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Impact of alternative fuels on the operational and environmental performance of a small turbofan engine

R.M.P. Gaspar, J.M.M. Sousa *

IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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ABSTRACT

A wide range of alternative jet fuels is studied in this work for use in a small two-spool turbofan engine. These embrace the five production pathways currently approved by the American Society for Testing and Materials. Both neat products and blends (within certified limits) have been considered. The present analysis is based on a 0-D thermodynamic modeling of the aero-engine for off-design and transient simulations. In addition, the selected approach incorporates fuel effects on combustion and the impact of fuel properties on the flame temperature, as well as on the droplet evaporation rate. Predicted performance and pollutant emission outputs for the alternative fuels are presented at different operating conditions, namely: take-off, top of climb, cruise, low power and ground idle. The results are discussed and comprehensively compared with data available in the literature. It was concluded that the combustion of alternative fuels generally leads to enhancements in engine performance with respect to the use of conventional kerosene. Reductions in pollutant emissions occur mostly in soot, but also in nitrogen oxides and carbon monoxide, depending on the fuel and operating conditions. In contrast, increased emissions of unburned hydrocarbons are generally observed. Concerns about the aero-engine dynamic response are raised only in very few cases, involving the use of neat products.

1. Introduction

Standing as the only anthropogenic source of pollutant emissions in the lower stratosphere and upper troposphere, the reduction of its share in environmental air pollution is currently a major challenge for the aviation industry. At the 37th Session of the Assembly of the International Civil Aviation Organization (ICAO) held in 2010, ICAO Member States adopted collective global aspirational goals for the international aviation sector to improve annual fuel efficiency by 2%, as well as stabilizing CO_2 emissions at 2020 levels (the CNG2020 strategy) in order to reach carbon-neutral growth [1]. To achieve such an ambitious objective, the Sustainable Alternative Fuels route is viewed as a key element, along with technological and infrastructural improvements.

The use of biodiesel is nowadays well established in diesel engines [2], but most commercial aircrafts are powered by gas turbine engines, which have specific requirements as discussed below. Apart from the environmental benefits, the worldwide supply of alternative fuels to the aviation industry presents several advantages, such as the alleviation of petroleum dependence, stabilization of fuel prices, economic development in more diverse regions of the globe and the fact that changes in aircraft or infrastructures are not required (in the case of ”drop-in” fuels). On the other hand, the fuel production must not compete with food production, neither cause land-use change effects such as deforestation. The most significant challenge for a successful growth of alternative fuels is both economic and political [3].

Currently, there are five production pathways for alternative fuels [4] already approved by the American Society for Testing and Materials (ASTM), as follows: Fischer-Tropsch - Synthetic Paraffinic Kerosene (FT-SPK) in 2009; Hydrotreated Esters and Fatty Acids (HEFA) in 2011; Synthesized iso-Paraffins (SIP) in 2014; Fischer-Tropsch - Synthetic Kerosene with Aromatics (FT-SKA) in 2015; and Alcohol-to-Jet SPK (ATJ-SPK) in 2016. The maximum volume blending ratios approved are 50% for FT- and HEFA-SPK, 30% for ATJ-SPK and 10% for SIP. In terms of composition, most of the production pathways being developed provide jet fuels with low aromatics content when compared with conventional kerosene. Moreover, fuel properties such as the liquid density, viscosity, surface tension and normal boiling point have a substantial impact on fuel atomization and evaporation [5], which ultimately influences combustion efficiency [6]. Consequently, aircraft emissions are dependent on the properties of alternative fuels, namely volatility and aromatics content [7], as well as on engine hardware

* Corresponding author.
E-mail addresses: ricardomgaspar@ist.utl.pt (R.M.P. Gaspar), msousa@ist.utl.pt (J.M.M. Sousa).

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[8,9]. As a result of the steady increase of turbine inlet temperatures in aero-engines along the years, nitrogen oxides (NO_x) are nowadays considered the most critical pollutants in the aviation industry [10]. Together with these, carbon monoxide (CO), unburned hydrocarbons (UHC) and soot (or smoke) emissions are also regulated by ICAO [11].

In the past decades, computational simulations emerged to facilitate parametric studies on emissions, thereby reducing the excessive time and cost of experimentation [12]. Measurements in real aero-engines are very difficult to perform and experiments carried out in pilot-scale facilities are generally affected by scale factors as well as other small-scale phenomena [13]. On the other hand, very detailed numerical predictions are still expensive to achieve due to the high complexity of the associated phenomena, but good results have been obtained by the use of empirical correlations [14,15]. However, the latter must be coupled with an adequate thermodynamic representation of the aero-engine [16,17], so that different operating conditions may be investigated [18,19]. This approach has been followed in the present work, employing 0-D modeling of a two-spool turbofan to assess the impact of alternative jet fuels on its operational and environmental performance.

