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REVIEW OF LIQUID HYDROGEN TANKS FOR SHORT- AND MEDIUM-HAUL AIRCRAFT

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Summary. *Hydrogen is increasingly seen as a key energy carrier in transitioning towards a decarbonized global energy system. When considering the transportation sector, aviation stands out as one of the most hard-to-abate activities. Aviation is responsible for emitting 2.5% of the global* CO_2 *from fossil sources before 2020, and it has been increasing at a rate of 4-5% per year since 2010. Hydrogen as a sustainable fuel for propulsion is recognized as a potential solution to meet the emission goals, however, several technical hurdles must be addressed when designing the storage system. This paper focuses on storing hydrogen in its liquid form within short- and medium-haul commercial aircraft. Different technological options are presented, covering the possible solutions described in the open literature. The main challenge of integrating a liquid hydrogen tank into the airframe is associated with its low volumetric density when compared to conventional jet fuels. In fact, the large volumes occupied by the liquid hydrogen tanks can be detrimental to the aerodynamics of the aircraft. This paper indicates that a universal solution does not exist yet. The decision on the tank-fuselage integration is arbitrary and depends on the scope of the work: non-integral tanks provide shape flexibility, and integral tanks provide volumetric efficiency. Aluminum alloy 2219, and closed-cell foams are leading the field when assessing the selection of the tank materials. Promising alternatives to enable lighter and safer solutions, such as composite materials and internal insulation systems, still require further studies in the cryogenic region of operation.*

1 INTRODUCTION

The aviation sector stands out as one of the most carbon-intensive activities in transportation. It was responsible for emitting approximately 2.5% of the global CO_2 from fossil sources and land use before the COVID-19 pandemic [1]. The global CO_2 emission trend from aviation has continuously increased with a yearly rate of approximately 4-5% since 2010 [2]. The European Union outlined its vision in the “Flightpath 2050” document developed by the Advisory Council for Aeronautics Research in Europe (ACARE). Flightpath 2050 outlines goals and strategies to ensure competitive, sustainable, and safe aviation in order to reach the emission targets by 2050. It suggests that CO_2 emissions should be cut by 75%, NO_x emissions by 90%, and noise footprint by 60% in 2050 compared to the reference value of the year 2000 [3].

1.1 Motivation

The utilization of green hydrogen as an alternative fuel is widely regarded as one of the most promising and environmentally friendly options. This paper focuses on the possibility of storing hydrogen in its liquid form. Liquid hydrogen is maintained in cryogenic tanks at extremely low temperatures (-253 °C) and close to atmospheric pressure. The conventional storage of hydrogen in its gaseous state typically operates at ambient temperature and pressures ranging from 350 to 700 bar. Liquid hydrogen shows higher density, nearly twice that of gaseous hydrogen at 700 bar and ambient temperature [4]. Moreover, a liquid hydrogen tank operates at lower pressures, so it does not require thick walls, but insulation is necessary due to the cryogenic temperature. Gaseous tanks instead must be designed with very thick walls to withstand the high internal pressure [5]. Thus, a cryogenic tank may result thicker, due to the presence of insulation, and lighter than high-pressure tanks (for the same energy stored).

In the context of aviation, Figure 1 presents the viable methods of energy storage according to a study conducted by FlyZero [6]. The storage methods (fuel and tank) are compared by limiting their typical mass fraction of the total aircraft mass, namely around 20%, represented in Figure 1 by the yellow dashed line. Batteries (blue line), gaseous hydrogen stored at 700 bar (orange line), and hydrogen stored in ammonia (light blue line) achieve only short-range flights compared to kerosene-fueled aircraft (grey line). Furthermore, ammonia storage requires a complex component for the cracking process, i.e., the decomposition of ammonia in hydrogen and nitrogen, before hydrogen can be finally used [6]. Liquid hydrogen instead is the only method of alternative energy storage that allows it to meet the ranges of kerosene.

