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Clean combustion in gas turbine engines using Butyl Nonanoate biofuel

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HIGHLIGHTS

- Examined Butyl Nonanoate (BN) biofuel for gas turbine applications.
- BN produced ~15% larger droplet sizes compared to JP8 under similar condition.
- BN provided 15% reduction in NO emission compared to JP8 in the distributed combustor.
- CO emission was also lower compared to JP8, and contrary to HRJ biofuel.
- No start-up issues or combustion instabilities observed with the BN biofuel.

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ABSTRACT

Developing new and renewable biofuels for ultra-low emission gas turbine combustors is much desired to secure future power needs. Several fuels are being developed to replace fossil fuels with minimal carbon footprint and pollutants emission. Ease of transition between fossil fuels and biofuels is also desired for fuel flexibility in engine operation. In this paper, the performance of Butyl Nonanoate biofuel is evaluated and compared to both Hydrogenated Renewable Jet (HRJ) fuel and JP-8. The atomization characteristics are examined using Phase Doppler Particle Analyzer (PDPA) for favorable condition of fuel introduction to the combustor. The Biofuel provided 10–15% larger size droplets compared to JP-8 for a given atomizer and operational pressure. The combustion behavior of biofuel was also examined in a swirling colorless distributed combustor with focus on pollutants emission under high intensity simulated gas turbine conditions. The liquid fuels were directly fed into the path of the air stream prior to combustion without using any atomizer or spray device. The biofuel provided 6 PPM of NO and 35 PPM of CO at an energy release intensity of 27 MW/m^3-atm at 0.6 equivalence ratio. The recorded emissions are about 15% lower as compared to JP-8 for equivalence ratio higher than 0.65. For lower equivalence ratios, NO emissions were identical. The Butyl Nonanoate biofuel also exhibited lower NO emissions than HRJ biofuel. The CO emissions were lower with Butyl Nonanoate as compared to JP-8 (this is in contrast to HRJ biofuel which showed an increase in CO compared to JP-8). The examined biofuel did not show any instability with smooth transition between different fuels. These results provide promising behavior of Butyl Nonanoate biofuel for use in future energy needs without any modifications to the combustor injectors, while maintaining high performance.

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1. Introduction

Rapid depletion of fossil fuels and widespread concerns on energy security have motivated scientists and engineers to develop new fuels that are derived from environmental friendly sources to support the current and future energy needs in a sustainable fashion. Several authors have discussed the viability of such biofuels [1–4]. The current interest on alternative jet fuels for commercial and military application stems from multiple factors including sustained energy availability, high petroleum fuel costs, price volatility, lack of energy diversity, global climate impacts, and potential air quality. Civil and military jet aircraft require a near-term fuel replacement to conventional petroleum based jet fuel that is a "drop-in" hydrocarbon substitute that can function within the existing aircraft infrastructure while meeting rigorous safety and performance standards.

Such drop-in alternative jet fuel pathways can be grouped into five broad categories: jet fuel produced from unconventional sources of petroleum such as oil sands, very heavy oils, and oil shale; synthetic jet fuel from thermochemical processes involving natural gas, coal, and/or lignocellulosic biomass such as Fischer–Tropsch (F–T) synthesis and pyrolysis; advanced fermentation, catalytic, and other means of converting sugars to jet fuel; hydro-processing of conventional oils to synthetic jet fuel; and conversion of

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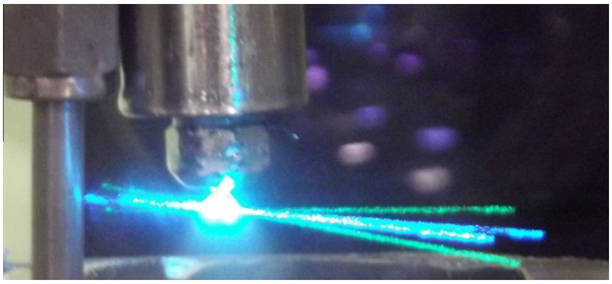

Fig. 1. Droplet size measurement using PDPA.

