ENVIRONMENTAL, ECONOMICAL AND TECHNICAL ASPECTS OF A CRYOPLANE IN THE PRELIMINARY DESIGN PHASE

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Abstract

Transferring to Liquid Hydrogen as aviation fuel, if produced on the basis of renewable energy, has the potential to reduce the contribution of aviation to the anthropogenic greenhouse effect.

This potential caused a renewed interest in the possibility to fly on hydrogen.

Based on the preliminary designs of three aircraft categories with high "fuel volume to payload volume" ratio, the influence of the properties of liquid hydrogen on the aircraft design and performance was investigated.

The designs were restricted by conventional configurations and it was preferred to be designed with a minimum change philosophy.

By designing a kerosene-powered and a hydrogen-powered aircraft based on the same design specifications for each category a fair comparison can be made on Direct Operating Cost, Performance and Environmental impact.

Comparing the designs of the three different categories made it possible to do a first exploration on the existence of designer rules for CRYOPLANE designs.

Introduction

Kyoto's agreement by the Ministers for the Environment in 1998 called for a reduction in the frame 2008-2012 to 95% of emission in 1990.

While continuous Civil Air Traffic growth of 4,5% per year for the next decades is predicted.

Progress in fuel efficiency due to technological advances in conventional engines is not enough to reduce the emission of Greenhouse gases. The theoretical potential for reduction of emissions in conventional engines is expected to be 2%. Hence, with the expected rate of growth of Civil Aviation of the 4,5%, the emissions of CO_2 would rise at a net rate of 2,5% per year.

Transferring to Liquid Hydrogen as aviation fuel, if produced on the basis of renewable energy, has the potential to reduce this contribution of aviation to the anthropogenic greenhouse effect.

But today's price of liquid hydrogen is much higher than of kerosene.

Although the actual reserves of crude oil are predicted to be enough for the next century, the production peak is expected to be reached in the next decade, due to the exhaustion of the easy access deposits.

Therefore it is expected that the decrease in oil-reserves and increase in hydrogen production will decrease the price difference dramatically.

Because of the fact that half of the world reserves are located in the Middle East countries, representing a high potential risk of instability at the time of making mid/long term predictions, or political intervention may cause the break-even point between the direct operating cost of a kerosene-powered and hydrogen-powered aircraft to be reached sooner.

These three statements caused a renewed interest in the possibility to fly on hydrogen.

Therefore this work was done as a part of "The CRYOPLANE project", supported by the European Committee.

Based on the preliminary designs of three aircraft categories with high "fuel volume to payload volume" ratio, the influence of the properties of liquid hydrogen on the aircraft design and performance was investigated.

The used categories were:

- Long range aircraft (380pax.,8500nm)
- Very large long range aircraft (550pax., 8500nm)
- Executive jet (12 pax., 3500 nm)

The designs were restricted by conventional configurations and it was preferred to be designed with a minimum change philosophy.
By designing a kerosene-powered and a hydrogen-powered aircraft based on the same design specifications for each category, a fair comparison can be made on Direct Operating Cost, Performance and Environmental impact.
Comparing the designs of the three different categories made it possible to do a first exploration on the existence of designer rules for CRYOPLANE designs.

Hydrogen as a fuel for aviation.

A new aviation fuel must satisfy safety requirements, environmental compatibility and high energy content per unit of mass. Also its production has to be based upon a renewable energy.

Hydrogen offers 2,8 times the energy content per unit of mass of kerosene. It can be produced by electrolysis of water by addition of electricity, which can be obtained from any renewable energy (hydropower, wind energy, byomass, etc…), and when Hydrogen is burned, the main product of the combustion is water, then the cycle is closed.

The major disadvantage is that Hydrogen has a low ratio of energy to volume, and for aviation it has to be cooled down to cryogenic temperatures to reach it's liquid state: -253° C. This places high demands on technologies for production, storage and distribution.

