DESIGN OF HYDROGEN STORAGE SYSTEMS IN NEW-GENERATION REGIONAL AIRCRAFT

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Abstract

New generation regional aircraft requires the implementation of electric propulsion technologies to achieve net zero carbon by 2050. Other than propulsion system, this revolution affects the whole aircraft architecture, demanding for the design of brand new configuration, with different performance and/or characteristics than conventional ones. One breakthrough consists in the use of hydrogen, which is a compelling option for sustainable mobility either to be burned or to feed fuel cells generating electricity. In both cases, this requires storing hydrogen on board, with less flexibility than conventional fuels due to volume and pressure requirements. To design appropriately hydrogen tanks, preliminary design of aircraft and its architecture need to be addressed. In this context, this paper showcases the pressure vessel detailed design to equip a hydrogen fueled regional aircraft. Starting from a multi-disciplinary analysis and optimization of the vehicle according the top level aircraft requirements, the hydrogen storing system is designed in detail considering different solutions. A further analysis shows the necessity to account the weight of the system versus its volume/surface ratio as a key parameter for preliminary design of such systems. In addition, the ratio between the actual volume of the tank and the volume of the hydrogen can give an overview of the system efficiency once the hydrogen rate is set to have a specific hydrogen duration.

Keywords: Hydrogen Tanks; Composite Structure Design; Aircraft Structure Design

1. Introduction

In the past decades, air transportation growth led to exponential increase in CO2 emissions which raised a concern among EU policy makers as aviation is one of the fastest-growing sources of greenhouse gas emissions. Despite the technological advances made to reduce the fuel burnt per passenger, environmental benefits have been outpaced by a sustained growth in air traffic. Before the COVID-19 crisis, different international and regional studies [1] demonstrated the terrible increasing emission trend and the International Civil Aviation Organization (ICAO) forecasted that by 2050 international aviation emissions could triple compared with 2015, accounting for a quarter of global carbon emissions. This was seriously taken into consideration in Europe where The EU is taking action to reduce aviation emissions as fast as possible and working with the international community to develop measures with global reach. In this context, a climate neutrality target is set by 2050, including the intermediate target of an at least 55% net reduction in greenhouse gas emissions by 2030. To achieve climate neutrality, the European Green Deal sets out the need to reduce transport emissions by 90% by 2050 (compared to 1990-levels), the aviation sector will have to contribute to the reduction much further with disruptive technologies rather than technological advancements.
As a result of comprehensive government and industry studies, electric aircraft propulsion emerged as a pivotal focus of research. This encompasses various architectures such as all-electric, hybrid electric, and turbo-electric systems. The aim is to significantly diminish the environmental impact of aviation and make it more sustainable for the future of passenger flight by replacing conventional fuel burning engines with electric motors. This system exhibits the advantage of producing no local

emissions since the electric motor is free from pollutants. Moreover, if the electricity required to feed the system is from entirely renewable sources, aircraft equipped with this technology could become zero-emission or below. This propulsion system offers diverse possibilities, involving the integration of electrical components through various technologies, such as Fuel Cells or batteries [2], significantly increasing the overall aircraft efficiency while reducing or eliminating pollutant emissions [3]. In particular, the first option relying on burning external source of hydrogen for operation [4] has the potential to meet the performance of all aircraft categories with superior upscaling flexibility.
However, the system integration requires further efforts in designing viable solutions to prevent increased system weight during the design phase and manage the inherent operational complexity. One of the major challenges relies on the efficient hydrogen storage onboard. As shown in a variety of scientific works, In the pursuit of sustainable aviation, hydrogen storage technologies will play a crucial role in determining the feasibility and efficiency of hydrogen-powered aircraft. Advancements in storage methods, including higher storage pressures and innovative materials, will be essential for realizing the full potential of hydrogen as a clean and renewable energy source for aviation [5].
In this context, the present paper showcases the hydrogen vessel detailed design to equip a new generation regional aircraft. Starting from a multi-disciplinary analysis and optimization which accounts for the aircraft mission and preliminary design to size the volume of the tank, different solutions are investigated along with their potentials. Finally, the tank sizing is generalized and used to different architectures for a 50 seat new generation regional aircraft in terms of weight vs. volume-surface ratio storage architecture. To better look into all the aspects that drive the design and then investigate preliminary this problem, the remaining of the paper is organized as follows. A first section attempts to provide an insight of the tank design, possible solutions and criticality of on-board storage systems. Then, the methodology adopted for structural and thermal analysis is first discussed highlighting the different assumptions made to keep simple the model and look into how some parameters affect the design. Then, different results are reported including the preliminary tank design for a brand-new 50 pax regional aircraft and a parametric analysis while varying the mass of the hydrogen. Finally, some concluding remarks are derived.