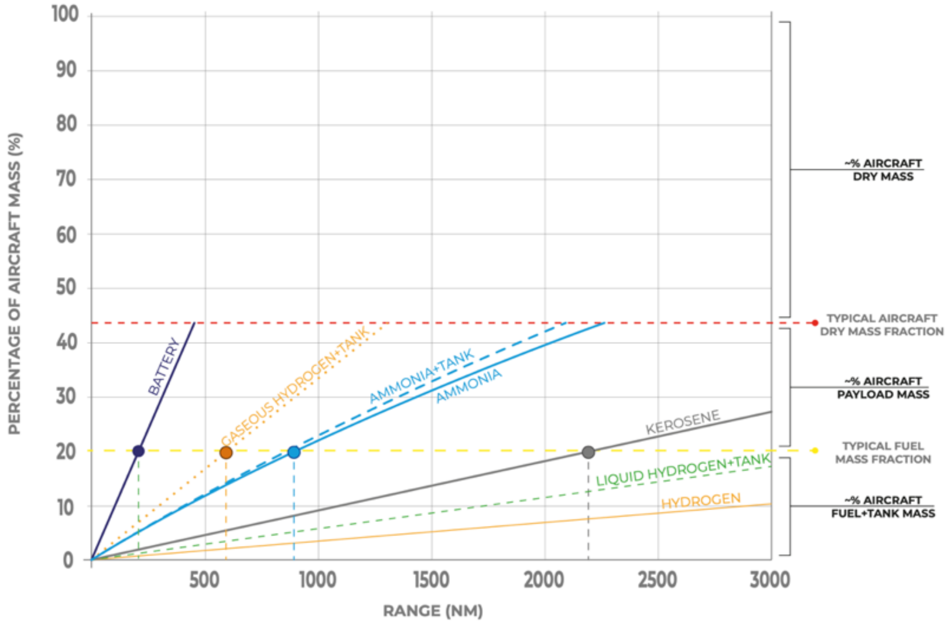


Figure 1: Fuel (continuous line) and fuel + tank (dashed lines) expressed as the percentage of aircraft mass as a function of the flight range [6]. The aircraft dry mass is defined as the weight of an aircraft without any usable fuel, passengers, and cargo. The payload mass is defined as the weight of passengers and cargo.

1.2 Objective and methodology

The objective of this work is to present an overview of the technological options of liquid hydrogen tanks for commercial aircraft referring to the state-of-the-art. The density of liquid hydrogen is approximately eleven times lower than the density of conventional jet fuels [7]. For this reason, the challenges of integrating liquid hydrogen tanks into the airframe are highlighted throughout this work. This paper sets the starting point of future works which is essential to design a hydrogen-fueled aircraft from scratch and improve the existing ones.

The methodology consists of reporting the main options found in the open literature in order to build liquid hydrogen tanks specifically tailored for commercial aircraft.

2 COMMON FEATURES OF CRYOGENIC TANKS

This section describes the common features of cryogenic tanks, focusing on the main criticalities affecting these systems which include (1) heat in-leaks, (2) cooldown, and (3) cryopumping. The insulation technologies are then briefly reported.

Cryogenic liquids are stored in tanks specifically designed to minimize heat in-leaks from the environment and to minimize weight in the case of mobile applications. The general configuration of these systems consists of an inner vessel in contact with the liquid, an outer vessel to provide structural support, and an insulation space in between. Pressure relief devices and a vent line are mandatory to allow pressure management within the inner tank.

2.1 Criticalities in cryogenic storage systems

The main criticality affecting cryogenic tanks concerns heat in-leaks. Non-ideal insulation between the cryogenic system and the environment is inevitable. Consequently, gradual warming is endured by the cryogenic liquid, thus boil-off gas is generated. Heat transfer within the insulation space occurs by (1) solid conduction, (2) radiation, (3) gas convection, due to the natural circulation of the residual gas molecules, and (4) gas conduction, due to the energy carried by the hot gas molecules colliding with the cold surfaces [8].

The cooldown effect is the process in which the tank and the auxiliary components are cooled from ambient to cryogenic temperatures. This effect inevitably entails the loss of valuable time and cryogen in the form of evaporation. Excessive cooldown time is a consequence of using thick metal walls and dense insulation. Therefore, minimizing the inner wall thickness not only minimizes weight but also limits the losses due to cooldown. [8].

The cryopumping effect mainly affects the tanks with temperatures lower than the boiling temperature of air – approximately 80 K [9]. If air is present in the gap between the inner and the outer vessel, e.g., due to leakage or outer wall rupture, condensation and solidification of air molecules may happen. The insulation effectiveness would significantly drop, and an LO_2-enriched mixture would generate a hazardous environment.

2.2 Insulation technologies

Four main technologies to insulate cryogenic tanks can be identified: (1) vacuum insulation, (2) multilayer insulation, (3) powder insulation, and (4) foam insulation. These technologies are not mutually exclusive, as they target different heat transfer mechanisms [8].

Vacuum insulation is a technique that allows to eliminate heat transfer due to gas convection and conduction, as it greatly reduces the number of molecules surrounding the inner vessel.