Hence, using Liquid Hydrogen (LH_2) in an aircraft leads to:

- Four times greater volume for the tanks than kerosene.
- Very good insulation of tanks, pipes, pumps.
- Tanks under more than 1 bar to avoid oxygen coming in.
- Spherical or cylindrical tanks to minimize the isolation and structural weight.
- New aircraft configuration. Kerosene-fueled aircraft carry their fuel in wing tanks; this will not be possible with LH_2.

Safety.

The introduction of a new fuel in aviation will be possible only in the case that the safety aspects of the new fuel, LH_2 in this case, can satisfactorily fulfill the safety standards of the actual fuel in use.

Liquid Hydrogen burns much faster than kerosene, but with a lower radiation heat and without making a fire carpet, as the kerosene does. LH_2 doesn't explode in open air, only in a confined space, so special attention has to be paid to the design of the fuel system, making vents, security valves, etc., to prevent leakage into the passenger cabin.

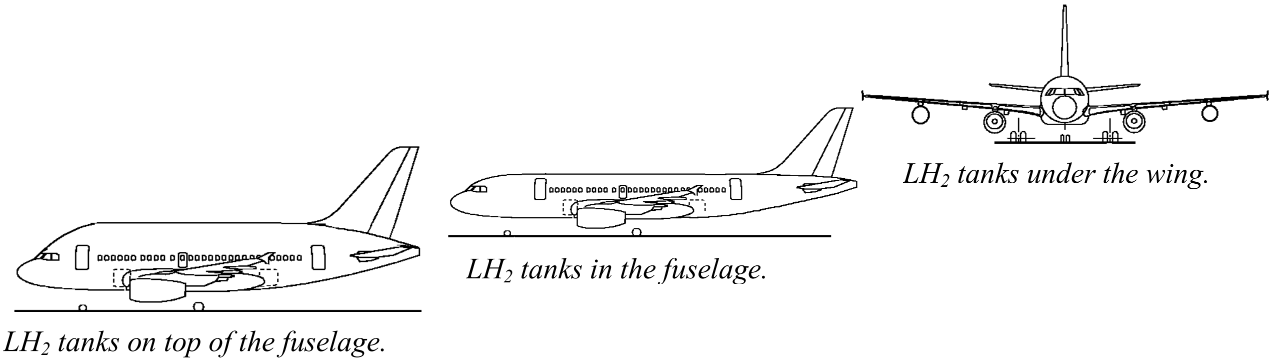
Studies reveal that passengers would have greater survival possibilities after a crash if they remained in the cabin and waited for the fuel to burn outside the aircraft. This will require changes in airworthy requirements.

Conventional aircraft configurations

How to store approximately 4 times as much fuel under pressurized, extreme cold conditions?

This is the main technical challenge in designing a CRYOPLANE.

The fact that a CRYOPLANE needs to store approximately 4 times the amount of fuel compared to a kerosene aircraft with the same design payload-range will deliver a larger aircraft for the CRYOPLANE and therefore the Operating Empty Weight (OEW) increases and also the drag caused by the wetted area.



LH_2 tanks under the wing.

LH_2 tanks in the fuselage.

LH_2 tanks on top of the fuselage.

Fig. 1 Conventional CRYOPLANE configurations

The fact that the density of liquid hydrogen is less than a tenth of the density of kerosene caused that the total fuel weight is only a 30 to 40% of the required kerosene fuel weight. This results in a decrease in MTOW.

In fact the ratio "Operating Empty Weight over Maximum Take Off Weight" appears to be almost constant. Namely OEW/MTOW=0.68.

Minimizing the physical dimensions of the CRYOPLANE minimizes the wetted area and the structural weight of the standard airframe structure, but it might increase the structural tank weight considerably if an "off-optimum" shape for a pressurized vessel is necessary.

In previous studies you find three configurations for CRYOPLANE based on modifying an existing kerosene design. These configurations are shown in Fig. 1.