2. On-board storage. Review and design of the tank system

The containment of hydrogen, whether in liquid (LH2) or gaseous (GH2) form, within tanks on board aircraft presents a significant challenge in the development of hydrogen-powered systems. There are various techniques to store hydrogen, including compression, liquefaction, and confinement in crystals, as shown in Figure 1. In the compression method, hydrogen gas is stored under up to 70 MPa pressure within the tanks [6], allowing for a more compact storage system. On one end, this enables aircraft designers to optimize space and weight constraints. On the other hand, this solution needs robust and lightweight tank materials that can safely handle the high-pressure hydrogen gas. Liquefaction is another method of hydrogen storage, where hydrogen gas is cooled down to extremely low temperatures until it becomes a liquid. In liquid form, hydrogen has a higher energy density than as a gas, making it an attractive option for applications with strict weight limitations.
Indeed, hydrogen storage on board of aircraft requires solutions that are low in weight, cost-effective, and have high density [7]. In liquid state, hydrogen tanks can store 0.070 kg/L, while compression tanks store around 0.030 kg/L [8]. However, the critical condition for this configuration is maintaining the tank temperature at -273℃ [9], requiring a cryogenic system. This system would absorb some of the energy produced by the fuel cell system and result in the loss of certain advantages, such as low weight [10]. While the liquefaction method offers advantages in terms of density, there are some difficulties that need to be overcome for its feasibility. These challenges include addressing evaporation losses in storage tanks, with typical evaporation losses ranging from 0.1% to 1% per day depending on the tank size [11]. Additionally, the high cost of materials used in the construction of the system poses another hurdle [12]. Moreover, proper tank design is crucial to withstand potential pressure increases that may occur while the aircraft is parked or inactive. The ideal tank design aims for low weight and minimal surface area, as the surface area directly affects boil-off conditions [13]. Finally. another challenge in hydrogen storage systems is the high cost of materials and manufacturing. The materials used to construct tanks must possess high strain, high fracture toughness, high stiffness, low permeation, and low weight to withstand the cryogenic temperatures required by certain storage

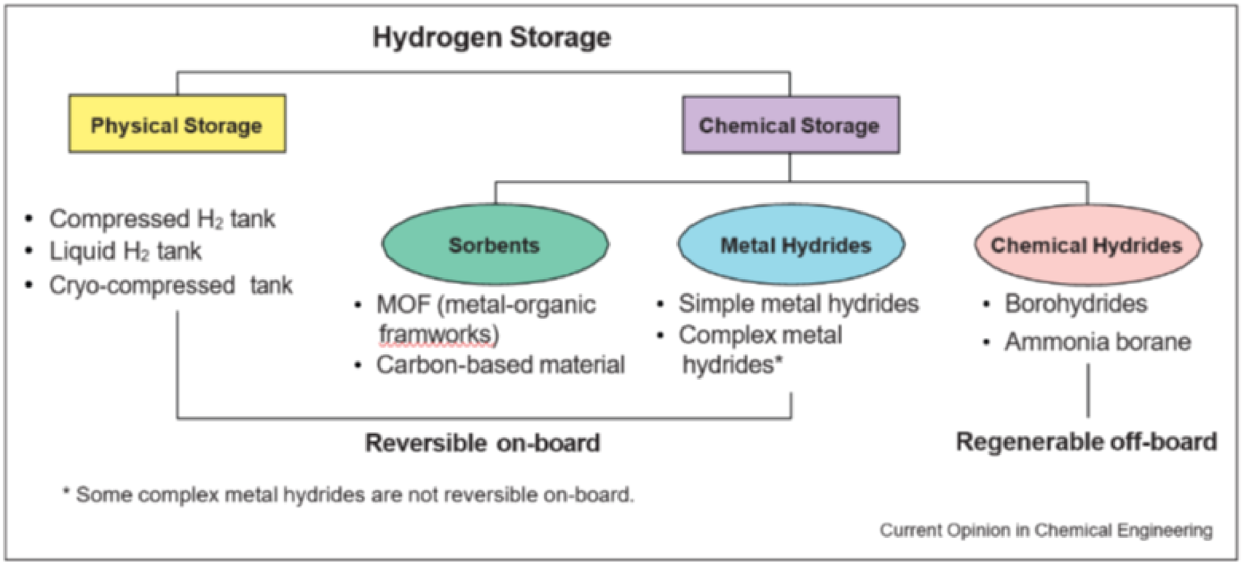


Figure 1 – Hydrogen Storage classification proposed in [6]

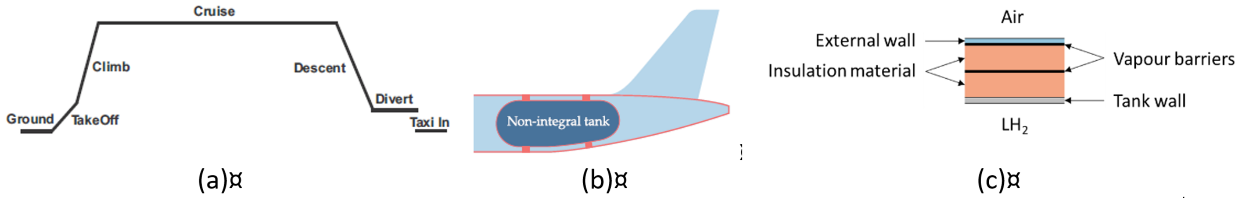


Figure 2 – Typical mission considered for preliminary sizing of the tank, (b) possible airframe configuration, and (c) possible tank configuration

methods [14]. Aluminum is a primary candidate for hydrogen tanks as it satisfies these requirements [15]. Carbon Fiber Reinforced Polymer (CFRP) is also suitable, providing a weight reduction of 25%. However, also special materials for thermal management are necessary.

