POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

On the Scalability of Liquid Hydrogen Propulsion for Commercial Aviation

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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Academic year: 2021-2022

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1. Introduction

The aim of this thesis is to assess the points of strength and weakness of a hydrogen-based commercial aviation, both from the point of view of the magnitude of energy supply required and the efficiency of hydrogen-burning aircraft. This assessment is done through the quantification of specific Key Performance Indicators, chosen specifically not only to reflect actual performance of current airliners, but also to allow the comparison with novel, hydrogen-based, solutions.
The introductory chapter is dedicated to an extensive literature review that ranges from the actual market of commercial aviation to the new emerging trends of hydrogen production. As the market results to be governed at 95% by two main products, the Narrow-Body (NB) and the Wide-Body (WB) model, it had been chosen to in-deep explore these two segments. Throughout the work, multiple exemplars of hydrogen-based concept aircraft are presented thanks to the MATLAB program HYPERION, a preliminary aircraft sizing software developed by the DAER of Politecnico di Milano. The variants proposed are then compared with similar concepts found in literature.

2. Hydrogen Production

Global aviation actually accounts for 3% of worldwide CO_2 production, with 920 million tons produced in 2019, the year before the Covid-19 pandemic outbreak that wreaked doubtless havoc to commercial aviation. It may not seem to be so much thinking about the capabilities of a modern aircraft, but in 2020, the year after, hydrogen production emitted quite the same amount of CO_2. [6, 8]. In 2020 87 million tons of hydrogen were produced and today is mostly used to make ammonia or in refineries: the 97% of global worldwide production exploits methods that produce between 9 and 12 kgCO per kgH_2 just by chemical reaction itself. Academic literature categorizes hydrogen production according to colors, each of which reflects different processes that need specific resources and produces different side products. Today the market is mainly covered by the darkest shades of the palette (Black, Brown Gray,...), while in the future a vast adoption of the shiniest side of the pattern (Green, Blue, Turquoise,...) is expected, obviously not without any trade. The best option in terms of emissions are Green and Turquoise Hydrogen, as they exploit electrical power to split molecules of water or methane without any carbon output in the process. Despite their sustainability however there is an intrinsic problem that limit their adoption. Hydrogen has the highest energy output per unit mass among every natural compound whereas water and methane are very stable molecules: in order to pair this energy difference incredibly huge amount of electric energy have to be spent in order to break bonds between atoms in such molecules. Literature [7, 10] discuss state-of-art and novel configuration, but generally 50 kWh/kgH_2 are needed for water electrolysis (Green Hydrogen) and between 10-15 kWh/kgH_2 for Methane Pyrolisis (Turquoise Hydrogen). The real threat to a hypothetical hydrogen adoption by commercial aviation indeed resides in the amount of energy required, coupled with the enormous hydrogen quantity needed, for a sustainable hydrogen-based value chain. Moreover it is recalled that Hydrogen is exploited in liquid form in proposed aircraft due to space and mass constraints, increasing so the electric energy base load.

3. Hydrogen Supply

Hoelzen et al. [4] depicts various hydrogen airport demand scenario by 2050, while Sens et al. [11] propose a techno-economic well-to-tank assessment of various hydrogen supply chain, each of which based on water electrolysis as production method.

Combining the results from these two articles it is found that: considering the best case efficiency proposed by Sens et al. (around 55% = 60.60 kWh/kgLH_2) for liquid Green Hydrogen supply, a medium airport (like Hamburg) would need between 1.3% and 2.8% of the France highest ever Annual Nuclear Energy Power Output (379.5 TWh) in order to produce, liquefy and provide the quantity of hydrogen required for operations. For a large airport, like Frankfurt, the share sky rises between the 5% and 15%. It is also remarked that in airport demand analysis from [4], only Regional and NB aircraft were considered. While in the second analysis, Sens et al. focused only water electrolysis as the main hydrogen production method. If to the 60.6 kWh/kgLH_2 global value is subtracted the energy for electrolysis and is added the energy for pyrolysis, this would instead result in 20-30 kWh/kgLH_2: funding the provision so on Turquoise Hydrogen would results in aforementioned metrics referred to France Nuclear Output to be at least halved.

