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ABOUT LOW EMISSION COMBUSTION WITH REPLACEMENT FUELS
(Paper review)

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Abstract:

*In the frame of the research project Alfa-Bird (**Al**ternative **F**uels **a**nd **Bi**o-fuels for Ai**r**craft **D**evelopment), a synthesis on the theme "future alternative fuels and low-NO_x technologies" was performed by authors under the leadership of Airbus.*

Based on a literature survey of the open literature plus the significant inputs available within the project, a systematic analysis of the type of fuel, the type of testing and the comparison between a reference fuel and resulting product was conducted. The focus is put on the four fuels selected for tests within the Alfa-Bird fuel matrix.

No contra-indication compared to existing low-NOx strategies was found. The products tested in the Alfa-Bird project show a better behaviour concerning the LBO limit than conventional fuels, which is promising for a better flame stability in lean combustors. The fact that synthetic blends produce less soot is one argument for further developing of RQL burners, for instance.

Introduction

This paper review has been prepared as a part of the **Al**ternative **F**uels **a**nd **Bi**ofuels for Ai**r**craft **D**evelopment (Alfa-Bird) project.

One task of the project is a technical synthesis to set new standard requirements for these alternative components. In the frame of future alternative fuels strategy and implementation, we focused on future alternative fuels and low-NO_x technologies.

A literature survey is performed to assess the question of pollutant emissions issued from replacement fuels compared to conventional. This survey covers recent open literature, as well as the results of the Alfa-Bird project.

The literature survey covered reports on new fuels tested on existing hardware designed for conventional fuel. No specific burner designed from scratch for replacement fuel was found by us in the literature. As a follow-up to this study, it is recommended to start research programmes on fine-tuning of low-emission combustors using the most promising replacement fuels.

In the following we detail why there is no change in comparison with the know-how built up with conventional fuels. The main source of NO_x is thermal NO_x that depends on the adiabatic flame temperature, which itself is correlated to the lower heat value. All products tested in Alfa-Bird project produce more NO_x than conventional fuels. As a counterpart, the LBO limit is pushed further in the lean domain. CO and UHC depend greatly on the quality of the atomization, where the aspect of fuel tuning is underlined. It is also highlighted that due to their low aromatic content, synthetic fuels produce little soot.

The Alfa-Bird project

Alfa-Bird (Alternative Fuels and Biofuels for Aircraft Development) was a project co-funded by the EU in the 7th Framework Programme for Research and Technological Development. It started in July 2008 and ended in June 2012. Alfa-Bird was an R&D project aiming at viable technical solutions. Its objective was to investigate and develop a variety of alternative fuels for the use in aeronautics, motivated by the need to ensure a sustainable growth of the civil aviation, regarding the impact of fossil fuels on climate change, and in the context of oil prices that are highly volatile and increasing in the long term.

The criteria for alternative fuel selection were the security, the analogy with kerosene Jet A1, the production chain including costs, processing and storage from well to wing. Attention was paid to disconnect as much as possible from the food market, as well as to select processes where the least quantities of sweet water are involved.

The 4 fuels selected were FSJF (Fully Synthetic Jet Fuel, Coal-to-Liquid), FT-SPK (Fischer-Tropsch Synthetic Paraffinic Compound, Gas-to-Liquid), a blend of FT-SPK and 50% naphthenic cut, and a blend of FT-SPK and 20% hexanol. This fuel matrix offers the possibility to evaluate the potential of different chemical families which are paraffinic compounds, naphthenic compounds and oxygenated compounds. This is also representative of a short, middle, and long term view.

Open literature survey

A literature survey was performed on replacement fuels on a wider range than the one covered by Alfa-Bird, but still in connection with the project. Specific research on emissions from replacement fuels in aviation is still marginal.

The literature sampling focuses on the last decade essentially. It was observed that due to its novelty, the range of tested products remains extremely broad due to the explorative nature or novelty aspect of replacement fuels. Neither absolute reference nor benchmarking method has imposed itself yet.