Addressing all these challenges opens different possible solutions. Among these, the current paper will show the design of a multilayer tank which requires the design of multiple layers with different functionalities. Once the preliminary concept of the aircraft is conceived, a 492kg of hydrogen is preliminary sized as to fulfill the considered mission (see Figure 2). Afterwards, a detailed design is undertaken to characterize the multilayer tank to be included in the rear part of the aircraft. A first layer is necessary to be designed starting from the needed volume and defined as tank wall. Materials that possess high strength, high fracture toughness, high stiffness, as well as low density and low permeation to hydrogen are ideally needed for the tank wall construction [16]. In this case, both carbon fiber composites and aluminum alloys are considered taking into account that fracture toughness is particularly important due to the cryogenic temperatures where many materials become brittle. Given the large fuel volume, successful configurations require innovative designs with small frontal and surface areas as well as minimal weight. Minimizing the surface area is particularly important to limit the amount of heat entering the tank, which would lead to boil-off of the liquid and thus loss of fuel. For this reason, an efficient and lightweight insulation system is of prime importance to minimize boil-off, while adding minimum mass to the overall vehicle structure. The insulation system therefore, ideally, possesses a low thermal conductivity along with a low thermal diffusivity and a low mass density [16]. To this end, a multi-material insulation barrier is designed for thermal management considering low density foams, aerogels, and multilayer insulations (MLI), which are integrated as to obtain the desired thermal conductivity and, as such, the proper thermal management. Finally, a fairing is designed to be applied at the outer surface (external wall) to prevent the insulation from external damage.

The design carried out allows to obtain a baseline tank model, whose geometrical and material prop-

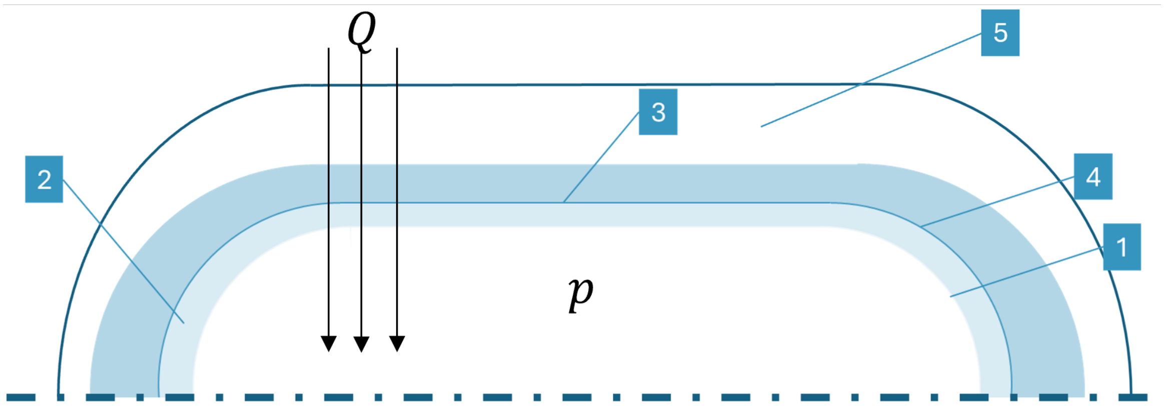


Figure 3 – Preliminary LH2 Tank Configuration used for sizing

erties can be varied to obtain the optimal configuration. The preliminary results which lead to the configuration conceived in this work show the superior strength to weight ratio of the carbon composite tank wall. Especially thanks to the different properties achievable along the different directions and tailored to the effective stresses arising, composite solution allows to reduce weight of about 20%. However, this requires to address different challenges as regard to the damage tolerance means of compliance. The established model allows to investigate the different parameters affecting the design and to plot the trends characterizing the weight of the tank against material and configuration. The final paper will present this trend along with the most critical parameters for efficient tank design. A key feature for both thermal management and load bearing capabilities is the volume/surface ratio of the tank, which can be used as a figure of merit enabling a suitable comparison between different tank configurations. This is an important parameter while exploiting the volume available in the rear fuselage, including also the use of multiple tanks, as it varies the volume and the surface of single tanks. Indeed, the use of multiple tanks increases the overall system weight but can reduce the external volume needed, saving space and extra-weight in the airframe. In addition, none of the considerations can be generalized as they strongly depends upon the hydrogen rate formulation.

3. Methodology

This section presents the overall methodology adopted to conduct preliminary tank sizing and extract figures of merit. The concept is first presented. Then the structure and thermal analysis methods are detailed.

3.1 Overall Concept

The overall tank concept for storage of liquid hydrogen is depicted in Figure3. The configuration conceived is based on a multifunctional composite structure consisting of four main layers. The first layer (1) constitutes the inner tank made of carbon epoxy structure and able to contain the hydrogen. The second layer (2) represents the first heat flux barrier selected here as an open cell insulator. The third layer is again a carbon epoxy material, able to withstand internal pressure of the system. Even though the base lamina material is the same, a different lamination sequence and a different thickness is considered for the skirt (3) and the dome (4), as different stress levels arise due to the pressure. Finally another thermal barrier (5) is included as closed cell insulator to balance the external temperature. As for the geometrical configuration, to keep simple the analysis, the shape factor of the tank is kept fixed. In particular the radius of the cylindrical and spherical components is the same, obtaining a hemispherical dome. In addition the overall length of the tank is equal to three times the radius of the cylinder.

3.2 Structural Analysis

To design the structure of the composite, the main requirements are retrieved through ANSI/AIAA S-081B 2018 Standard for Space Systems Composite Overwrapped Pressure Vessels.