4. Aircraft Design

Proposing Liquid Hydrogen as the founding chemical for aircraft propulsion is not a trivial matter: several heavy modifications must be applied from the methods of aircraft conceptual design up to the proper sub-system layout, without however deviating too much from current certification policy. Actually the aviation most popular fuel is Jet-A, a kerosene-based blend fuel specific for gas turbine-powered aircraft: one liter of this fuel has the same energy content of roughly four liters of LH_2, but the latter is 2.7 lighter in mass with a reduction of 65% referred to actual Jet-A. Starting from combustor technology, literature seems pretty well furnished, as Micromix combustion principle has been analyzed from Aachen University since the end of '90 [3]. In this combustion principle the fuel stream is injected in gaseous state perpendicular into the airflow and it burns without premixing: it forms a multitude of miniaturized diffusion-like flames, which reduce retention time of NO_X precursor and boosts power output per injector. This enables a leaner combustion reaction and Osigwe et al. [9] claim that this results in a +15% extended turbine blade life. In **Figure 1** a 3D rendering for can-combustor Micromix integration is showed.

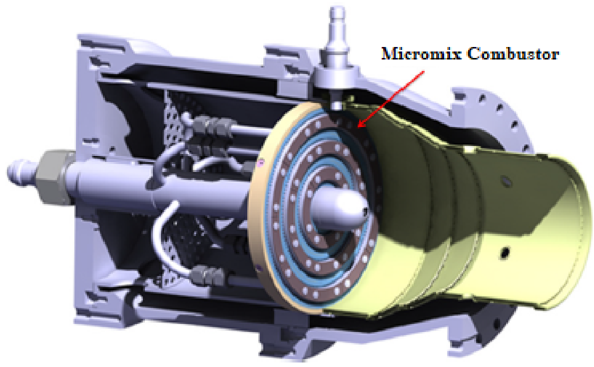

Figure 1: Micromix Can-Casing integration from [3]

It must be however recalled that Hydrogen has a Boiling point of 20.28 °K (-252.87 °C) and requires really big, heavy and technologically advanced tanks. One of the most important KPI regarding tank sizing is Gravimetric Index (GI) defined in **(Equation 1)** which reflects the mass penalty due to tank as it has to be added to the Operative Empty Mass: this value may vary a lot depending on tank volume and shape but Hute et al. [5] confirm that the GI for aviation tanks may exceed 60%. The latter moreover assess that optimum tanks are those with maximum diameter that can be inscribed into the fuselage and that the latter metric is the most important parameter that govern the GI.

$$\eta_{\text{Grav.}} = \frac{M_{\text{Fuel}}}{M_{\text{Fuel}} + M_{\text{Tank}}} \tag{1}$$

Generally a NB aircraft with 180 passengers contains roughly 15 ton of jet-fuel at full cargo enabling at least 4000km of range: considering a GI=60%, a tanked filled with LH_2 that has the same energy content would weight between 9-9.5 tons, but the volume would be more than 4x times more extensive. In addition the thickness of such advanced cryogenic tanks should be also considered. As the fuselage diameter of a NB model stands between 3 and 4 meters, the order of magnitude of tank encumbrance would be more than 6 meters of fuselage length. If the aim is to carry the same number of passengers for the same nominal range, this will lead so to a fuselage lengthening, inducing additional mass to Airframe and OEM that may overcome the mass saving due to hydrogen adoption and requiring so indeed more energy to carry the same dry mass. Another effect to consider is that less mass is lost during flight so range is intrinsically less enhanced: as the OEM increases due to tank accommodation and fuselage lengthening also the landing mass would probably be a structural problem not trivial to settle. As a matter of fact, the design optimization process would require peculiar effort.

5. Narrow-Body Design

As the NB model constitute more than 60% of the global active fleet [15], a conceptual design of a hydrogen-based NB aircraft should perform at least the same mission with the same energy in order to be competitive on the market. Specifically, parameters as Cruise speed, Nominal Range and Nominal Payload must be equal to current top-of-the market exemplars. In HYPERION software is chosen firstly to model the actual A320 family, with special attention to the A320-200 variant, in order to have a reliable comparison with current technology. Then, for hydrogen concepts design it's chosen to impose the design mission of the A320 figured in **Table 1** and constrain the Non-Propulsive Airframe (i.e. The dry mass of the Aircraft without the engines) equal to that one of A321-200, as it offers a fuselage 7 m longer than the A320 and may have enough room for a potential cryogenic tank.