Multilayer insulation (MLI) consists of 30-80 alternate layers of low-emittance sheets to minimize radiation, and low-conductivity spacers to attenuate solid conduction. Low-emittance sheets are usually made of a thin plastic material coated by a high-reflectance metal. Spacer materials typically involve glass fibers thanks to their numerous discontinuities and irregular geometry. To obtain high-performance insulation, MLI is coupled with ultra-high vacuum in the insulation space, 1.3×10^{-10} MPa, to virtually eliminate gas conduction and convection [8].

Powder insulation involves filling the space between the inner and outer vessel with a low-conductivity, low-density powder, such as perlite and silica aerogel. The small size of the particles and the voids between them partially disrupt solid and gas conduction, however, these remain the primary heat transfer mechanisms. Radiation contributes very little. When using powder filling, it is essential to install a vapor barrier around the packing material to prevent atmospheric gases from diffusing into the insulation, i.e., to tackle the cryopumping effect [8].

Foam insulation involves the use of expanded organic solids – such as polystyrene, polyurethanes, rubber, and silicones – to cover the inner vessel. The low density of the foams, which is an order of magnitude less than that of powder insulations, results in a low heat transfer via solid conduction. However, the structure of the foam allows for more continuous paths compared to powder insulations. As a result, gas conduction through the interstitial spaces becomes the dominant heat transfer mechanism along with radiation [8].

3 TECHNOLOGICAL OPTIONS OF LIQUID HYDROGEN TANKS FOR COMMERCIAL AVIATION

This section presents possible technological options for liquid hydrogen tanks for commercial aviation. The technological options are defined as the various engineering solutions required to incorporate the liquid hydrogen tanks within the aircraft. These include the shape, the tank arrangement, the tank-fuselage integration, and the material selection.

3.1 Shape of the liquid hydrogen tanks

The shape of cryogenic storage tanks needs to be characterized by a low surface-to-volume ratio to limit the heat transfer into the stored liquid hydrogen.

Spherical tanks exhibit a low surface-to-volume ratio; thus, they minimize the heat in-leaks, consequently reducing liquid hydrogen boil-off. However, in the context of aviation, spherical tanks are not attractive due to their challenging manufacturing process, and large frontal areas which lead to higher drag forces and penalized aerodynamics [10].

Conversely, cylindrical tanks are simpler to manufacture but exhibit a higher surface-to-volume ratio, resulting in increased heat in-leaks. Nevertheless, their ease of integration into the tubular fuselage offers a higher volumetric efficiency. For this reason, cylindrical tanks with hemispherical heads are mostly employed. This modification incurs a weight penalty and necessitates an increase in the length of the tank accordingly [11]. Dished bottoms instead of hemispheres may be a viable solution which results in small disadvantages in terms of surface area, but a reduction of the length of the tank makes the choice reasonable [12].

3.2 Tank arrangement

Modern aircraft carry kerosene in integral tanks located in the wings. This configuration avoids large changes in the center of gravity location as the fuel is consumed providing stability throughout the flight. However, such a configuration is unviable in the case of liquid hydrogen due to the significant volume required [11]. Thus, liquid hydrogen has to be distributed along the longitudinal axis of the aircraft which is very sensitive for the stability of the vehicle.

Along the longitudinal axis of the aircraft, the tanks can be placed in four positions: forward (at the front of the fuselage), aft (at the back of the fuselage), in the upper part of the fuselage, and the lower part of the fuselage (see Figure 2). For short-haul flights, a single liquid hydrogen tank can be located in the aft position. On the other hand, medium- and long-haul flights require a forward and an aft tank to maintain the center of gravity within the allowable range [13].

From the cross-sectional point of view, two options are considered: part section where the tank cross section partially occupies the fuselage cross-section, and full section where the tank cross section occupies both cargo and passenger deck. These positions are not mutually exclusive. A full-section layout consists of embarking large quantities of liquid hydrogen to perform long-range flights while penalizing the fuselage volume occupied by passengers and cargo [14]. For the part-section layout, two possible options are viable: in the upper part of the fuselage, or the lower part of the fuselage reducing the space for the cargo. The part-section layout does not reduce the cabin space, but it embarks a smaller quantity of liquid hydrogen. As a result, this layout allows shorter flyable ranges when compared to full-section layouts [14].