Pressure and thermal loads are only considered in this study, and 6.5 bar is the Maximum Expected Operating Pressure (MEOP), namely the highest expected operating pressure during the lifetime. Meanwhile a stress safety factor equal to 2.0 is specifically adopted for composite structure in order to out of envelope conditions and manufacturing defects may occur. The operation temperature is set as initial guess to be 218^oK at layer 3-4 (flight temperature) and 90^oK at layer 2.
The design of the inner tank is carried out considering the temperature gradient and sizing the thickness to withstand buckling. A carbon epoxy lamina is considered stacked by filament winding as $[\pm 45, \pm 5, 90]_s$ and the resulting equivalent material properties are used to size the layer. The minimum thickness is obtained considering

$$\sigma_{cr} = \frac{E}{3\left(1-\nu^2\right)}\left(\frac{t}{R}\right) \tag{1}$$

The design of the outer tank is carried out considering the maximum operative pressure and sizing the thickness to withstand stresses along longitudinal and radial directions. A carbon epoxy lamina is considered stacked by filament winding as $[\pm 5, \pm 45, 90_3]_s$at the skirt and by $[\pm 5, \pm 45, 90_2]_s$ at the dome. The difference is due to the different stress arising under pressure. The spherical dome is subject to radial stresses only, while the skirt is stressed longitudinally twice than the radially. The resulting equivalent material properties are used to size the layer.

$$\sigma_r = \frac{pr}{2t}; \qquad \sigma_l = \frac{pr}{t} \tag{2}$$

3.3 Thermal analysis

In conjunction with the reservoir structure model, a thermal analysis of the system was conducted. As mentioned earlier, liquid hydrogen is stored at approximately 23K. Proper storage is critical due to the significant temperature difference between the hydrogen and the external environment, which can range from 218K during cruise phases to 300K in the Taxi condition, creating a ΔT of about 473K. Minimizing this temperature delta is crucial to exploit the self-maintaining capacity of hydrogen temperature through the boil-off condition. This phenomenon allows hydrogen temperature control without additional cryogenic cooling systems by managing system pressure, while admitting a loss of hydrogen without it being used to power booster systems. Without delving into the classical heat transfer mechanisms (conduction, convection, and radiation), the following approach was used: to estimate the overall system dimensions, the starting point was the thicknesses indicated in the structural configuration for the composite layers, which can be considered thermalized given the temperatures involved. The following assumptions were made:

- Tank system heat flux equals the latent heat of vaporization of liquid hydrogen: Q = 447.60 kJ/kg;
- Evaporation rate (time required to empty the tank without using hydrogen for fueling but only to maintain constant system temperature) = 8 kg/h;
- External shell composite wall temperature of the tank equal to 90 K;
- Ambient temperature (T_{amb}) = 300 K;
- Flight temperature (T_{flight}) = 218 K;
- No structures acting as thermal bridges (piping, support systems, etc.);
- Use of materials with high insulating properties (low conductivity K) such as Aerogel (0.013 W/mK) and PolyMethyl-MethAcrylate foam PMMA (0.034 W/mK).

The following steps were taken:

1. Two-Dimensional Modeling: An in-plane model of the tank was created, treating the surfaces as flat sheets and omitting convective heat transfer with the external environment the equation used is typical of conductive heat transfer:

$$q = \frac{k\Delta T}{(s)} \tag{3}$$

   here, k represents the thermal conductivity of the material, and (s) denotes the thickness of the layer under consideration.

2. Three-Dimensional Modeling: Given the cylindrical geometry of the reservoir, the heat flux characteristics of the central trunk cylinder versus the spherical caps were analyzed. Heat flux was divided by the overall surface area of the structure, and the heat flux of the cylinder and spherical cap were analyzed individually.

In the three-dimensional case, convective heat transfer with the external environment was also evaluated.

4. Results

This section reports and discusses the preliminary results obtained. First, a possible tank for a 50 passengers regional aircraft is designed having fixed amount of mass equal to 492 kg according to the preliminary design accounted [17]. Then, different trends are depicted while varying the hydrogen mass, considering both a constant evaporation rate and a constant evaporation time.