These previous studies were mainly based on changing existing short or medium range kerosene aircraft into a CRYOPLANE. These aircraft categories have a typical "Fuel volume over Payload volume" ratio (up to 15%) and a typical "tanks on top of the fuselage" configuration as long as the cockpit-cabin connection is kept. The "tanks on top of the fuselage" solution is most times combined with a tank after the rear bulkhead in the fuselage.

When considering the typical "Fuel volume over Payload volume" ratio varying from 25%, the required tank volume also significantly drives the fuselage-design. Typical examples of this high ratio category are long-range wide bodies (For example Airbus A340, A380 and Boeing 747-400 and 777) and business jets.

The optimum tank layout for these aircrafts is tanks in the fuselage. In case of a wide body fuselage tanks in the front and rear are optimal, while taking the cockpit-cabin connection into account. (Fig. 2.) For business jets flying on hydrogen, tanks in the rear only are the best solution.

Besides the standard increase in the required fuselage volume, other more common geometrical drivers cause these different tank layouts.

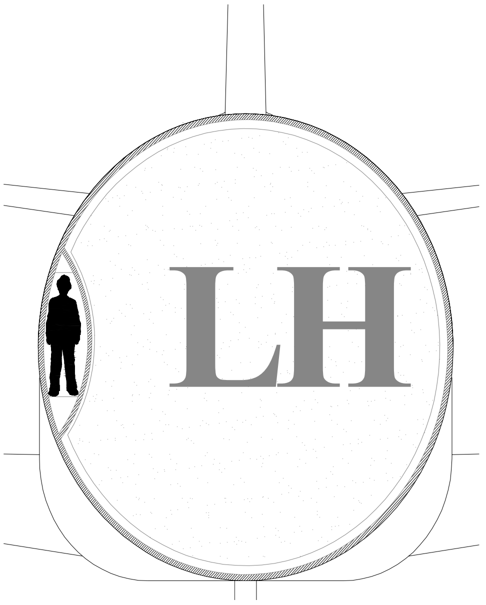


Fig. 2 Cross-section front tank 380 pax aircraft

These drivers for the different aircraft categories are:

- 80m.x80m.x80ft box
- Cockpit-cabin connection
- No tanks in disk burst areas
- Fuselage fineness $5<(H_f/L_f)<15$
- Fuselage shape factor $(H_f/W_f)<1.8$

These boundaries cause more exotic layouts.
For example the 80x80x80 box forces a wide body fuselage earlier in a multiple deck layout and the cockpit connection forces a single aisle fuselage in a tank on top layout.

The secondary effects of flying with a larger fuselage might be, when comparing to a kerosene design, larger engines.

The fuel consumption per passenger mile increases with 10 up to 35 %. The increase is mainly dependent of difference in fuselage size between a payload only fuselage and a fuselage storing the hydrogen and the payload. By this size-difference the required throttle-push might require larger engines, which cause additional fuel consumption.

In relation to a high "Fuel volume over Payload volume" ratio the aircraft is very sensitive for a total redesign of the fuselage.
For example the fuselage diameter of a 12 pax 3500nm business jet is mainly driven by the required amount of fuel which need to be stored in the fuselage. As a result, the diameter is increased with almost a half meter, as shown in Fig.3. The final increase in fuel consumption is 35 %.

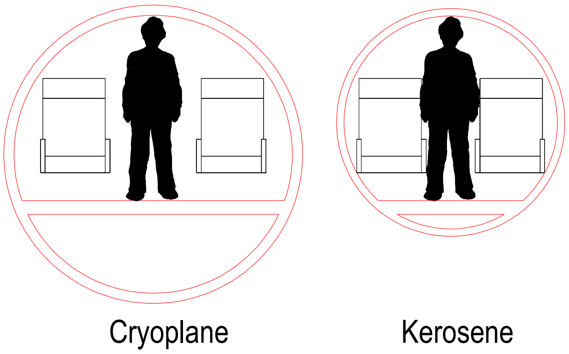


Fig. 3 Change in fuselage diameter for the CRYO business jet

Economics.