	Design Mission
Nominal Range: [km]	4000
Seats:	180
Cruise EAS: [m/s]	138.9
Mach Cruise Number:	0.79
Cruise altitude: [km]	9.8

Table 1: Input NB design mission

Since initial results didn't seem satisfactory for hydrogen concepts, it was deemed necessary to explore various propulsive equipment that reflect current aircraft turbofan state-of-art.
For hydrogen-based models it has been decided to reproduce through HYPERION the performances of two high-bypass geared turbofans: the IAE V2500 and the PW1100G. Their parameters are resumed in **Table 2**.
It was introduced also a qualitative sensitivity analysis on payload and range augmentation for the NB model and the results is that hydrogen powered-aircraft would be more sensitive to payload variation rather than range augmentation, as for the former it must be accounted a wider

	BPR6	**BPR9**	**BPR11**
BPR	6	9	11
FPR	1.5	1.5	1.5
LCP	1.0	1.0	1.16
HCP	23.0	23.0	23.0
OPR	34.5	34.5	40.0
TIT °K	1280	1280	1280

Table 2: Propulsive Performances proposed for hydrogen concepts

fuselage length variation compared to the latter due to additional tank length and row placement.
Regarding literature benchmark, the three model presented seem pretty competitive when referred to similar design concept; this is probably aided by the fact that they result with the highest GI overall. **Table 3** shows the comparison between the best model found on literature, referred to the name FZN-1E, a NB concept from Aerospace Technology Institute of UK, and the best model proposed in the work, that one mounting the PW1100G referred to the name LH2BPR11.

	BPR11	**FZN-1E**
Passengers:	180	=
Nominal Range: [km]	4000	+12.5%
MTOM:[ton]	74.9	-5.6%
OEM: [ton]	50.5	-5.0 %
LH2 Mass: [ton]	4.7	-32 %
GI: [%]	67%	-7pt
ESFC: [kW/kN]	0.545	+3.3%
SEU: [kWh/pax km]	0.22	-40%
RWE: [-]	1.37	+54%
Overall Efficiency: [%]	44%	-3pt

Table 3: Percentage difference between the two best models on the benchmark

6. Wide-Body Design

For the Wide-Body segment, it has been chosen to take as reference the A350 family as starting point. Thereafter it had been carried out a hydrogen counterpart, based on the retrofit of the A350-900. Literature is indeed varied on the subject as there have been found different contrasting sources on hydrogen impact on WB aircraft design: for instance Verstraete et al. [13, 14] suggest that the for long-range the overall fuel mass saving would lead to approximately 12% increase in energy efficiency and 11% decrease in energy utilization. McKinsey [1] instead suggest a 43% block energy increase, due principally to the considerable OEM increment. In the work it is proposed first a sizing routine for a jet-fuel based that reproduce actual performances of A350-900, then it has been decided to propose a retrofit of such model in order to explore the capabilities for a long nominal range. Mission design parameters are summarized in **Table 4**.

	Design Mission
Nominal Range: [km]	10800
Seats:	332
Cruise EAS: [m/s]	138.9
Mach Cruise Number:	0.79
Cruise altitude: [km]	10.6

Table 4: Input WB design mission

The retrofit extends the design space offered in literature as the majority of concepts found are based, due to tank encumbrance, on the A380-800. The design philosophy is based on the airframe constrained to the Jet-Fuel counterpart and the objective is to find the best trade off between room available for tank and seat accommodation for the same Nominal Range. After a iterative process, the A350 cryogenic-hydrogen retrofit results in 100 less passengers seats and a payload 30% lighter in order to accommodate a 12.9 m long cryogenic hydrogen tank. This obviously impacts dramatically the KPIs regarding energy consumption and utilization. The configuration led to a energy mass saving of more than 60 tons, but a fuel volume of more than 330 m^3, three times more when referred to Jet-Fuel model, and figures of merit do not frame a nice situation as in the NB design. In **Table 5** are summarized the most useful KPIs, trivially favouring the Jet-Fuel model.