4.1 Tank design for regional aircraft

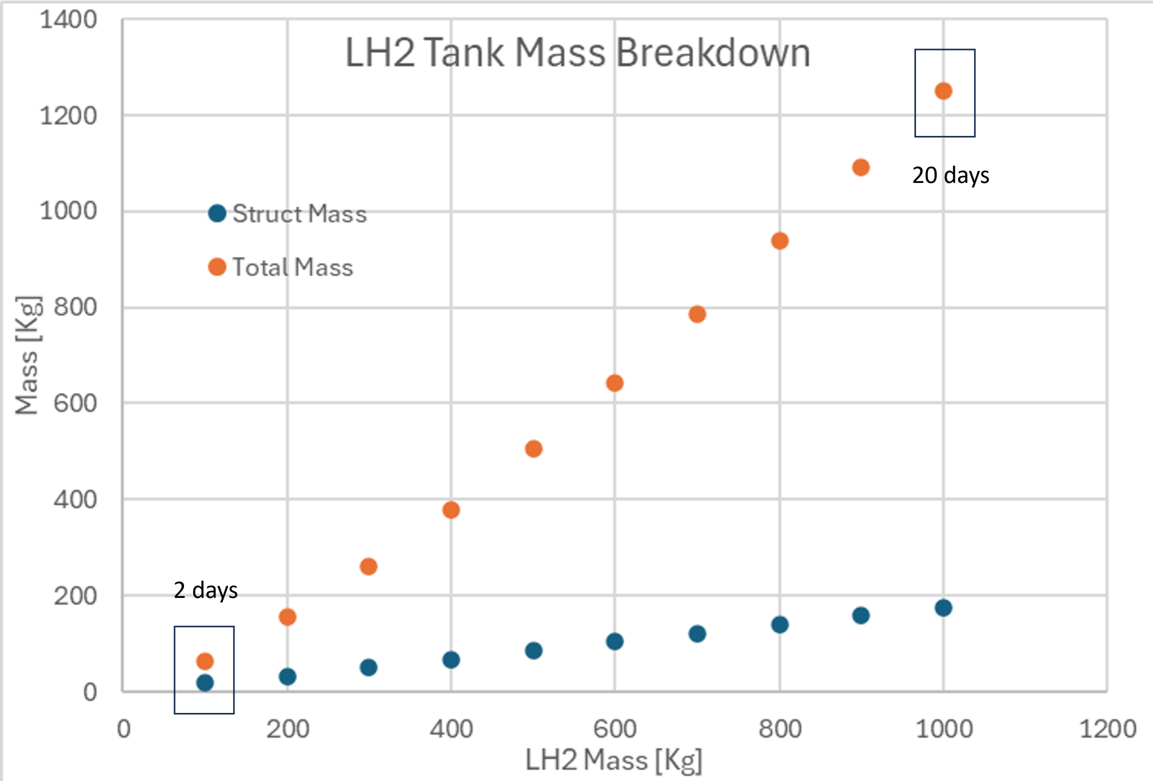
Based on the requirements in terms of hydrogen mass, the volume of the inner skin is sized to satisfy the geometrical considered constraints. Then, the three main carbon epoxy components are sized and found to be 1.1 mm, 2.6 mm and 1.4 mm, respectively for the zones 1,3 and 4 reported in Fig. 3. In particular, this is the minimum thickness homogenizing the material and does not take into account manufacturability of the plies. This will be taken into account in the future. However, it is worth noting that the skirt shows thicker material than the dome even though the layout has been slightly adjusted to withstand the specific load.

The thickness found is taken as initial guess for the thermal management, in order to then iterate and get through with the thermostructural analysis. Based on the requirements and the bidimensional assumptions, and given the first structural guess, the first aerogel layer thickness of 12.5 mm was obtained, which is acceptable to separate the inner and outer tank. Criticality arose when evaluating the interactions with the external environment, considering only conduction. Analyzing the typical system temperatures of 218 K during cruise and 300 K in the cabin, PMMA foam thicknesses of 68.2 mm and 102 mm, respectively, were obtained. The insulation thickness plays a key role in system management, resulting in an Outer Diameter/Inner Diameter ratio of 1.16. These thickness values were used in the initial evaluation of the three-dimensional structure.

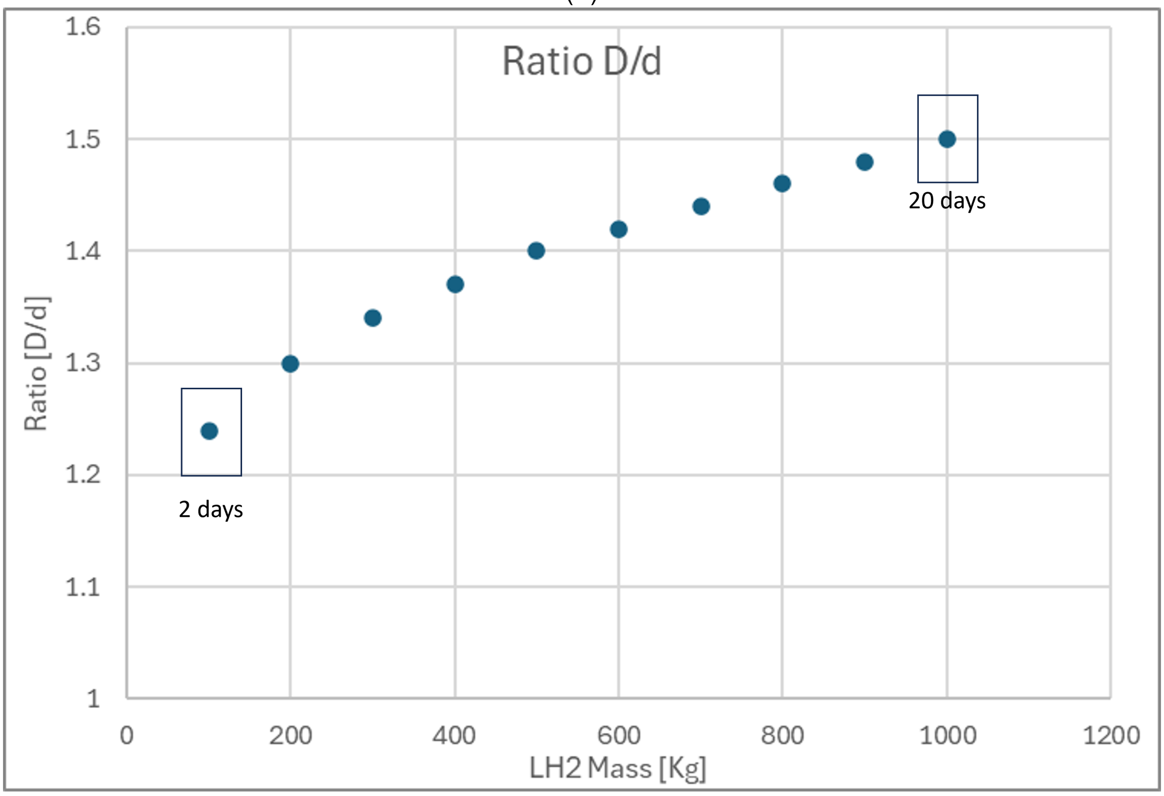
Starting from this analysis, the geometry of load bearing structure is corrected implementing an iteration process, leading to a slightly increase of overall mass. A further enhancement of the model is carried out taking into account the three-dimensional assumption discussed in the previous section. The spherical geometry was found to conduct more heat than the cylindrical body, necessitating greater insulation thickness on the caps. However, equalizing the thickness between the two parts, the aerogel thickness was 13.2 mm, while the PMMA thicknesses were 115 mm at ambient temperature and 66 mm during flight conditions. These thicknesses are significant when considered on the radius of the geometry.