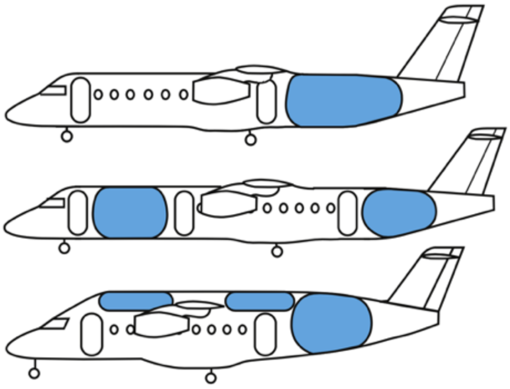


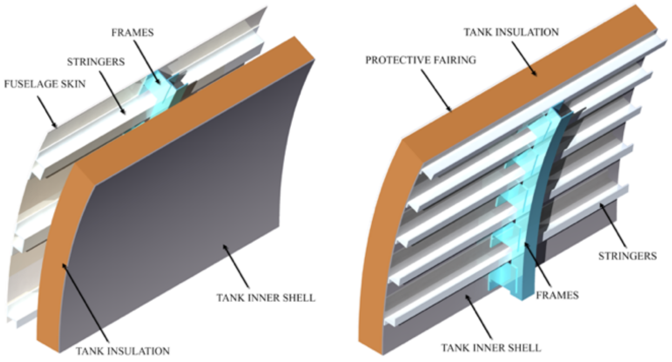
Figure 2: Representation of the different tank arrangements studied by Verstraete et al. [15].

3.3 Tank-fuselage integration

The tank-fuselage integration is defined as the process of incorporating the liquid hydrogen tanks within the fuselage. There are two options: non-integral, and integral tank (see Figure 3).

When the outer wall of the tank does not coincide with the aircraft skin, it is called non-integral tank. Since there is a gap between the outer wall and the aircraft skin, the non-integral tank is not loaded as part of the aircraft structure. The tank is supported by a conventional airframe and it must withstand only the load stemming from the tank. It does not have to conform to the shape of the aircraft; hence its architecture can be simple. However, as the structural elements of the non-integral tank do not cope with the fuselage loads, non-integral tanks lead to inefficient volume utilization. As a result, the aircraft will be characterized by a high frontal area and, thus, high drag. Non-integral tanks imply a challenging maintenance procedure since they require the complete removal of the tank from the aircraft [11].

When the outer wall of the tank coincides with the aircraft skin, it is called integral tank. In this case, the gap between the outer wall and the aircraft skin is eliminated, hence the integral tank is loaded as part of the airframe. The tank serves as the aircraft structure and carries fuselage loads as well as providing fuel containment. This configuration requires a complex architecture and poses many manufacturing hurdles. Nevertheless, as the structural elements of the integral tank also cope with the fuselage loads, its adoption leads to weight savings. Integral tanks enable an efficient utilization of the volume inside the fuselage, which translates into a low frontal area and, thus, low drag. Finally, integral tanks are more readily accessible for inspection and repairs since they only require the removal of the heat shield [11].



(a) Non-integral tank. (b) Integral tank.

Figure 3: Tank structure of the non-integral (left) and the integral (right) solutions [16].

3.4 Material selection: tank wall

The tank wall material is required to possess (1) low conductivity, (2) low thermal diffusivity, (3) low coefficient of thermal expansion, (4) low density, (5) high strength, (6) high fracture toughness, and (7) low permeation to hydrogen [10]. A material that provides all these features simultaneously does not exist. Low density and high strength are the most crucial attributes when dealing with aviation since they allow weight savings, reduced thermal conduction, and mechanical integrity. Moreover, a high fracture toughness is fundamental as the tank operates at cryogenic temperatures where many materials become brittle.

From Figure 4, the most desirable material needs to be located in the top-left corner. The two most suitable options are polymer matrix composites (brown area), and metals (red area). Ceramics (yellow area) offer high strength-to-density ratios but they are prone to brittle fracture.

Polymer matrix composites (PMC), in particular carbon fiber-reinforced polymers, are attractive for aero applications to store liquid hydrogen due to their low density and high strength. Nevertheless, the main drawback of PMCs concerns their high susceptibility to hydrogen permeation due to their low density, inducing the hydrogen embrittlement phenomenon. For this reason, a thin metallic liner that serves as a hydrogen barrier is required. PMCs incur high manufacturing costs, along with issues regarding their fabrication [10].

Metals have a higher density than PMCs, which leads to a higher mass of the tank. In addition, brittle failure at cryogenic temperatures is more prone in metals than in PMCs. However, certain metals remain ductile at cryogenic temperatures such as austenitic stainless steels, aluminum alloys, titanium, and copper [10]. Aluminum alloys are the prime candidates for aerospace applications. They offer relatively high strength-to-density ratios and show minimal susceptibility to hydrogen embrittlement due to their face-centered cubic structure [17]. In general, metals are more characterized, cheaper, and easier to fabricate than PMCs.