With today's prices the competitiveness of Hydrogen and kerosene is not feasible. LH_2 produced from renewable sources is too expensive, and even the lowest prices quoted today are well above actual low price of untaxed kerosene.

Nevertheless, it is expected that in short/medium term, kerosene will be taxed to the same amount of other fuels, whether for ecological reasons or due to the depletion of cheap crude oil.

Hence, in the short term, LH_2 could be made competitive through administrative measures, and in long term the expected improved technology for it's production and the mass production as a direct result of global use will make the trend favorable for the LH_2.

Maintenance costs of the complicated fuel system are expected to be higher than for a conventional kerosene aircraft, due to the extreme conditions of the LH_2. However the benefits of the increment in payload will compensate this penalty.

Therefore if it is assumed that the price per energy content for kerosene and hydrogen would be the same (= the price of 4 gallon Hydrogen is equal to 1 gallon kerosene) the increase in DOC is expected to be between 3 and 5% more. Therefore the break-even point for operating a CRYOPLANE is up to 5 years after the break-even point for the fuel prices. It is expected that this DOC break-even point is around 2040.

Environmental compatibility.

When kerosene is burnt in an aeroengine the primary products of the combustion are water and CO_2. In addition, several other products appear, like CO, soot, unburned HC, SO_x and NO_x. This is totally undesired due to their contribution to the Greenhouse effect.

When LH_2 is used, the only primary product of the combustion is water, hence no CO_2 is produced, and none of the others, except for the NO_x, which is an indirect result of the presence of N_2 in the air. But, as it has been said, the amount of NO_x can be drastically reduced by a proper design of the combustion chamber.

It has to be taken into account that the amount of water produced by an engine running on LH_2 will be considerably higher than for a kerosene engine. The time of residence of the water at those altitudes is hundred times lower than that for the CO_2, which is nearly 100 years.

At this moment the relation between contrails and cloud forming is investigated. The final result might influence the final verdict over the environmental friendliness of CRYOPLANES, but at this moment no direct link is proven.

The formation of contrails is another aspect that should be investigated, not many data is available about this fact. The presence of contrails at those altitudes could contribute to the Greenhouse effect, but the formation of these contrails is not yet fully clear.

Contrails appear at certain altitudes attending to thermodynamic conditions, pressure and temperature, but they appear when the presence of condensation nuclei is sufficiently high. These nuclei are formed due to the presence in the surrounding air of particles of dust, SO_x, soot, etc., and as the LH_2 does not produce them, contrails' formation and their effect to the global warming are not clear.

But at this moment it is believed that trading the CO_2 emission for H_2O vapor does not influence the environment in a negative way.

Conclusions.

Liquid Hydrogen is a very promising solution for a new fuel for aviation. It can be obtained through electrolysis of water on the basis of a renewable energy and its effect on the atmosphere has a low impact. Hence it fulfils the two primary requirements to substitute kerosene; it is environmentally clean and constitutes an infinite source of energy.

Storing all the hydrogen in or on the fuselage is the best solution for designing a CRYOPLANE. Storing Hydrogen under or in wings is only interesting for minimal modification of an existing design. A tank after the rear bulkhead in the fuselage is a very effective solution, which is easy to combine with all the other tank layout options.

For making a preliminary design of a CRYOPLANE the constant factor for OEW/MTOW=0.68 can be assumed for the first weight calculations.

The increase in fuel consumption is strongly dependent of the fuselage design.

The fuselage design of a CRYOPLANE is finding an optimal solution for payload and fuel storage.

CRYOPLANES are expected to become economical interesting around 2040 without political interference.

The replacement of CO_2 emission with H_2O appears to be also more environmental friendly at higher altitudes.

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