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ENERGY TRANSITION IN AVIATION: THE ROLE OF CRYOGENIC FUELS

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Abstract. Aviation is the backbone of our modern society. At present, around 4.5 Billion passengers travel through the air every year and aviation is responsible for around 5 % of anthropogenic causes of Global Warming (Lee et al, 2009). With the increase in global GDP, the number of travellers is expected to increase to 7.5 Billion by 2037 and to around 15 Billion by 2050. Even though the crude oil prices are low at the moment, with finite petroleum reserves available on our planet, it is expected that the Jet fuel prices will increase in the future. Moreover using kerosene causes several emissions which are bad for the environment. Liquefied Natural gas (LNG) and Liquid Hydrogen (LH2) can provide an attractive alternative for aviation.

Keywords: aviation, energy transition, cryogenic fuels

INTRODUCTION

The air traffic is expected to grow at a rate of approximately 5% per year for the next couple of decades (Airbus, 2017), implying that numbers of aircraft will double every 15 years. As a result, the environmental impact of aviation will increase significantly. Moreover, whereas surface transportation systems are able to reduce their CO_2 and other emissions significantly, thanks to the increased use of electric/hybrid vehicles, the aviation sector is restricted in the energy source. The European Advisory Council for Aeronautical Research and innovation in Europe (ACARE), has set challenging goals for reducing the environmental impact of aviation. Targets for the year 2050 include a 75% reduction of CO_2 emissions per passenger kilometre and a 90% reduction in NO_x emissions. These targets are relative to the capabilities of typical new aircraft in 2000 (ACARE, 2011).
One of the other main challenges for future aviation is the energy source. Currently, aviation consumes around 1.1 Billion litres of Jet Fuel every day and it is anticipated this would increase by 3% every year despite the improvements in aircraft efficiency. On the other hand, the oil reserves are depleting, thus creating a discrepancy in the supply and demand which will lead to an increase in the fuel cost. This increase in fuel cost has already increased the fuel share in the total operating cost of an airline to around 30% to 40% (IATA, 2010). Further increase in fuel prices would have disastrous consequences for airlines. Therefore other means of releasing energy to drive the aircraft engines will have to be tapped.

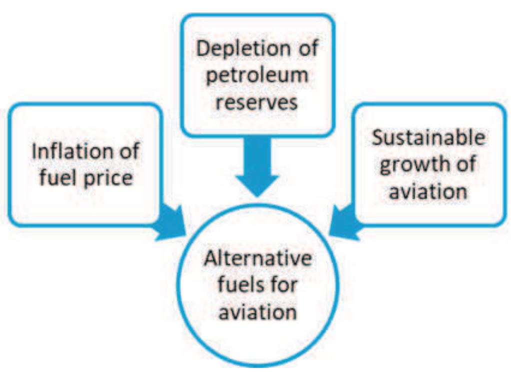

Figure 1. Motivation of alternative fuels for aviation.

LIQUEFIED NATURAL GAS AND LIQUEFIED HYDROGEN AS FUELS

Thus if aviation has to maintain its growth then the problem of energy source for aviation has to be solved first. Some analysts have high hopes on biofuels however there are serious problems with biofuel which include; scaling of production, fuel consistency, availability of biomass, conflict with the food chain, high price, competition with surface transport, unavailability of subsidies in aviation, etc. Therefore biofuel can be a part of the solution but not the solution itself.

There are several criteria in selecting a fuel for aviation. One of the main criteria is the energy density, as reducing weight and volume is of paramount importance for aviation. Both Specific Energy Density (SED, amount of energy per unit mass of the fuel) and Volumetric Energy Density (VED, amount of energy per unit volume) is important in this regard. Fig. 2 shows several fuels/ energy sources in terms of their SED and VED (Gangoli Rao et al, 2014). It can be seen that Jet-A / kerosene has good SED and VED and therefore is suitable for aviation. It can also be seen that LH2 has high SED but a poor VED, implying that we would require a huge volume to carry any reasonable amount of hydrogen. The main advantage of carrying LH2 is that there is no CO_2 emission from the combustion of fuel. The engine will emit water vapour and some amount of NO_x as exhaust. Researchers have shown that there are several positive effects of using LH2 for aviation on the environment. At present LH2 production is expensive and not environmentally friendly; however as we move towards a hydrogen-based economy by utilizing renewable energy sources, the price of hydrogen is expected to reduce substantially. The recent future energy scenario from Shell (Sky Energy Scenario (Shell Scenarios, 2018)), lays out a roadmap for the usage of hydrogen in various sectors in order to meet the Paris Climate goals (UN, 2015). Hydrogen can be produced from renewable energy and is seen as a long term fuel for aviation (Rondinelli, 2014). But using LH2 in aviation has several challenges including large volume required for fuel storage, safety, logistics, passenger perception, etc, as investigated in the Cryoplane Project (Slingerland, 2005).