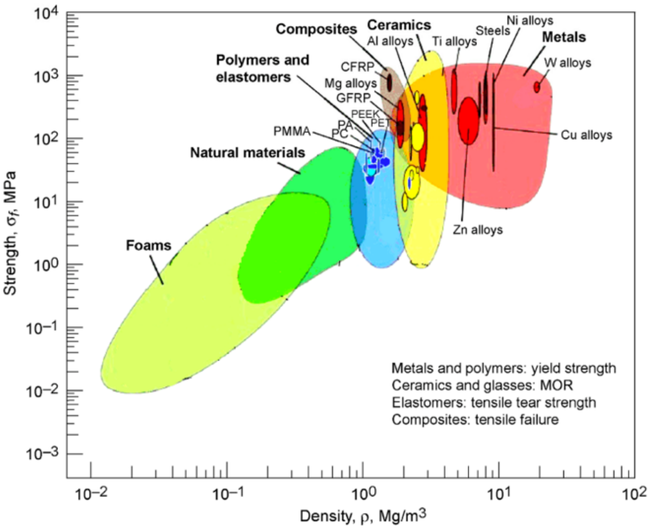


Figure 4: Strength (y-axis) versus mass density (x-axis) for various materials. CFRP is carbon-fiber-reinforced polymer; GFRP, glass-fiber-reinforced polymer; PA, polyaniline; PC, polycarbonate; PEEK, polyetheretherketone; PET, polyethylene terephthalate; and PMMA, polymethylmethacrylate [10].

3.4 Material selection: insulation

An effective and lightweight insulation system is of prime importance for liquid hydrogen tanks, as it minimizes the boil-off of liquid hydrogen while adding minimum mass. The insulation system is required to possess (1) low mass density, (2) low thermal conductivity, (3) low thermal diffusivity, (4) low coefficient of thermal expansion, and (5) resistance to compression loads [10]. The thermal diffusivity needs to be low to minimize the steady-state heat flux in the tank. The coefficient of thermal expansion is associated with the number of distortions endured by the insulation material. Lastly, compression loads refer to vibration phenomena, and dimensional changes, which may penalize the insulation effectiveness.

From Figure 5, the most desirable material needs to be located in the bottom-left corner. Polymer foams are the most suited candidates for their low conductivity, low density, and structural stability. Additionally, MLI combined with a vacuum jacket (not present in the graph) offers the highest performance among all the insulation technologies. Its density is comparable to low-density foams, and its apparent thermal conductivity is approximately two orders of magnitude lower than the best low-conductivity material.

Several families of open and closed-cell polymer foams are suitable insulation materials for aero applications. Open-cell foams offer the possibility to easily insulate more complex shapes since they are flexible and thermo-formable [18]. However, as these foams feature an open-cell internal structure, the cryopumping effect due to possible leakages and ruptures can be detrimental. To tackle cryopumping, a vapor barrier enveloping the foam layer is mandatory. Open-cell foams are usually employed for three reasons: (1) to tackle condensation and solidification of atmospheric gases by serving as a purged layer, (2) to accommodate dimensional changes, and (3) to support the exterior composite fairing, which serves as the aircraft skin in the case of an integral tank [11]. Closed-cell foams are more rigid and less thermo-formable than open-cell foams, but they still are excellent candidates for this application [11]. They do not suffer from the cryopumping effect because of the closed-cell conformation which makes them almost unaffected by gas penetration. They are generally more resistant to thermal cycling and compressive loads. From the literature, there are four main candidates for this family of foams: (1) polystyrene, (2) Rohacell, (4) polyvinylchloride, and (3) polyurethane.

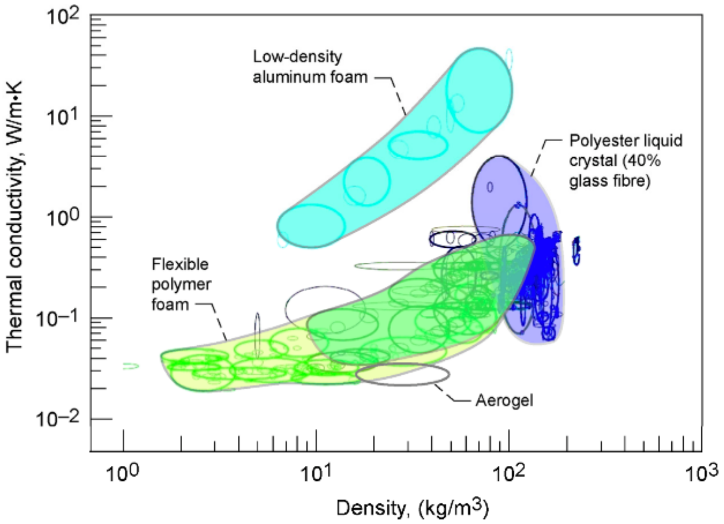


Figure 5: Thermal conductivity (y-axis) versus mass density (x-axis) for various insulation materials [10].

