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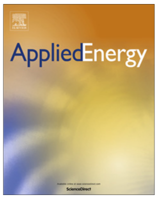

Emissions characterization tests for hydrotreated renewable jet fuel from used cooking oil and its blends

Marco Buffi [a,*], Agustin Valera-Medina [b], Richard Marsh [b], Daniel Pugh [b], Anthony Giles [b], Jon Runyon [b], David Chiaramonti [a]

[a] *RE-CORD and CREAR, Industrial Engineering Department, University of Florence, Viale Morgagni 40, 50134 Florence, Italy*
[b] *Gas Turbine Research Centre, Cardiff University, Heol Cefn Gwrgan, Margam, SA13 2EZ Wales, UK*

HIGHLIGHTS

- Fundamentals of combustion for renewable jet fuel and its blends were studied.
- HRJ influence in terms of flame stability and chemiluminescence was investigated.
- Tests were performed in an optical combustor at various ERs and operating pressures.
- The HRJ/Jet A-1 blend at 20/80% volume fraction showed the lower emission index.
- Homogeneous OH* and lower soot formation were observed increasing HRJ into blends.

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ABSTRACT

Experimental trials have been conducted using an optical swirl burner to compare the heat release and emission profiles from the application of four different aviation fuel blends with changing inlet conditions. The mixtures comprised fossil Jet A-1 and a HRJ (Hydrotreated Renewable Jet fuel) batch produced from used cooking oil processing, and blended in discrete ratios. Changes in the produced emissions were quantified with varying combustor pressure and equivalence ratio, in addition to analysing the distribution of combustion heat release using OH* chemiluminescence, and monitoring operational rig temperatures. Results suggest the presence of HRJ can reduce emissions and lead to a more compacted and homogenous heat release zone, beneficial as localised hot-spots can lead to the generation of soot and thermal NO_x. An increase in pressure was also shown to compact the flame brush at constant thermal power, due to density changes in the combustion air, and reduced bulk flow. The presented heat release distributions and experimental data are useful for the validation of numerical simulations, particularly for the use of alternative fuels. The work also highlights the correlation of flow/acoustic perturbations with heat release, crucial in characterising global combustion behaviour.

1. Introduction

Sustainability is of primary importance to the aviation sector, and the drive for continuous improvement represents a major challenge for the industry as a collective. For instance, it is estimated that by 2020 global emissions produced from the sector will increase by 700% compared to 2005 [1,2]. The target set by the EU Advanced Biofuel Flight Path initiative, promoting the annual use of up to 2 million tonnes of alternative aviation fuel by 2020, provides a clear indication of European emission reduction goals. The International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) have established a strategy to tackle climate change, which includes technical enhancements to engine operation, emissions trading and the provision and development of new fuels [3].

Today the use of sustainable fuels in aviation requires renewable hydrocarbon-based blends to qualify through ASTM D4054: '*Standard Practice for Qualification and Approval of New Aviation Turbine Fuel and Fuel Additives*' [4] and ASTM D7566: '*Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*' [5]. So far, five aviation biofuels have been approved according to ASTM D4054: Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK), produced from iso-butanol derived from feedstock such as sugar and corn, Synthesized iso-paraffins (SIP) (renewable farnesene hydrocarbon), developed by Total and

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* Corresponding author.
E-mail address: marco.buffi@unifi.it (M. Buffi).

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Amyris, produced by converting plant sugars into farnesene, Hydro-processed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK), made from vegetable oil-containing feedstock, Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), and finally Fischer-Tropsch Synthetic Kerosene with Aromatics [6]. Various other biofuel production processes are currently under review for ASTM certification.

Other work has been undertaken to produce high quality alternative blends based on sustainable biomass [7], with oil from feedstocks such as Camelina, Jatropha, algae [8,9] and waste lipids [10,11]. In addition, synthesized mixtures comprising alcohol, esters and other oxygenated compounds have been tested in atmospheric swirl burners [12] and gas turbine combustors [13,14] as prospective jet fuel substitutes [15], but their use is still limited by ASTM requirements. Contemporary research efforts are focusing on the combustion characterization of renewable fuel mixtures to better understand potential operational issues. In order to select hydrocarbon groups that can reasonably well simulate and represent Jet A-1 properties, the latest developments in the sector are investigating the formulation of jet fuel surrogates [16–22]. This also supports the development of a compositional based specification, and facilitates the development of concepts for 100% drop-in fuels from renewable sources, together with multi-component blends [23].