4.2 Constant Evaporation Rate

In order to have a clear view of the minimum mass and volume needed to carry hydrogen on board, the mass of the hydrogen needed is used as input parameter and then thermostructural model is enabled combining thermal and structural analysis discussed in the previous session. In addition, the evaporation rate is assumed constant while varying the mass of the hydrogen. Figure 4 shows the



(a)



(b)

Figure 4 – Mass (a) and Volume ratio (b) obtained varying the liquid hydrogen mass under constant evaporation rate. Evaporation time is highlighted for extreme cases.

main results obtained in terms of structural and insulation mass. It is worth noting that increasing the liquid hydrogen mass return an increasing structural mass to withstand the existing operative loads and a way more increasing mass of the insulation materials.

Without going into dives of different layer breakdown, which mostly begs for an optimization process, the thermal exchange becomes here crucial, as it drives the mass increase of the whole system when the hydrogen mass increases (see Figure 4 (a)) Specifically when 1 ton hydrogen is needed to be stored, the insulation material weight 5 times the structural material. In addition, the effective volume increases further when compared to the hydrogen volume. This trend can be observed plotting the ratio between the actual diameter of the tank and the inner diameter of the tank against the liquid hydrogen mass (see Figure4 (b)), Here, most of the volume increase is due to the insulation material volume while the thickness of load bearing structures increases slightly due to varying geometry. However, looking at the overall performance of the tank, keeping the evaporation rate constant would vary the evaporation time (time elapsed between refuelling and whole evaporation of the hydrogen due to boil off in static conditions) depends upon the volume of the hydrogen, as highlighted in Figure 4 for the extreme cases considered here.