As previously stated, MLI coupled with vacuum employs thermal radiation shields perpendicularly oriented to the heat flow direction. These shields consist of alternating layers of low-emissivity metal foils and thin insulating spacers, designed to prevent direct metal-to-metal contact. Perforations are made in the metal foils to facilitate the evacuation of residual gases during vacuum setup. In the context of aviation, double-aluminized mylar combined with Tissuglass is considered the best MLI available in terms of thermal insulation and insensitivity to compression loads [18]. The thermal conductivity is around 10^{-5} – 10^{-8} W/m K.

4 FINAL COMPARISON OF THE SELECTED TECHNOLOGIES

Table 1 presents a collection of the selected technologies based on the available literature. Many works performed parametric studies considering different strategies regarding tank-fuselage integration, wall materials, and insulation technologies. For the sake of conciseness, only the most efficient configurations are presented.

Table 1: selected technological options found in the literature of liquid hydrogen tanks for commercial aviation.

	Tank-fuselage integration	**Liner material**	**Wall material**	**Insulation type**
Verstraete [18]	Integral	Linerless	AA2219	Polyurethane foam
Sekaran et al. [19]	Non-integral	AA5085	Polyethylene	Polyurethane foam
Rao [20]	N/A	N/A	Carbon fiber-reinforced polymer	N/A
Goldberg [21]	Non-integral	AA5086	Polyethylene	Rohacell foam
Silberhorn et al. [22]	Non-integral and integral	N/A	Carbon fiber-reinforced polymer	Polyurethane foam
Winnefeld et al. [23]	Non-integral	Linerless	AA2219	Rohacell foam
Dietl et al. [12]	Non-integral	Linerless	AA2219	Polyurethane foam
Gomez et al. [13]	Integral	Metallic liner	AA2219	Internal foam insulation
Rompokos et al. [24]	Integral	Linerless	Aluminum alloy not specified	Polyvinylchloride foam
Van Woensel [25]	Integral	Polymeric liner	AA7075	Internal foam insulation
Dannet [26]	Non-integral	Linerless	AA2219	Polyurethane foam
Huete et al. [27]	N/A	Linerless	Aluminum alloy not specified	Polyurethane foam
Cipolla et al. [14]	Non-integral	Linerless	AA2219	Polystyrene foam
Onorato et al. [16]	Non-integral and integral	Linerless	AA2219	Polyurethane foam
Mantzaroudis et al. [7]	Non-integral	AA2219	Carbon fiber-reinforced polymer	Polyurethane foam

From Table 1, it is clear that the development of a universal technological solution for liquid hydrogen aviation tanks does not exist. This is due to the fact that the tank design is strongly related to the computational process and the adopted airframe. The analysis of the studies presented reveals a diverse range of configurations, but common traits can be identified.

Most of the works selected the non-integral tank to allow flexibility in shape and enable the study of the effects of different geometries within the aircraft. Conversely, some works adopt the integral tanks in order to achieve high performances in terms of volumetric efficiency.

By assessing the tank wall material, aluminum alloy 2219 emerges as the most favored one, attributed to its excellent strength-to-weight ratio and well-documented properties in the cryogenic region [11]. Further studies should concentrate on polymeric composites and liner materials to reduce mass and compensate for the higher volumes required by liquid hydrogen compared to conventional jet fuels. Some literature works have adopted carbon fiber-reinforced polymers with a liner but more testing at cryogenic temperatures is mandatory for practical use [28]. Metal matrix composites are also considered as a potential alternative to monolithic metals thanks to the combination of high strength, and low susceptibility to hydrogen permeation [10].