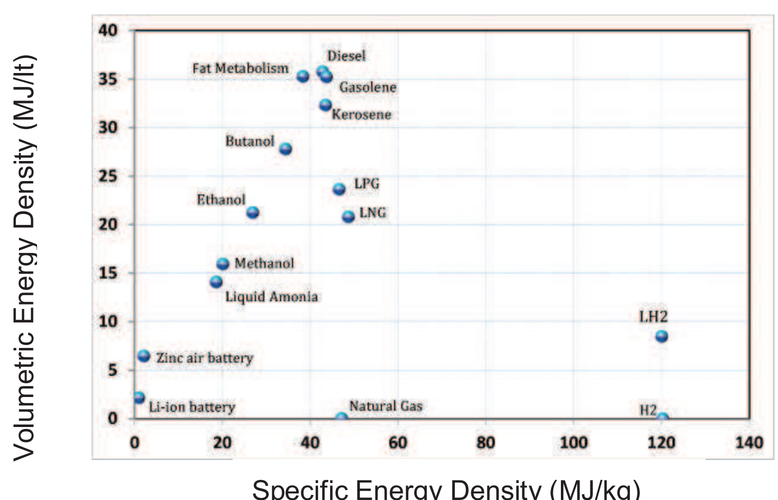

Figure 2. Comparison of various energy sources for aviation

From Fig. 2 it can also be seen that LNG is in between kerosene and LH2, both in terms of SED and VED. Currently, LNG is one of the cheapest fuels available (Nicotra, 2012). The gas reserves in the world are enormous, especially with the discovery of shale gas, thus implying that LNG prices would be stable. LNG is one of the cleanest fuels and recently it has been proved that LNG can be generated by using renewable energy. Due to a higher energy density than kerosene, using LNG can reduce the amount of fuel that needs to be carried on board. Moreover, being a low carbon fuel, burning LNG or LH2 will reduce the CO2 emission significantly. Some of the advantages and disadvantages of using LNG is summarized below.

There are several criteria for fuel selection in aviation. The table below gives a simplistic comparison of different energy sources. It can be seen that apart from emissions, there are really no other disadvantages of kerosene and that is why it is widely used. It can also be seen that LNG has several advantages as compared to other fuels/energy sources (apart from kerosene).

Parameter	Kerosene	Biofuel	Syn-Ker	Batteries	LNG	LH2
Energy Density	+	+	+	- -	+	+ +
Vol. Density	+ +	+ +	+ +	- -	+/-	-
Emissions	- -	+	+	+ +	+	+
Cost	+ +	-	- -	+	+ +	-
Availability	+ +	-	- -	- -	+	+/-
Infrastructure	+ +	-	- -	+/-	+	-
Safety	+	+	+	-	+/-	- -
Compatibility	+ +	+ +	+ +	-	+/-	-
Policy	-	+	+	+	+/-	+

Advantages of LNG

- Lower fuel weight compared to kerosene.
- ~25 % reduction in CO_2 emission.
- > 60% reduction in NOx and particulate emissions.
- Usage of the cryogenic heat sink can increase engine thermal efficiency.
- The LNG is substantially cheaper than conventional jet fuels.

Disadvantages of LNG

- Requires pressurized tanks for storage resulting in increased aircraft Operating Empty Weight (OEW).
- Requires insulation to keep the fuel cool, increasing aircraft OEW further.
- Increased storage space for LNG compared to conventional jet fuels.
- Airport facilities and logistics for tanking LNG are required.

Using natural gas as a fuel is not a problem for the engine as natural gas is a clean fuel and can be burnt in a premixed or partially premixed mode. This substantially reduces the NOx formation within the combustor when compared to kerosene. However, an additional heat exchanger has to be used for evaporating the LNG to natural gas. Since LNG is a cryogenic fuel and therefore a good heat sink, it can be used in a beneficial manner to enhance the thermodynamic efficiency of the engine for intercooling, bleed cooling, air-conditioning, etc (van dijk et al, 2009). Using the cryogenic fuel for cooling the bleed air used for turbine cooling was found to be most beneficial with SFC reductions in the order of 6%.

AIRCRAFT DESIGNS USING CRYOGENIC FUELS

A Multi-Fuel Blended Wing Body (MF-BWB) aircraft was designed in the AHEAD project. The aircraft uses LNG and Biofuel as energy sources (shown in Fig. 3). The fuel is stored in cylindrical insulated tanks within the fuselage of this aircraft and the biofuel is stored in the wings. The energy ratio between the two fuels is around 75-25.

Figure 3. The Multi-Fuel Blended Wing Body investigated in the AHEAD project.