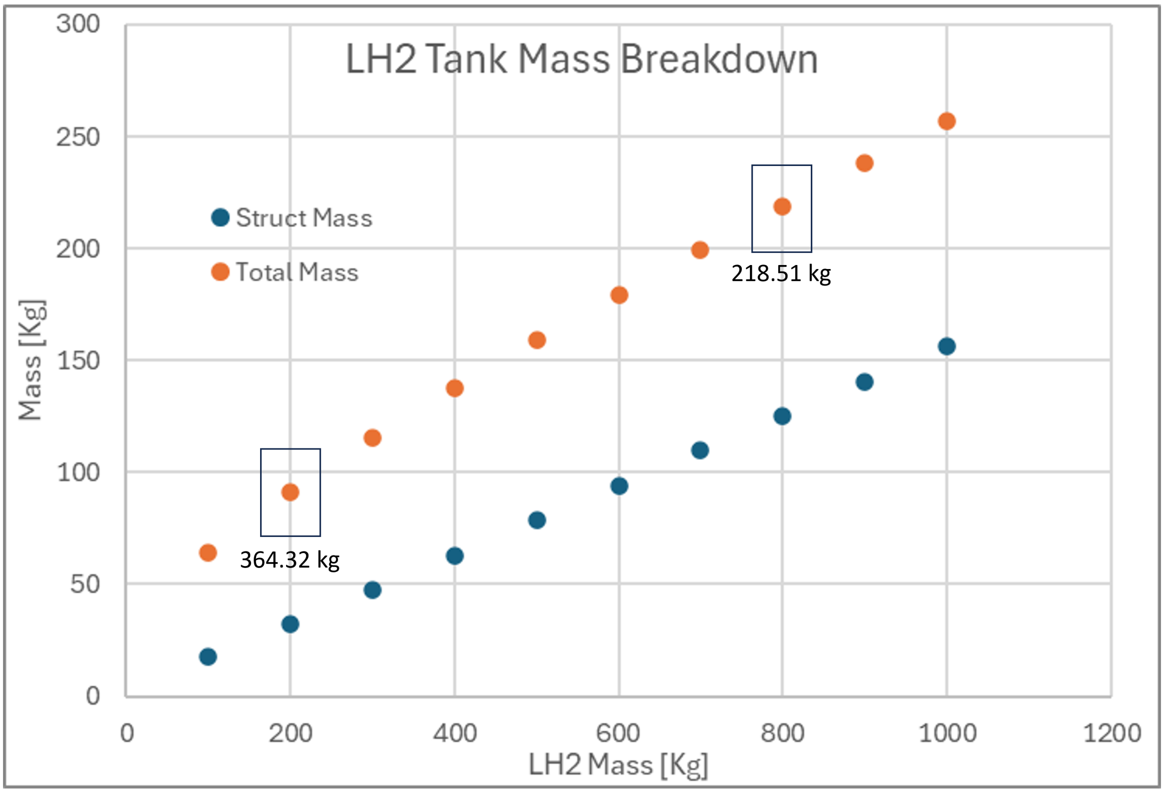
4.3 Constant Evaporation Time

To achieve a more clear comparison of the mass and volume demands for carry hydrogen flying, the same analysis is carried out while varying the quantity of fuel needed and keeping constant the evaporation time. This latter strongly depends upon the volume of the hydrogen, requiring further thermal analysis iteration. The results are shown in Figure5. In particular, the mass of the multi-functional layered structure shows an increment according the the mass of hydrogen contained with slightly increase of insulation material mass (see Figure 5 (a)). In addition, the effective volume increases when compared to the hydrogen volume but keeping lower the ratio between outer and outer volume. This trend can be observed plotting the ratio between the actual diameter of the tank and the inner diameter of the tank against the liquid hydrogen mass (see Figure 5 (b)), Here, most of the volume increase is due to the inner volume rather than the thickness of insulation and the load bearing structures. As a consequence the ratio decreases with increasing mass. To further look into this trend, the changes of mass and volume of carrying on board liquid hydrogen into one or multiple tanks is highlighted in Figure 5. Specifically, having 800Kg of hydrogen stored in four smaller tanks of the same length (2x2 matrix configuration) would require 67% additional mass and 28% additional volume compared to a single tank.

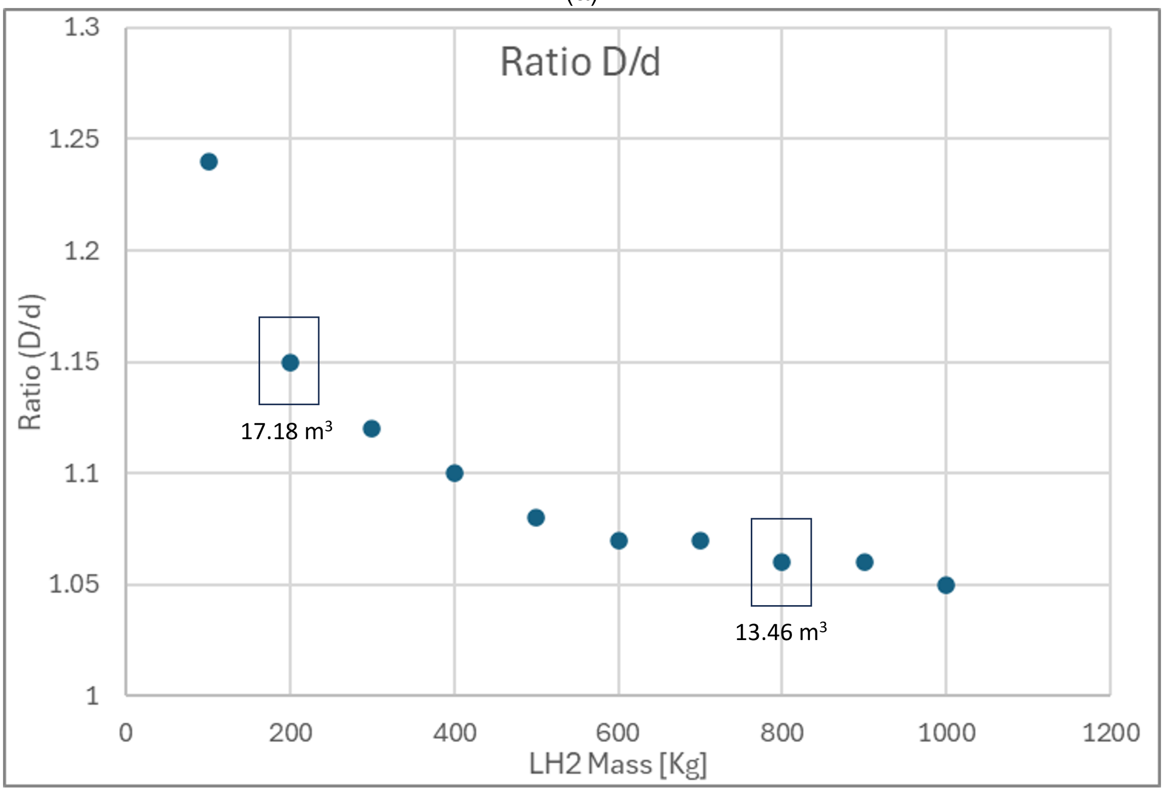
It is worth noting that this investigation does not account for additional system mass, which can be approximately considered as 30% additional mass. In addition, the mass of the constraints is neglected in this study as well as the presence of defects and possible damage which could slightly increase the size of the structure withstanding loads. Nonetheless, these assumptions does not alter the generality of the presented investigation. Otherwise, taking all these variables into account as well as removing temperature constraints at the different layers pave the way for an optimization study that will be conducted in the future investigations.

5. Concluding remarks

The review of current trends in hydrogen storage and usage demonstrate the superior performance of the LH2 as to the aeronautical applications. However, the cryogenic temperatures needed add complexity to the storage system and can result in some energy losses, additional weight and a complex thermal management. Overcoming these challenges in hydrogen storage systems is essential for the wide-spread adoption of hydrogen-powered aircraft. Ongoing research and technological advancements in materials, design, and manufacturing techniques aim to address these issues and optimize the efficiency, safety, and affordability of hydrogen storage solutions for aviation applications. The present paper looks into the tank modelling for preliminary yet accurate design of hydrogen storage system for a brand new regional aircraft. The model used allows to consider different materials and configurations resulting in a multi-layered vessel with different layers working with multiple functions. Starting from the preliminary sizing, the model is used for the weight assessment of the whole system including thermal management and load bearing components. The same model is used to parameterize important design features which can be used back to preliminary design as figures of merit to



(a)



(b)

Figure 5 – Mass (a) and Volume ratio (b) obtained varying the liquid hydrogen mass under constant evaporation time (48h). Total mass (a) and volume (b) needed to carry on board 800 liters of hydrogen are highlighted considering 4 tanks and 1 tank.

compare different configurations. Despite qualitative results have been achieved (multilayer configuration needs to meet the requirements with lower weight possible, superior properties of composite materials, effect of volume/surface ratio), the paper shows already relevant trends achievable with the conceived model and further insight for a more general aeronautical application (from short to long range applications). In particular, constant evaporation time should be taken into account to have a comparative analysis of the solutions adopted. In addition it is important to maximize the volume and the ratio between volume and length (i.e.: using minimum number of tanks possible) to reduce weight and overall volume needed.