Nevertheless, trends and attitudes regarding the use of replacement fuels and their pollutant emissions could be extracted. We report on this with an approach product-by-product in the following.

The survey briefly covers a few studies of synthetic Fischer-Tropsch (XTL) fuels and hydrogen and their impacts on aviation emissions. Also studies with alcohol fuels and biodiesels are presented in short.

Moses and Roets [1] run tests on the fully synthetic Coal-to-Liquid (CTL) type jet fuel from Sasol and Jet A as a reference fuel in a commercial combustor with an 80°, four-nozzle arc sector rig. The results showed that the simulated landing take-off (LTO) cycle NO_x and CO emissions for CTL fuel were 4 % and 19 % lower than for Jet A, respectively. At individual power points, the NO_x emissions were at the same level whereas the CO emissions were lower for CTL fuel, especially at the idle.

Also the smoke number of CTL fuel was lower than that of Jet A, but differences in CO_2 and unburned hydrocarbon (UHC) emissions were negligible.

In various studies, hydrogen has showed to have potential to remarkably decrease the greenhouse gas emissions in aviation. Both Nojoumi et al. [2] and Yilmaz et al. [3] compared a conventional aircraft and a LH_2 aircraft by studying some sample flights, including emission estimations. They claimed that since burning hydrogen only produces water vapour and NO_x, the greenhouse gas emissions of an LH_2 aircraft are low. CO_2 is generated only in hydrogen production and compared to kerosene, the life cycle emissions may be decreased by nearly 140 kg CO_2 per MWh. The production of hydrogen is the most important factor on emissions and when renewable hydrogen sources are favoured, greenhouse gas emissions can be even zero. Also the NO_x emissions of an LH_2 aircraft were found to be lower, which was explained inter alia by the wider flammability limit of hydrogen that allows the use of hydrogen fuel in a wider range of margins than conventional jet fuels.

In his study Janic [4] claimed that replacing conventional aircrafts by LH_2 aircrafts will be the prerequisite for stopping the growth of greenhouse gas emissions from aviation. LH_2 aircrafts have potential to restrict the growth or even decrease the total CO_2 and NO_x emissions but at and above the cruising altitudes of 31 000, a cryogenic aircraft emits about 2.6 times more H_2O than conventional aircraft. H_2O emissions are therefore the primary concern of the usage of LH_2 aircrafts.

Several studies by Moliere et al. [5], Padala et al.[6], Zhang et al.[7], Glaude et al. [8] show that in comparison to conventional fuels, the use of alcohol fuels reduce NO_x emissions. In some of the studies also CO_2 and CO emissions were shown to decrease. For biodiesels the studies by Bolszo and McDonell [9], Park et al. [10] and No [11] on the contrary show an increase in NO_x emissions. For other pollutants the results differ between the studies.

Hydrotreated vegetable oil (HVO) type biodiesel instead does not seem to increase NOx emissions [12,13,14]. In the studies run with passenger cars and heavy duty engines NO_x emissions were found to decrease. Also reductions in other emission components were observed. HVO type biodiesel can also be modified to aviation fuel and the results of the flight tests on scheduled passenger aircrafts have been positive in both fuel suitability and CO_2 emissions.

Analysis of the Alfa-Bird data

Focus on the combustion kinetics (experimental approach)

Dagaut et al. [15] studied the kinetics of reformulated kerosene combustion and pollutants formation. The data was obtained by two experiments: a pool fire experiment that was used to analyse the polyaromatic hydrocarbons (PAH) from soot samples, and a pressurized jet-stirred reactor (JSR) that was used to investigate the kinetics.

The pool fire experiment was performed for rapeseed oil methyl ester (RME), methyl decanoate and hexanol in 20 % volume blends with kerosene Jet A.

Results from pool fire experiment show that blending oxygenates to kerosene tends to decrease the concentration of PAHs in soot and also significantly reduce the mass of soot. The PAH reduction with 20 % in volume oxygenate blended in kerosene ranged between 5 and 73 % and the mean reduction was 41 %, 36 % and 16 % when used RME, methyl decanoate and hexanol as oxygenate, respectively. The mean reduction of all three oxygenates tested was 31 %.

