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Quantification of aldehydes emissions from alternative and renewable aviation fuels using a gas turbine engine

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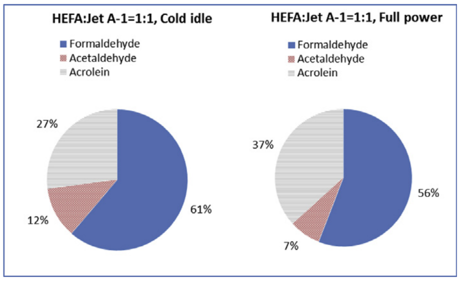
HIGHLIGHTS

- Formaldehyde is a major aldehyde species (~60% of total aldehydes) for all fuels.
- Acetaldehyde emissions are below 2–3 ppm for all fuels.
- HEFA fuel blends had the same level of formaldehyde emissions as Jet A-1.
- Neat GTL fuel and FAE blend had the lowest formaldehyde emissions.
- Formaldehyde emissions were 2–3 times higher at idle than that at full power.

GRAPHICAL ABSTRACT



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ABSTRACT

In this research three renewable aviation fuel blends including two HEFA (Hydrotreated Ester and Fatty Acid) blends and one FAE (Fatty Acids Ethyl Ester) blend with conventional Jet A-1 along with a GTL (Gas To Liquid) fuel have been tested for their aldehydes emissions on a small gas turbine engine. Three strong ozone formation precursors: formaldehyde, acetaldehyde and acrolein were measured in the exhaust at different operational modes and compared to neat Jet A-1. The aim is to assess the impact of renewable and alternative aviation fuels on aldehydes emissions from aircraft gas turbine engines so as to provide informed knowledge for the future deployment of new fuels in aviation. The results show that formaldehyde was a major aldehyde species emitted with a fraction of around 60% of total measured aldehydes emissions for all fuels. Acrolein was the second major emitted aldehyde species with a fraction of ~30%. Acetaldehyde emissions were very low for all the fuels and below the detention limit of the instrument. The formaldehyde emissions at cold idle were up to two to threefold higher than that at full power. The fractions of formaldehyde were 6–10% and 20% of total hydrocarbon emissions in ppm at idle and full power respectively and doubled on a g kg^{-1}-fuel basis.

1. Introduction

Air transport has been steadily increasing by ~5% per year globally over the past three decades and forecasted to continue to increase in the next decade (Belobaba et al., 2009). With the increase in demand for air transport, emissions from aircraft engines have to be monitored and controlled to protect public health and the environment, particularly in the vicinity of airports.

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There are a variety of air pollutants emitted from aircraft engines that can potentially affect human health and the environment. Common species such as NO_x (Nitrogen Oxides), CO (Carbon Monoxide), UHC (Unburned Hydrocarbon) and smoke are regulated by ICAO (International Civil Aviation Organization) (ICAO, 2008) and considered as primary species in emission inventories. CO_2 as a greenhouse gas is considered as a global concern rather than a local issue. There is an increasing concern and need to include additional emission species which have potential health and environmental concerns in emission inventories. These species are often called HAPs (Hazardous Air Pollutants), which are part of VOCs (Volatile Organic Compounds). ICAO reported some examples of HAPs that have been identified as representative pollutants from airport sources including formaldehyde, acetaldehyde, acrolein, 1,3-butadiene, benzene, Naphthalene, toluene, xylene and propionaldehyde (ICAO, 2011). These compounds play an important role in the atmospheric chemistry and urban air quality (ICAO, 2011; Leikauf, 2002; Koenig, 2000) and have major health concerns. They are also precursors to free radical ozone productions (Lea-Langton et al., 2009). The research for aviation activity related or sourced HAPs is at early stages and knowledge on these HAPs emissions is very limited (ICAO, 2011). It is reported that formaldehyde, acetaldehyde, acrolein and methyl ethyl ketone are the main species of carbonyl emissions from the engine exhaust and are toxic, mutagenic and even carcinogenic to human body (He et al., 2009; Pang et al., 2006). Both formaldehyde and acetaldehyde were classified as a probable human carcinogen by EPA in 1987 and exposure to them can cause irritation of the eyes, nose and respiratory tract (EPA, 1989). Formaldehyde has a strong potential to form ozone and is classified as an active ozone formation precursor. Ozone is an irritant gas that can pose hazards to mucous membranes of eyes and respiratory tract.