	LH2WB	**A350**
MTOM:[ton]	210.7	+34%
Passengers:	232	+43%
OEM: [ton]	149.6	-5.0 %
On-Board Energy: [MWh]	788	+31% %
ESFC: [kW/kN]	0.590	+7%
SEU: [kWh/pax km]	0.314	-9%
RWE: [-]	1.40	+10%
Overall Efficiency:	38%	40%

Table 5: Percentage difference between the proper A350 and its hydrogen retrofit

The energy supply required for the hydrogen provision for this model is unbelievably high: 1.4 MWh for only one liquid full hydrogen tank. This model burns roughly 1.8 tons of hydrogen per hour, producing more than 16 tons of water per hour. In order to provide stably the quantity of liquid hydrogen needed for this aircraft, for each hour of flight there must be a renewable electric power plant on the ground running at 111MW of power, which produces only the electricity required for hydrogen production (by water electrolysis), liquefaction and dispatch. Thanks to Turquoise hydrogen, it is recalled that energetic metrics are roughly halved.

7. Conclusions

The wind turbine HALIADE-X, from GE Renewable[2], is taken as reference in order to frame the order of magnitude of equivalent electric consumption: it is a 220 m diameter offshore wind turbine of which best variants reach 74 GWh of AEP and a Nominal Power of 14 MW (Capacity Factor = 60%). In **Table 6** metrics of consumption according to a Green Hydrogen based supply are figured for three variants explored, two NB and the WB retrofit. The EPI is the Equivalent Power Installed: refers to the equivalent energy per hour that is needed to produce, supply an liquefy the amount of burning LH_2. The $kgCO_2e/kgH_2$ are put equal to 11.88 according to [12]. As the chemical oxidation of hydrogen is enhanced within the combustor is assumed a combustion efficiency close to one, so the water vapor mass exhaust is close 9:1 ratio referred to hydrogen burnt. If the methane pyrolysis (Turquoise Hydrogen) had been exploited energy consumption metrics would be roughly halved.

LH2 model:	BPR 6	BPR 11	LH2WB
Cruise thrsust: [kN]	53	53	110
LH_2 per hour: [t]	1.2	0.9	1.8
H_2O per hour: [t]	10.5	7.8	16.4
CO_2 per hour if SMR: [t]	13.8	10.2	21.5
EPI @55% Eff.: [MW]	71	53	111
Equivalent turbines @Max:	6	4	8
Equivalent turbines @60%CF:	9	7	13
Full tank refilled per year:	187	259	52

Table 6: Consumption metrics of concepts explored:

Regarding the state-of-art of specific components needed for cryogenic hydrogen accommodation within the aircraft, literature offers a plenty of optimistic studies that continue to confirm the feasibility of the concept. Cryogenic hydrogen tanks are nowadays commonly spread all over the world, and hydrogen-powered Gas Turbines are almost ready to be tested in operational environment. Thanks to HYPERION software, two of the most popular aircraft family had been assessed and consequently two conceptual designs for hydrogen burning aircraft are derived. The NB model seems quite competitive and effective when referred to similar exemplars found in literature, while the WB retrofit seems to be fairly penalized. Hydrogen-Based aircraft are expected to be equal or slightly less efficient [1] than current level of state-of-art, and the results of this work are in line with expectations. Regarding Hydrogen Supply for commercial aviation, the energy required for hydrogen production, liquefaction, dispatch and storage would be gargantuan: each hour of flight a NB requires a on-ground power plant that runs at 53-to-71 MW of power level in order to provide the amount of cryogenic hydrogen required. The metric sky rises to a 111 MW power plant needed for the hydrogen supply of a WB model. The latter coincides with the average power output of 13 off-shore wind turbines of 220m of diameter. Literature suggests that energy required for the LH_2 supply of only one medium-to-large airport is on the order of magnitude of a fraction of the France Nuclear AEP. From the electric energy input required for hydrogen production to the aircraft energy required to thrust between the 75% and 85% of hydrogen energy content is lost throughout the whole value chain.

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