In the JSR experiment the concentrations of various species during the oxidation of the fuels were measured. Since the experiment was concentrating on the kinetics of the reactions, it does not offer much valuable information of the emissions.

Comparison of the performance of a real airblast nozzle working with normal/alternative fuel

The four selected alternative fuels, Coal-to-Liquid (CTL), Gas-to-Liquid (GTL), GTL with 50 % naphthenic cut and GTL with 20 % hexanol, were studied by the Karlsruhe Institute of Technology. In the figures presented, the fuels are referred to with their fuel reference numbers 8040, 8289, 8286 and 8291, respectively.

Tests were performed by an AVIO burner with a combustion chamber. It had two radial swirlers and a fuel atomizer at the axis of the burner. For kerosene, pressure atomizer was used.

Figure 1 displays the Emission Indexes (EI) of CO for the fuels tested. It was found that the Emission Index of CO decreases when the equivalence ratio decreases moving from unity towards smaller values, i.e. the conditions become leaner. The Figure 1 also shows that kerosene seems to have a smaller Emission Index of CO than any of the alternative fuels.

Figure 2 displays the Emission Indexes of NO_x. NO_x emissions increase as the equivalence ratio approaches stoichiometry because the adiabatic flame temperature increases. It was also claimed that the GTL fuel has comparatively higher Emission Index of NO_x than other alternative fuels tested since GTL has the highest heat of combustion that causes relatively higher adiabatic flame temperatures and thus NO_x emissions. Kerosene seems, however, again to have smaller Emission Index than the alternative fuels.

The lean blow out (LBO) limits of all the alternative fuels tested were found to be higher than for kerosene. Higher flame temperatures and higher laminar flame velocities of alternative fuels were suggested to be the main reasons. Furthermore, the GTL fuel seemed to have the highest LBO stability at most of the conditions tested. The results support the suggestion of the importance of flame temperature in LBO limit since as already mentioned, the GTL fuel also has comparatively higher heating value than other fuels tested and thus relatively higher flame temperature. All tested alternative fuels were also found to have a leaner blow out equivalence ratio than kerosene.

Effect of fuel reformulation on pollutants emissions: Specification of pollutants formed by reformulated kerosene

Thomson et al. [17] studied reformulated kerosene combustion and pollutants formation by investigating gaseous species, soot and temperature in different atmospheric co-flow diffusion flames. The alternative fuels tested were Gas-to-Liquid (GTL or FSJF), Coal-to-Liquid (CTL), a blend of 80 % GTL and 20 vol-% hexanol (Hex20-GTL), and a blend of 80 vol-% GTL and 20 % naphthenic cut.

The measurements of gaseous species were performed only for the first three fuels, i.e. for GTL, CTL and Hex20-GTL. All measurements were done both along the centreline and at several radii. The burner used was a co-annular non-premixed flame burner.

Only significant differences in gaseous species between CTL and GTL species concentrations were acetylene and, in particular, ethylene, the concentrations of which were higher for GTL than for CTL. This might have been expected since GTL contains considerably more n-paraffinics than CTL. In comparison with GTL and Hex20-GTL, the trends of gaseous species were as well found to be similar. Ethylene was again the exception, having a concentration peak in the Hex20-GTL flame at the height of z = 32 mm while the corresponding peak in GTL flame is at z = 36 mm.

The experiments and results that are already presented in report D 2.1.1 were also presented again. Since no new aspects were brought, they are no more discussed here.

Spray atomization and evaporation

D'Herbigny et al. [20] studied the injection, atomization and evaporation of alternative fuels by spray visualization and PDI measurements. The fuels discussed were CTL, GTL, GTL with 20 vol-% of hexanol and GTL with 50 vol-% of naphthenic cut.

Experimental conditions were ranging from atmospheric conditions to high pressure and high temperature. Semi-angle of the spray and the droplet size and velocity distributions at two stations in the test chamber were analysed. The test rig used was designed to partially meet the conditions of a combustion chamber in terms of pressure and temperature. Airblast injection system was also used.