In the presented work, emission profiles and flame heat release patterns (using OH^* chemiluminescence) have been analysed for neat and blended hydro-treated renewable jet fuel (HRJ – produced with used cooking oil as feedstock) in a swirl-stabilised combustor. The HRJ consists of a full-paraffinic fuel, with the range of kerosene produced in the framework of the EU FP7 ITAKA project [24]. The main limiting factor for HEFA-derived fuels is the aromatic content, which has to range from 8.4 vol.% due to concerns about preservation of seal integrity [25], and according to ASTM D1655 must not exceed 25 vol.%. Generally, lower aromatic concentrations provide benefits in terms of reduced particulate matter [26–29] leading to a cleaner combustion in aviation turbines and auxiliary power units (APUs). The use of a reduced aromatic content fuel is significant also in terms of aldehyde emissions (i.e. ozone formation precursors): Li et al. [30] studied three renewable aviation fuel blends using a gas turbine, demonstrating that alternative fuels/blends showed equivalent or lower aldehyde emissions compared to Jet A-1.

Other recent studies have investigated the effect of hydrocarbon species on fundamental combustion characteristics such as derived cetane number, autoignition temperature, laminar flame speed and extinction strain rate [31,32]. These parameters have to be experimentally studied in dedicated test rigs [33] and the applied analysis of combustion regimes is also required to characterise flame stability. An altitude relight test rig employed by Mosbach et al. [34] used optical diagnostics to show that significantly lower soot luminosities can be observed with synthetic-derived aviation fuel (i.e. an almost iso-paraffinic fuel as HRJ [22]) compared to corresponding Jet A-1 flames. High speed chemiluminescence images of transient flame phenomena were also captured, but limited differences were observed for the change in fuel composition. Optical diagnostic features such as burning regimes, emission spectra, flame height, and chemiluminescence are of practical relevance, particularly for aerospace applications [35–38]. The study of these features in terms of OH^* is crucial for evaluating heat release in relation to flame stability, and have been employed with engine [39] and gas turbine applications [34].

In order to develop numerical models, Chong and Hochgreb [40] first studied the spray combustion characteristics of biodiesel and Jet-A1 in a gas turbine at a constant thermal power output of 6 kW, with reaction zones evaluated using chemiluminescence. The same authors [41] used the measured data to develop a discrete multicomponent model for biodiesel spray combustion. A similar approach has been used to simulate jet fuel combustion phenomena, with Jones et al. [42] using swirl-stabilised liquid kerosene flames and LES (Large Eddy Simulation). A parametric study is presented in this work, characterising the operability of a Jet A-1 flame, with incremental increases in blended HRJ fraction to give four experimental mixtures: 100% Jet A-1, blends at 80/20 and 50/50%vol to 100% HRJ biofuel. Fuel performance is evaluated using a representative gas turbine swirl combustor with optical access, and exhaust emissions quantified using industry standard analytical suite. The influence of pressure has also been studied at various operational equivalence ratios.

2. Materials and methods

Experiments were performed using a pressurised swirl combustor in the high pressure optical chamber (HPOC) at Cardiff University's Gas Turbine Research Centre (GTRC). A schematic representation of the experimental system is given in Fig. 1.

2.1. Fuel

The renewable fuel batch consisted of 5 kg of 100% Used Cooking Oil (UCO) derived kerosene (HRJ), sourced from SkyNRG and adopted by Metropolitan Manchester University (MMU) for ITAKA experimental tests in gas turbines [43]. The adopted Jet A-1 is a commercially available aviation fuel, which meets the DEFSTAN 91/91 and ASTM D1655 standards. The four different blends were prepared by mixing HRJ and Jet A-1 and are listed in Table 1, together with operational equivalence ratios and combustor pressures.

2.2. Experimental rig

The HPOC was used to facilitate pressurised operation, with the system capable of blending up to 5 different fuels and operate at conditions of up to 16 bar_a at 900 K. Diametric quartz windows allow optical access to the burner exit from radial and axial positions. The HPOC was fitted with a generic premixed swirl burner (as shown in Fig. 2) designed and characterised in previous research [35–38]. The burner is operated with a 700 mm cylindrical quartz exhaust confinement tube, with an expansion ratio of 3.5 from the burner nozzle exit (141 mm internal diameter). The outlet has a geometric swirl number (ratio of tangential to axial

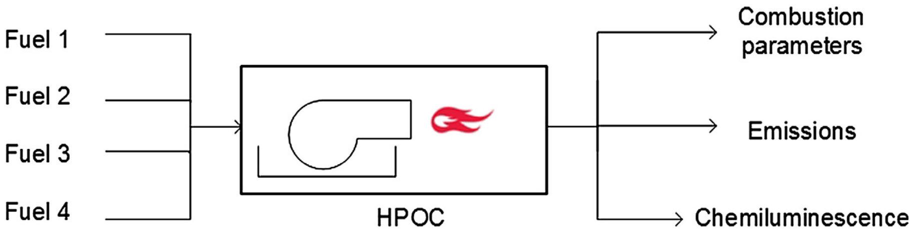

Fig. 1. Schematic of the high pressure combustion apparatus, including fuel inputs, optical chamber and output measurements.