2. Sustainable alternative fuels

In addition to a conventional civil aviation turbine fuel, namely Jet A-1, which is defined by ASTM D1655 specification limits (ASTM D7566 for alternative fuels certification), ten types of alternative fuels varying in feedstock and/or production process were selected to be studied in the present work, as presented in Table 1, with properties obtained in the literature [7,20–32] and details given in Appendix A. Distillation properties are important for both fuel handling and mixture preparation. Although such characteristics may be associated with engine performance, these processes were not dealt with in this study. It should also be noted that, although GTL and CTL are not sustainable fuels (fossil fuel dependence), due to the lack of reliable information on BTL (FT-SPK from biomass) and assumed similar fuel properties (same refining process), their study is still considered as relevant here.

The production pathways mostly differ on feedstock and on relevant productions steps. Fuels produced from the FT-SPK pathway are based on the conversion of syngas into liquid hydrocarbons via Fischer-Tropsch synthesis, presenting a wide range of feedstock possibilities such as coal, natural gas, wastes or lignocellulosic biomass. The HEFA-SPK process produces hydrocarbons by deoxygenation and hydroprocessing from vegetable or waste oils. In the ATJ production pathway, alcohol synthesis is first required from feedstock such as sugars and starches, followed by several other chemical processes. SIP jet fuel (mostly farnesane) is essentially produced through sugar fermentation. In the CH pathway, catalytic hydrothermolysis is applied, with a feedstock ranging from sugars and starches to lignocellulosic biomass. The HDO-SK fuel production has a similar type of feedstock, but it involves a hydrodeoxygenation step. Green Diesel is produced from vegetable oils and animal fats also via the HEFA process [21].

The composition analysis of these fuels evidences an overall lack of aromatics, when compared to Jet A-1. Among the set studied here, those most similar in composition to Jet A-1 are CH and ATJ-SKA. In a life cycle greenhouse gas emissions analysis, it can be proven that although indirect land use change (among others) must be carefully accounted for, there is an overall improvement in life cycle emissions with all alternative pathways [3]. In fact, research results demonstrate that, in general, the decrease in greenhouse gases emissions may be greater than 50% from a life cycle perspective, when compared with conventional production. However, this route is still considered an expensive solution, whose viability is dependent on crude oil prices. Nevertheless, it is expected that, following higher energy demand and petroleum depletion, the price of conventional jet fuel will steadily increase. In addition, the maturation of alternative fuels is also expected to yield future decreases in the prices of these products.

Table 1
Alternative fuels selected to be studied in the present work.

Designation	Feedstock	Pathway
CTL	Coal	FT-SPK
GTL	Natural gas	
HEFA R-8	Mixed fats	HEFA-SPK
HEFA Camelina	Camelina oil	
CH	Carinata Oil	CH
ATJ-SPK	Corn	ATJ-SPK
ATJ-SKA	Biomass	ATJ-SKA
SIP	Sugars	SIP
HDO-SK	Biomass	HDO-SK
Green Diesel	Vegetable oil	HEFA

3. Simulation methodology

The simulation methodology chosen to carry out the present study is based on thermodynamic modeling of a typical two-spool turbofan in a 0-D approach. The aero-engine is defined with the implementation of a diffuser followed by a low-pressure compressor (LPC), a high-pressure compressor (HPC), a combustion chamber (burner), a high-pressure turbine (HPT), a low-pressure turbine (LPT) and a convergent core nozzle, through the core of the engine (hot flow). Bypass air (cold flow) also runs through the fan and the convergent fan nozzle. This type of turbofan and station numbering is schematically presented in Fig. 1, in accordance to Aerospace Recommended Practice 755A.

It is required that all fuel properties are read in the beginning of each calculation. Values of the net heat of combustion, liquid fuel density and viscosity at two different temperatures, surface tension, boiling point and distillation temperature range, hydrogen content, hydrogen-to-carbon ratio, molecular weight, and critical temperature and pressure are read for each fuel. Subsequently, for cases where a certain fuel property is not known a priori, as well as for estimates at variable temperature, correlations used for petroleum fractions [33] are considered for the alternative fuels. Prior to the engine simulations, all estimated fuel properties were validated against available data from the referenced literature for a variety of fuels and, as a rule, only small errors were obtained. The modeling of fuel properties is completed with the implementation of a blending option [33–35], so that these may be obtained for an intended volume blend ratio of a given alternative fuel and Jet A-1.

In order to account for physical effects of the fuel on combustion, the impact of fuel properties on the flame temperature [6,36], as well as on the droplet evaporation rate [37], is modeled and has been validated for kerosene and kerosene blends, also based on results published in the aforementioned references. The larger deviations from experimental data were obtained in the estimates made for the critical pressure, with an average error of approximately 13%, but its influence in the calculation of the evaporation constant was found to be negligible. Still, it must be pointed out that the evaporation model assumes (quasi) steady-state evaporation, which for higher burner ambient pressures than those critical for a given fuel, and at high flame temperatures, becomes mostly transient. For such cases, maximum evaporation rate at the fuel critical pressure was assumed, as an approximation.