The results show that all the fuels tested have similar spray expansion behaviour. Also the evolutions of the Sauter mean diameter and the mean components of the velocity were found to be similar between all the fuels. Thus the fuel performances are equivalent with respect to the measured quantities.

Although there was not a significant difference between the particle sizes of the fuels, it can be observed from the results that the blend of GTL and 20 vol-% hexanol shows slightly smaller particle sizes than pure GTL. [18] This supports the results found by Padala et al., stating that ethanol forms smaller particles in comparison to gasoline [6].

The results on vaporisation of the same products show no significant change in fuel placement as a function of the fuel.

Evaluation of Well to Wing greenhouse gas emissions

Thellier [19] studied the Well-to-Tank greenhouse gas emissions of various alternative fuels. The fuels considered were Direct Coal Liquefaction (DCL), Indirect Coal Liquefaction (ICL), Gas-to-Liquid (GTL) and Biomass-to-Liquid (BTL) fuels. It was found that all fossil based alternative fuels, i.e. DCL, ICL and GTL, emit as much or more greenhouse gas emissions than conventional jet fuel, even when the use of Carbon Capture and Storage (CCS) during the production process was taken into consideration, whereas BTL produces less greenhouse gases than Jet A.

Life cycle greenhouse gas emissions have also been discussed in several other reports. Stratton et al. [20], for example, stated that the emissions of all alternative jet fuels relying exclusively on fossil fuels have higher emissions than conventional jet fuel. Nevertheless, when based on renewable feedstocks, Fischer-Tropsch fuels and Hydrotreated Renewable Jet (HRJ) fuel, i.e. hydrotreated vegetable oils (HVO), have a potential to reduce greenhouse gas emissions by 10-50 %, while the corresponding reduction with certain biofuels could rise up to 100 %, i.e. zero life cycle greenhouse gas emissions.

Conclusion

The larger carbon footprint in the production chain for replacement fuels should be kept in mind. However, the sensitivities regarding the production of pollutants are unchanged in the engine.

A replacement fuel with higher LHV than conventional fuel tends towards higher adiabatic flame temperatures, hence higher thermal NO_x.

The importance of atomisation was underlined also in tests cases where a deterioration towards higher NO_x, CO, UHC and soot levels were observed. This is very often depending on the blend cuts. For instance the proportion of alcohol has a significant impact on the droplet size, underlining the importance of fuel tuning.

Significant NO_x reductions were observed when optimising the air-to-fuel-ratio, especially in the lean domain. Staged combustion was confirmed as efficient to reduce NO_x significantly.

Due to the low rate of aromatics in synthetic fuels, the production of soots is negligible. This is underlined by one paper on fully synthetic jet fuel, and confirmed by the Alfa-Bird tested samples. The lean-blow-out limit was observed to be higher also for the same products than for conventional Jet A1.

Therefore, no contra-indication of existing low-NO_x technologies was underlined by this survey. It sounds promising, for instance, to use state-of-the-art RQL technology in aeroengines because it allies the simplicity of the RQL principle (single annular chamber, low-complexity injection compared to staged injection, stable combustion) with a decrease in its principal drawback, namely the soot production.

It is recommended to orientate future studies towards the experimental testing of these products with the latest generation of low-NO_x technologies such as LPP, RQL, PERM or LDI strategies.