Regarding the insulation technology, the literature advocates for the use of closed-cell foams, in particular polyurethane foam. The use of MLI and vacuum insulation is not attractive for aviation. After all, the use of closed-cell foams only requires a single tank wall, while MLI needs two walls due to the vacuum jacket. The outer wall leads to an increased mass since it needs to sustain the high-pressure difference between the vacuum and the atmosphere [27]. Moreover, a possible vacuum loss due to a mechanical failure may pose catastrophic safety hazards leading to the complete vaporization of liquid hydrogen during flight. Therefore, foam-based systems are considered the best alternative also due to this safety aspect. Some works have adopted internal foam insulation in which the foam layer is placed between a liner, in contact with liquid hydrogen, and the inner wall. An internal insulation technology would be less susceptible to mechanical damage and cryopumping in the case of leakages. However, the challenge of internal insulation is to find an effective material or a combination of materials impermeable to hydrogen and that operates at cryogenic conditions.

5 CONCLUSIONS

To meet the emission goals and decarbonize the aviation sector, the development of liquid hydrogen tanks is fundamental. This task still needs further testing and new approaches but some conclusions can be drawn when assessing the open literature:

- regarding the tank-fuselage integration, some studies adopt the non-integral tank for its simplicity and shape flexibility to enable the study of different geometries, while others adopt the integral tank to maximize volumetric efficiency;
- the preferred tank wall material is aluminum alloy 2219 thanks to its strength-to-weight ratio, low-cost, and well-characterized properties at cryogenic temperatures;
- alternative wall materials such as polymeric and metallic composites are promising due to their low density but they are expensive, difficult to manufacture, and still require further investigation at cryogenic temperatures;
- regarding the insulation technology, closed-cell foams, in particular polyurethane, are preferred for their safety and simplicity over MLI and vacuum insulation systems which can lead to catastrophic failure in case of vacuum loss;
- future research on insulation should explore internal insulation systems that could offer improved mechanical resistance and reduced cryopumping risks.

This paper indicates that a universal solution for liquid hydrogen tanks does not exist. The decision on the tank-fuselage integration depends on the scope of the work: non-integral tanks provide shape flexibility, and integral tanks provide volumetric efficiency. Aluminum alloy 2219, and closed-cell foams are leading the field when assessing the selection of the materials. Promising alternatives to enable lighter and safer solutions, such as composite materials and internal insulation systems, still require further studies in the cryogenic region of operation.

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REFERENCES

[1] Hannah Ritchie, “What share of global CO_2 emissions come from aviation? - Our World in Data.” Accessed: Apr. 22, 2024. [Online]. Available: https://ourworldindata.org/global-aviation-emissions

[2] D. S. Lee *et al.*, “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018,” *Atmos Environ*, vol. 244, Jan. 2021, doi: 10.1016/j.atmosenv.2020.117834.

[3] European Union, “Flightpath 2050. Europe’s vision for aviation: maintaining global leadership and serving society’s needs.,” Jun. 2011, doi: 10.2777/50266.

[4] National Institute of Standards and Technology (NIST), “Thermophysical Properties of Fluid Systems.” Accessed: Apr. 22, 2024. [Online]. Available: https://webbook.nist.gov/chemistry/fluid/

[5] A. J. Colozza, “Hydrogen Storage for Aircraft Applications Overview,” 2002. [Online]. Available: http://www.sti.nasa.gov

[6] H. Webber and S. Job, “Realising zero-carbon emission flight: primary energy source comparison and selection,” 2021. Accessed: Jun. 20, 2024. [Online]. Available: https://www.ati.org.uk/wp-content/uploads/2021/10/FZ_0_6.1-Primary-Energy-Source-Comparison-and-Selection-FINAL-230921.pdf

[7] V. K. Mantzaroudis and E. E. Theotokoglou, “Computational Analysis of Liquid Hydrogen Storage Tanks for Aircraft Applications,” *Materials*, vol. 16, no. 6, Mar. 2023, doi: 10.3390/ma16062245.

[8] K. D. Timmerhaus and T. M. Flynn, *Cryogenic Process Engineering*. Springer Science, 1989. doi: 10.1007/978-1-4684-8756-5.

[9] R. R. Ratnakar *et al.*, “Hydrogen supply chain and challenges in large-scale LH2 storage and transportation,” *Int J Hydrogen Energy*, vol. 46, no. 47, pp. 24149–24168, Jul. 2021, doi: 10.1016/J.IJHYDENE.2021.05.025.

[10] S. K. Mital, J. Z. Gyekenyesi, S. M. Arnold, R. M. Sullivan, J. M. Manderscheid, and P. L. N. Murthy, “Review of Current State of the Art and Key Design Issues With Potential Solutions for Liquid Hydrogen Cryogenic Storage Tank Structures for Aircraft Applications,” Cleveland, OH, 2006. Accessed: Apr. 29, 2024. [Online]. Available: http://www.sti.nasa.gov

[11] G. Daniel. Brewer, “Hydrogen Aircraft Technology,” 1991, *CRC Press, Boca Raton, FL*.

