrected NO level. The UOP HEFA-SPK, Gevo ATJ, and SB-JP-8 all showed very low NO emission (under 1 ppm), while the Amyris Farnesane minimum NO was approximately 1.5 ppm. For the ultra-low NO regime at various equivalence ratios, the NO levels remained 1–2 ppm for each of the fuels at most conditions. Additionally, for most of the fuels, NO was below 1 ppm at equivalence ratios of ~ 0.6 to 0.65.

Figure 4 shows CO emission for each of the biofuels examined. CO is much less dependent on peak temperatures and more dependent on equivalence ratio and residence time in the combustor. CO emission for each of the fuels started high, at near stoichiometric conditions. As the equivalence ratio decreased to approximately 0.75, minimum CO emission level was reached that corresponded to an increased probability of oxygen reacting with the remaining CO. As equivalence ratio was decreased further, the apparent residence time reduced to a point where there was not enough time for CO oxidation. At equivalence ratios of 0.4–0.6, the CO yield remained constant due to a balance between decreased residence time and equivalence ratio. Even further decrease in equivalence ratio, below $\Phi = 0.4$, led to encroachment on the lower flammability limit, leading to incomplete combustion and a rise in CO. UOP HEFA-SPK and SB-JP-8 provided the lowest CO yields of approximately 1000 ppm at an equivalence ratio of 0.75, while Gevo ATJ provided a minimum CO of ~ 1200 ppm closer to an equivalence ratio of 0.8. Amyris Farnesane provided its minimum CO yield of ~ 1300 ppm at an equivalence ratio of 0.75. At equivalence ratios of 0.4–0.6, there was near uniform yield of CO for each of the

fuels examined in the range of 2400–2900 ppm, with the Gevo ATJ providing the lowest CO yield.

5 Conclusion

Results obtained from four different potential drop-in liquid biofuels for power generation and propulsion applications showed good potential for use as fuels in a high-intensity combustor. The effect of equivalence ratio and biofuel properties on thermal field uniformity and pollutants emission characteristics were examined using a reverse cross-flow combustor at a thermal intensity of $20 \text{ MW/m}^3\text{-atm}$. OH^* chemiluminescence signatures provided global flame structure corresponding to the thermal field under various conditions. The OH^* chemiluminescence signatures showed significant reduction in signal intensity at low equivalence ratios.

Pollutants emission results showed ultra-low NO levels (less than 1 ppm) for all the fuels examined except Amyris Farnesane, which was ~ 1.5 ppm, at an equivalence ratio of ~ 0.6 . Additionally, operation over a large operating region at equivalence ratios of 0.4–0.6 resulted in NO emission between 1 and 2 ppm for all of the fuels examined. CO emission was found to be lowest between an equivalence ratio of 0.7 and 0.8 for the fuels, with UOP HEFA-SPK and SB-JP-8 fuels each having minimum CO levels at ~ 1000 ppm, Gevo ATJ a minimum of ~ 1200 ppm, and Amyris Farnesane a minimum of ~ 1300 ppm. CO emission reduction was restricted by residence time constraints due to the burner geometry, and CO emission increased to 2400–2900 ppm under a steady emission regime for equivalence ratios of 0.4–0.6. In this level region, Gevo ATJ had the lowest CO yield followed by SB-JP-8, with UOP HEFA-SPK and Amyris Farnesane providing very similar yields.

The results showed promise for use of four potential drop-in biofuels in a high thermal intensity combustor while yielding ultra-low emissions. Results showed the combustor provided NO levels near unity, and CO yield ~ 1000 ppm at favorable equivalence ratio conditions. The results also showed that at equivalence ratios in the range of 0.6–0.8, the resulting CO and NO emissions were also minimum. The ultra-low emissions as well as the observed global OH^* chemiluminescence signatures provide the demonstration of a lab-scale gas turbine combustor at high intensity using various drop-in biofuels.

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