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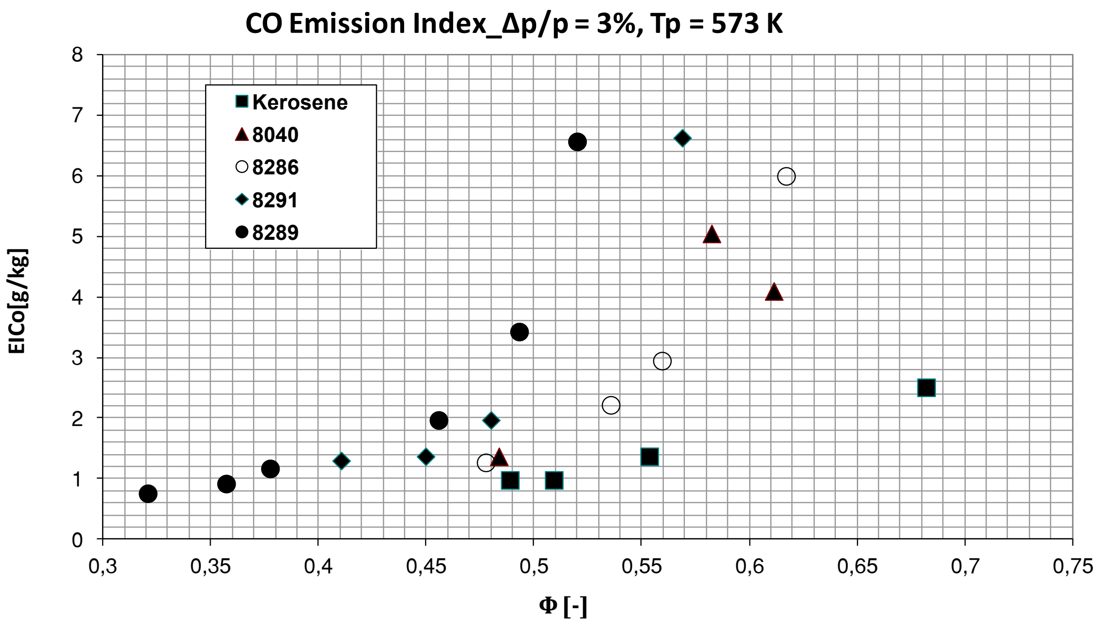

Figure 1: *Emission Index of CO for the fuels tested. [16]*

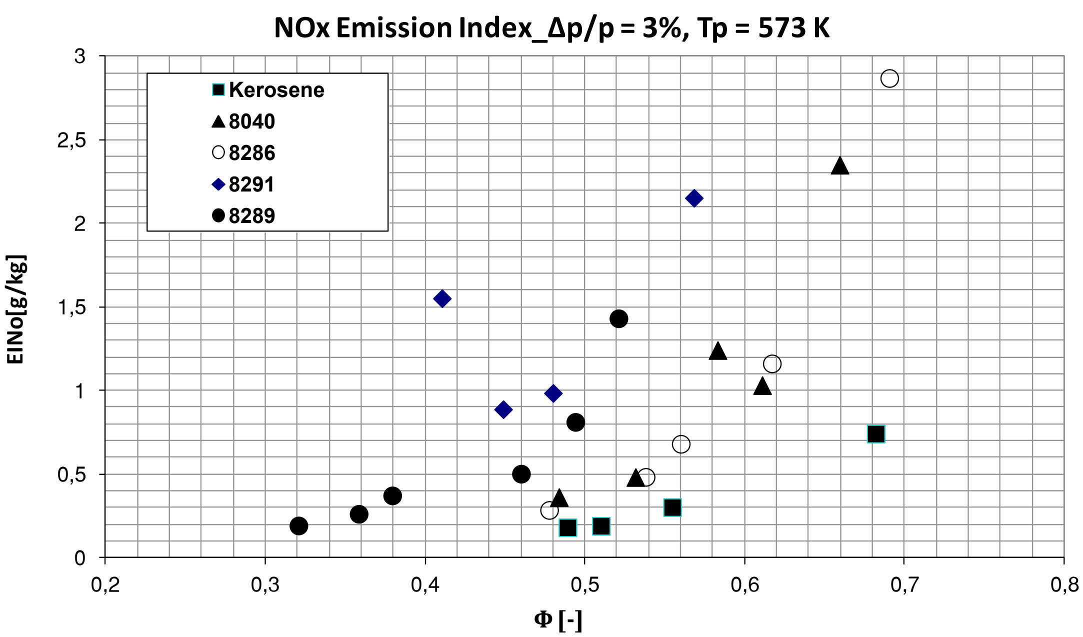

Figure 2: *Emission Index of NO_x for the fuels tested. [16]*