Knighton et al. (2007) measured 20^+ VOCs including aldehydes and benzene using the tunable infrared laser differential absorption spectroscopy for formaldehyde and the proton transfer reaction mass spectrometer for other VOCs from CMF56-2-C1 engines of a DC-8 aircraft during APEX program using three different fuels: two batches of JP8 containing 17.5% and 21.8% aromatics respectively and a high sulphur jet fuel. They found that formaldehyde and benzene concentrations were hardly detectable at the higher engine thrust conditions, until the engine thrust was reduced to 15% or lower, where they started to increase quickly as the engine thrust continued to reduce to idle. Li et al. (2011) assessed aldehydes emissions under atmospheric pressure and 600K using a radial swirler industrial low NO_x gas turbine combustor and compared aldehydes emissions between B100 (100% Waste cooking oil Methyl Ester or WME), B20 (80% Kerosene: 20% WME) and pure kerosene. In their experiment, the same FTIR (Fourier Transform Infrared) instrument as in this paper was used to determine aldehydes including formaldehyde, acetaldehyde and acrolein. Their results showed that formaldehyde was the most prevalent aldehyde species for all the fuels, accounted for up to 50%.

There has been an increasing interest in the development of alternative fuels for aviation due to energy supply security concerns and potential environmental benefits (CO_2 reduction). The alternative aviation fuels include both synthetic and renewable jet fuels (Bulzan et al., 2010). Synthetic fuels, also called FT-SPKs (FT- Synthetic Paraffinic Kerosenes), are derived from coal (CTL-Coal To Liquid) or natural gas (GTL-Gas To Liquid) via the FT (Fisher Tropsch) process. Extensive researches and tests have been done on these fuels for the certification purposes. The blends of up to 50/50 (by volume) of FT-SPK with JP-8 or Jet A have been approved in the USA for the US military and civil aviation use (Mil-Dtl-83133h, 2011). However, these alternative fuels are not renewable as coal and natural gas are fossil fuels. Although biomass can be used in the FT process to produce BTL to make it renewable, the cost is high and the availability of a large amount of biomass is a question (Rye et al., 2010). The interests therefore have been moved to Hydrotreated Renewable Jet (HRJ) or Hydrotreated Vegetable Oil (HVO). HRJ or HVO is hydrocarbon aviation fuels produced from vegetable/plant oils or animal fats via hydroprocessing. This type of fuel is also called bio-SPK, "green jet" or HEFA (Hydrotreated Ester and Fatty Acid).

All alternative/renewable aviation fuels are required to be drop-in fuels (Blakey et al., 2009), which mean that they must be completely interchangeable and compatible with conventional kerosene based jet fuels and can be added to conventional jet fuels as a substitute without a need to modify the engine and fuel system. These alternative/renewable aviation fuels have no or trivial amount of aromatic hydrocarbons and sulphur (Corporan et al., 2011), which are an advantage over conventional kerosene based fuels because of its benefits on the reduction of particulate matter emissions (Lobo et al., 2011). Lobo et al. (2012) compared regulated gaseous and particulate matter emissions from the same engine as in this paper between CTL, GTL fuels and Jet A-1 and reported a significant reduction in PM emissions by CTL and GTL fuels and remarkable hydrocarbon reductions by GTL fuel. Christie et al. (2012) measured PAH emissions from the same engine using neat CTL, neat GTL fuels and 50/50 GTL/Jet A-1 blend and reported a significant reduction by GTL but an increase by CTL. There are other potential benefits from these alternative fuels that need to be identified. This forms the objective of this paper, i.e. to assess and quantify aldehydes emissions of three renewable aviation fuel blends and one alternative fuel (GTL), and compare them with conventional Jet A-1 fuel.

2. Experimental

2.1. Fuels

The neat conventional kerosene based Jet A-1 was used as the reference fuel. Three renewable fuel blends and a neat GTL fuel (can be used as a component of aviation fuel) were tested. Table 1 shows the blending ratio and selected chemical and physical properties of each fuel. Two separate fuel tanks were used with one for Jet A-1 and the other for testing fuels.

2.2. Engine

An Artouste MK113 APU (Auxiliary Power Unit) engine was used as a test bed for the emission measurements. It is a single spool gas turbine engine, in which a centrifugal compressor is driven by two stage turbine through a single rotating shaft. All operating parameters of the engine such as fuel flow rate, RPM, exhaust temperatures and pressure and fuel consumption were monitored and recorded throughout the tests. Table 2 presents the selected

Table 1
Selected properties of the fuels tested.

Fuel code	Fuel blending ratio	Specific heat (MJ kg^{-1})	Sulphur (ppm)	H/C ratio	Density (kg m^{-3})	Aromatics (wt%)
Jet A-1	Jet A-1 100%	43.2	669	1.89	803.5	16
E	100% GTL	44.4	<5	2.19	737.9	~0
F	HEFA[a]:Jet A-1 50:50	43.5	335	2	780	8
H	FAE[b]:Jet A-1 10:90	42.18	601	2	810	15.5
I	HEFA:Jet A-1 75:25	43.9	181	2.1	763.6	4.5

[a] HEFA-Hydrotreated Ester and Fatty Acid.

[b] FAE: Fatty Acids Ethyl Ester.