calorific liquids from micro-organisms to synthetic jet fuel [5]. Through both ground and flight tests, the USAF has already approved a 50% blend of F–T fuels with conventional jet fuels. It is expected that the certification of a 50% blend of hydro-processed renewable oils with conventional jet fuel should occur in the near future [6]. Commercial and military aviation have set ambitious alternative fuel and environmental targets for the next half century. The International Air Transport Association has set a goal of 10% alternative fuel use by 2017, carbon neutral growth in 2020, and a 50% decrease in aviation CO_2 emissions by 2050, relative to 2005 levels. In a detailed research on the viability of different alternative jet fuels, it was concluded that switchgrass F–T fuel and camelina HRJ have the potential to reduce life cycle greenhouse gas emissions by 60–80% [5]. Synthetic isoparaffin-rich fuels produced by hydro-processing camelina oil show great promise as "drop-in" alternatives to petroleum jet and diesel fuel. Recent evaluations of HRJ fuel derived from camelina oil indicate the fuel performed just as well as petroleum based fuel but with lower exhaust and GHG emissions. Using updated estimates of camelina cultivation and commercial scale estimates of oil recovery and refining requirements a life cycle GHG savings of 75% and 80% was estimated for camelina-derived HRJ and Green Diesel (GD) relative to their petroleum fuel counterparts. Using data from recent field trials, GHG savings of >67% were achieved [7]. Also reduction in NO_x emissions can be achieved via biofuels. On the other hand, CO emissions depend on the engine type [4]. The use of biofuels have also been extended to furnaces with emission reduction of both NO and CO [8]. A study on biofuel using T63 test engine revealed that there was minimal changes in CO emission with slight increase in THC (10%) at idle with biodiesel concentrations of 20%. This increase was attributed to incomplete combustion of biodiesel at the low power setting. At the higher power conditions, there was little or no change in CO and THC. The addition of biodiesel had negligible effects on oxides of nitrogen (NO_x) emissions for all the test cases. This was expected, because the primary route for NO_x formation is via thermal NO_x, and the relative combustion temperature was not changed during the blends tests. Only slight reductions in oxides of sulfur (SO_x) emissions were observed as the biodiesel concentration was increased, which was likely a dilution effect, because the biodiesel did not contain sulfur [9].

The quest for developing biofuels from untraditional sources as a new energy source is a topic of ongoing work at several institutions and organizations. In that sense, Butyl Nonanoate is a chemical that has not been used as a biofuel before. It is characterized by a lower calorific value, higher viscosity and density. This fuel has been processed at Michigan State University for use as a new biofuel. The combustion characteristics of this novel fuel will be evaluated with view to its use in gas turbines (both stationary and aviation). The most important parameters are the ability of the fuel to be atomized (which depend on surface tension, viscosity, and density), along with the pollutants emission resulting from the combustion of this fuel. The combustion characteristics of this Butyl Nonanoate fuel will be compared to standard JP-8 to determine its viability for use in gas turbine applications.

The performance of Butyl Nonanoate will be evaluated and compared to JP-8 and HRJ fuels in terms of droplet formation and pollutants emission. These fuels will be examined in a colorless distributed combustor [10,11] for performance evaluation. Colorless distributed combustion (CDC), which is based on the principles of High Temperature Air Combustion (HiTAC [12]), have been shown to provide ultra low emissions with high efficiency under different configurations [13–16]. Fuel flexibility have also been demonstrated using CDC combustors [17,18]. The examined fuels included both gaseous and liquid fuels with no change to the combustor geometry or fuel introduction method [18]. The resultant emissions from different fuels using this combustor were found to be lower than the regulations set by Environmental Protection Agency (EPA) [19], outlining the potential application of this combustor design.

2. Experimental facility

The atomization characteristics of biofuel were first evaluated using a standard atomizer. The droplets diameter was measured using a phase Doppler particle analyser and an average was calculated to evaluate the atomization of the novel Butyl Nonanoate biofuel. Fig. 1 shows the experimental setup used for droplet diameter evaluation.

The pollutants emission from the biofuel was also measured where the fuel was fed to a swirling distributed combustor operating at a nominal heat load of 6.25 kW and energy release intensity of 36 MW/m^3-atm. Different liquid fuels were injected in a preheated air stream (for simulating gas turbine combustor intake with elevated temperature after air exiting the compressor) upstream the combustor.

The combustion chamber utilized was a cylindrical chamber; air was injected tangentially at half the height of chamber for all the cases investigated here. For enhancing the residence time of reactants in the combustor, a tube was extended inside the combustor for exiting the product gases from the combustor. Fig. 2 shows a schematic diagram of the combustor used. More detailed description of the combustor geometry is given in Ref. [11].

For combustion, air was supplied using an air compressor. Air flow rates were measured using choked flow orifice systems. Precision stainless steel orifices were used to choke the flow of the gases and upstream pressure was controlled to supply the required mass flow rate of gases. The upstream pressure was controlled using pressure regulators to maintain a steady pressure and avoid

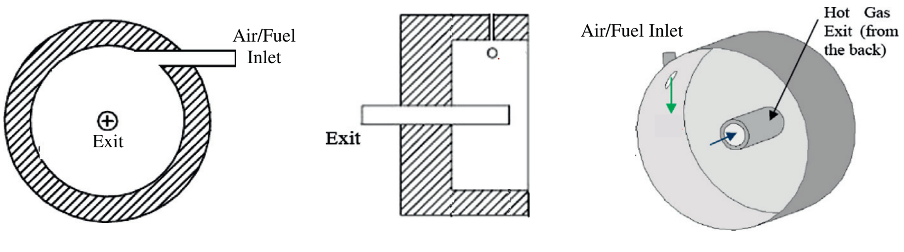

Fig. 2. Schematic of the combustor used.

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