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References

[1] Kreimeier, M., Stumpf, E., Gottschalk, D., 2016. Economical assessment of air mobility on demand concepts with focus on Germany, in: 16th AIAA Aviation Technology, Integration, and Operations Conference. Presented at the 16th AIAA Aviation Technology, Integration, and Operations Conference, American Institute of Aeronautics and Astronautics, Washington, D.C. https://doi.org/10.2514/6.2016-3304

[2] González-Espasandín, Ó., Leo, T.J., Navarro-Arévalo, E., 2014. Fuel Cells: A Real Option for Unmanned Aerial Vehicles Propulsion. Sci. World J. 2014, 1–12. https://doi.org/10.1155/2014/497642

[3] Zhang, M., Eastham, F., Yuan, W., 2016. Design and Modeling of 2G HTS Ar-mature Winding for Electric Aircraft Propulsion Applications. IEEE Trans. Appl. Supercond. 26, 1–5. https://doi.org/10.1109/TASC.2016.2539548

[4] Wilberforce, T., El-Hassan, Z., Khatib, F.N., Al Makky, A., Mooney, J., Barouaji, A., Carton, J.G., Olabi, A.-G., 2017. Development of Bi-polar plate design of PEM fuel cell using CFD techniques. Int. J. Hydrog. Energy 42, 25663–25685. https://doi.org/10.1016/j.ijhydene.2017.08.093

[5] Cardone, L., De Rosa, S., Petrone, G., Franco, F., Greco, C.S., Review of the recent developments about the Hybrid Propelled Aircraft, In: AEROTECNICA MISSILI E SPAZIO. - ISSN 0365-7442. - (2023). [10.1007/s42496-023-00173-6]

[6] Zhang, Z., Hu, C., 2014. System design and control strategy of the vehicles using hydrogen energy. Int. J. Hydrog. Energy 39, 12973–12979. https://doi.org/10.1016/j.ijhydene.2014.06.010

[7] Zhang, F., Zhao, P., Niu, M., Maddy, J., 2016. The survey of key technologies in hy-drogen energy storage. Int. J. Hydrog. Energy 41, 14535–14552. https://doi.org/10.1016/j.ijhydene.2016.05.293

[8] Niaz, S., Manzoor, T., Pandith, A.H., 2015. Hydrogen storage: Materials, methods and perspectives. Renew. Sustain. Energy Rev. 50, 457–469. https://doi.org/10.1016/j.rser.2015.05.011

[9] Mori, D., Hirose, K., 2009. Recent challenges of hydrogen storage technologies for fuel cell vehicles. Int. J. Hydrog. Energy 34, 4569–4574. https://doi.org/10.1016/j.ijhydene.2008.07.115

[10] Zhang, Y., Jia, Z., Yuan, Z., Yang, T., Qi, Y., Zhao, D., 2015. Development and Application of Hydrogen Storage. J. Iron Steel Res. Int. 22, 757–770. https://doi.org/10.1016/S1006-706X(15)30069-8

[11] Preuster, P., Alekseev, A., Wasserscheid, P., 2017. Hydrogen Storage Technologies for Future Energy Systems. Annu. Rev. Chem. Biomol. Eng. 8, 445–471. https://doi.org/10.1146/annurev-chembioeng-060816-101334

[12] Barthelemy, H., Weber, M., Barbier, F., 2017. Hydrogen storage: Recent improvements and industrial perspectives. Int. J. Hydrog. Energy 42, 7254–7262. https://doi.org/10.1016/j.ijhydene.2016.03.178

[13] Ahluwalia, R.K., Peng, J.-K., Hua, T.Q., 2015. Sorbent material property requirements for on-board hydrogen storage for automotive fuel cell systems. Int. J. Hydrog. Energy 40, 6373–6390. https://doi.org/10.1016/j.ijhydene.2015.03.025

[14] Verstraete, D., Hendrick, P., Pilidis, P., Ramsden, K., 2010. Hydrogen fuel tanks for subsonic transport aircraft. Int. J. Hydrog. Energy 35, 11085–11098. https://doi.org/10.1016/j.ijhydene.2010.06.060

[15] Zielinski, A., 2001. Hydrogen-assisted degradation of some non-ferrous metals and alloys. J. Mater. Process. Technol. 109, 206–214. https://doi.org/10.1016/S0924-0136(00)00797-4

[16] Mital S, Gyekenyesi J, Arnold S, Sullivan R, Manderscheid J, Murthy P. Review of current state of the art and key design issues with potential solutions for liquid hydrogen cryogenic storage tank structures for aircraft applications; 2006. NASATM-2006e214346

[17] Marciello V., Cusati V., Nicolosi F., Saavedra-Rubio K., Pierrat E., Thonemann N., Laurent A., 2024, Evaluating the economic landscape of hybrid-electric regional aircraft: a cost analysis across three time horizons, Energy Conversion and Management.