[12] T. Dietl *et al.*, “Polaris - Design of a Liquid Hydrogen Turbo-Electric Transport Aircraft,” in *Deutscher Luft- und Raumfahrtkongress*, 2018. doi: 10.25967/480344.

[13] A. Gomez and H. Smith, “Liquid hydrogen fuel tanks for commercial aviation: Structural sizing and stress analysis,” *Aerosp Sci Technol*, vol. 95, Dec. 2019, doi: 10.1016/j.ast.2019.105438.

[14] V. Cipolla, D. Zanetti, K. Abu Salem, V. Binante, and G. Palaia, “A Parametric Approach for Conceptual Integration and Performance Studies of Liquid Hydrogen Short-Medium Range Aircraft,” *Applied Sciences*, vol. 12, no. 14, 2022, doi: 10.3390/app12146857.

[15] D. Verstraete, P. Hendrick, P. Pilidis, and K. Ramsden, “Hydrogen fuel tanks for subsonic transport aircraft,” *Int J Hydrogen Energy*, vol. 35, no. 20, pp. 11085–11098, Oct. 2010, doi: 10.1016/j.ijhydene.2010.06.060.

[16] G. Onorato, P. Proesmans, and M. F. M. Hoogreef, “Assessment of hydrogen transport aircraft: Effects of fuel tank integration,” *CEAS Aeronaut J*, vol. 13, no. 4, pp. 813–845, Oct. 2022, doi: 10.1007/s13272-022-00601-6.

[17] A. Zielinski, “Hydrogen-assisted degradation of some non-ferrous metals and alloys,” *J Mater Process Technol*, vol. 109, no. 1–2, pp. 206–214, Feb. 2001, doi: 10.1016/S0924-0136(00)00797-4.

[18] D. Verstraete and K. Ramsden, “The Potential of Liquid Hydrogen for Long Range Aircraft Propulsion,” PhD Thesis, Cranfield University, 2009.

[19] P. R. Sekaran, A. S. Gohardani, G. Doulgeris, and R. Singh, “Liquid hydrogen tank considerations for turboelectric distributed propulsion,” *Aircraft Engineering and Aerospace Technology*, vol. 86, no. 1, pp. 67–75, 2014, doi: 10.1108/AEAT-12-2011-0195.

[20] A. G. Rao, “Advanced Hybrid Engines for Aircraft Development AHEAD - Project Final Report,” 2015.

[21] C. Goldberg and D. Nalianda, “Techno-economic, Environment and Risk Analysis of an Aircraft Concept with Turbo-electric Distributed Propulsion,” PhD Thesis, Cranfield University, 2017.

[22] D. Silberhorn, G. Atanasov, J.-N. Walther, and T. Zill, “Assessment of Hydrogen Fuel Tank Integration at Aircraft Level,” in *Deutscher Luft- und Raumfahrtkongress*, Darmstadt, 2019.

[23] C. Winnefeld, T. Kadyk, B. Bensmann, U. Krewer, and R. Hanke-Rauschenbach, “Modelling and designing cryogenic hydrogen tanks for future aircraft applications,” *Energies (Basel)*, vol. 11, no. 1, Jan. 2018, doi: 10.3390/en11010105.

[24] P. Rompokos, A. Rolt, A. Rolt, T. Sibilli, and C. Benson, “Cryogenic fuel storage modelling and optimisation for aircraft applications,” in *Proceedings of the ASME Turbo Expo*, American Society of Mechanical Engineers (ASME), 2021. doi: 10.1115/GT2021-58595.

[25] C. W. C. Van Woensel, “Integration of a Liquid Hydrogen Fuel Tank into the Concept of the Flying-V,” Delft University of Technology, Delft, 2021. [Online]. Available: http://repository.tudelft.nl/.

[26] G. Dannet and I. Staack, “Integration of cryogenic tanks and fuel cells for future hydrogen-powered aircraft,” Master Thesis, Linkopings University, 2021. [Online]. Available: www.liu.se

[27] J. Huete and P. Pilidis, “Parametric Study on Tank Integration for Hydrogen Civil Aviation Propulsion,” *Int. Journal of Hydrogen Energy*, vol. 46, pp. 37049–37062, 2021.

[28] J. Hohe *et al.*, “Performance of fiber reinforced materials under cryogenic conditions—A review,” Feb. 01, 2021, *Elsevier Ltd*. doi: 10.1016/j.compositesa.2020.106226.