The Multi-Fuel aircraft requires a new type of engine can burn two different types of fuels. The engine that was investigated and designed within the project is shown below. The main features of this engine are:

Multi-fuel Capability:

One of the primary requirements of the multi-fuel BWB aircraft propulsion system is the capability of using multiple fuels. The engine features two combustion chambers, one in between the high pressure compressor and the high pressure turbine which uses the cryogenic fuel, and the other in between the high pressure turbine and the low pressure turbine that uses biofuel (Gangoli Rao, 2015; Yin et al, 2018).

Low Emissions:

The combination of these fuels reduces CO_2 emission. The vitiated products of combustion from the first combustor enables the usage of flameless combustion technology in the second combustion chamber, thereby reducing the NOx emission substantially (Levy et al, 2012).

Bleed Cooling:

The cryogenic fuel is used to cool the turbine bleed cooling air. This is done by a cryogenic heat exchanger in which the compressed air from the last stages of the compressor is extracted to heat up the cryogenic fuel. The colder bleed air is then used to cool the high pressure turbine blade. This process reduces the amount of air required for turbine cooling air substantially and increases the performance of the engine (Yin et al, 2018).

The first combustion chamber (located between the HPC and HPT) burns cryogenic fuel (such as liquid hydrogen/liquid natural gas) in a vaporized state, whereas, the second combustor is an Inter-stage Turbine Burner (ITB) and uses kerosene/biofuels in the flameless combustion mode. Since the flammability limit for Hydrogen / Methane is wider than for kerosene, the combustion in the first combustion chamber can take place at very lean conditions and is beneficial from NOx emission perspective (Reichel et al, 2015). A combustor capable of working on H_2 was designed within the AHEAD project and was demonstrated at atmospheric conditions by the group of Prof. Paschereit (Reichel et al, 2018).

Using Hydrogen / Methane in the first combustion chamber increases the concentration of water vapour and reduces the oxygen concentration within the gases, thereby creating a high temperature vitiated environment at the inlet conditions at the Inter Turbine Burner (ITB). This is beneficial to obtain Flameless Combustion (FC) which takes place at low O_2 concentration and high temperatures (above the auto-ignition temperature of the fuel). This helps to minimize emissions of CO, NOx, UHC, and soot (Perpignan et al, 2018; Perpignan et al, 2018)

The initial results are promising as the CO_2 emission can be reduced by more than 50% when compared to B777-200 ER for a long-range mission (>10,000 km). The climate impact of such an aircraft was evaluated in detail and it was found to be substantially lower than a conventional aircraft (Grewe et al, 2017). The operating cost is also lower by 20-25% due to the lower cost of LNG. The CO_2 emissions can be further reduced by using LH2 instead of LNG.

A group of students worked on the design of a Multi-Fuel A320 class of aircraft for short and medium-range mission (Fig. 4). The results showed that the operating cost and emissions from the aircraft can be reduced substantially when compared to a conventional A320 aircraft. The operating cost was reduced by 10% due to lower emissions and cheaper fuel (Cont et al, 2014).

Figure 4. A Multi-Fuel A320 class of aircraft with podded LNG tanks and open rotors designed by students at TU Delft.

The mission of the aircraft is shown in Fig. 5. LNG is used as a fuel in the LTO (landing – takeoff) cycle and in the climb and descent phase. This is done to reduce the local pollution around the airport (soot, CO_2, NOx, UHC, VoC, etc) while in the cruise phase, kerosene is used in order to limit the emission of water vapour, which can lead to contrail formation. However, the main advantage of using such a multifuel configuration is the flexibility to use the aircraft in places were LNG is not available.

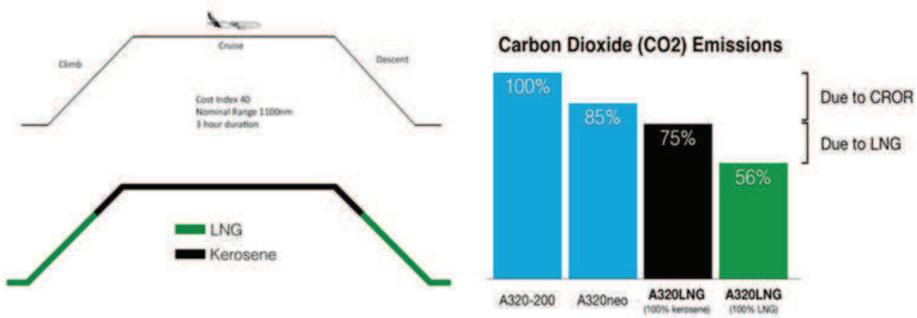

Figure 5. Mission and CO_2 emission reduction from the hybrid A320 class aircraft using LNG and kerosene on a typical mission

Both LNG and LH2 can offer several advantages as an alternative fuel for aviation, the logistical challenges and the high aircraft development cost are the main hindrances. However as the society will demand lower emissions from aircraft in the future (with the enforcement of the Emission Trading Scheme) and as the fuel will become more expensive in future, the breakeven point for switching over to a new fuel will become viable.

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